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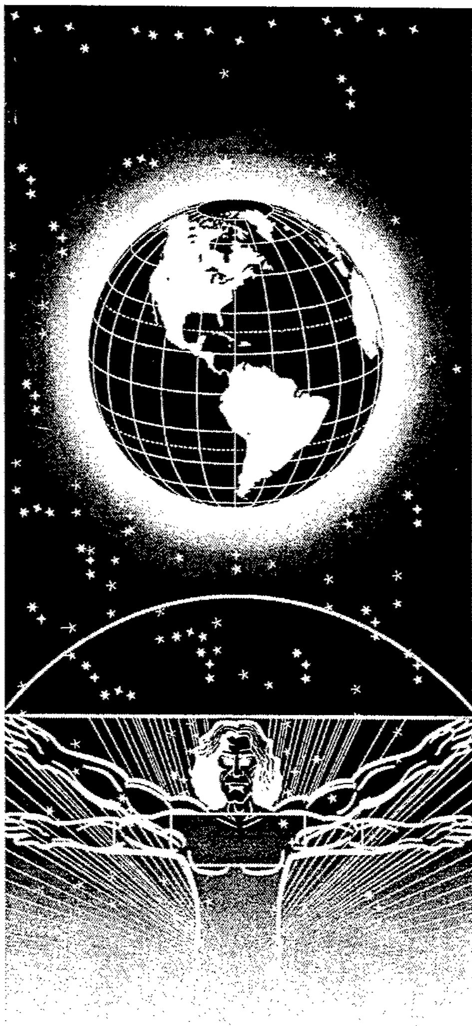

UNITED STATES AIR FORCE RESEARCH LABORATORY

TWENTY-PLUS YEARS OF NIGHT VISION TECHNOLOGY: PUBLICATIONS AND PATENTS FROM THE CREW SYSTEM INTERFACE DIVISION OF THE AIR FORCE RESEARCH LABORATORY AT WRIGHT-PATTERSON AIR FORCE BASE, OHIO

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This report has been reviewed by the Office of Public Affairs (PA) and is releasable to the National Technical Information Service (NTIS). At NTIS, it will be available to the general public.

This technical report has been reviewed and is approved for publication.

FOR THE COMMANDER

MARIS M. VIKMANIS
Chief, Crew System Interface Division
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13. ABSTRACT *(Maximum 200 words)*

For over twenty years, the Crew System Interface Division (HEC; www.hec.afrl.af.mil) of the Air Force Research Laboratory (AFRL), located at Wright-Patterson Air Force Base OH, has advanced night vision technology. This technology includes investigations into visual acuity through night vision goggles (NVGs), night vision imaging system (NVIS) cockpit lighting compatibility, wide field-of-view night vision devices, NVG measurement methodologies, plus human factors and aircraft integration issues. This document is a compilation of the complete text of selected publications and reports produced by AFRL/HEC addressing these various areas of night vision technology. It also includes a listing of relevant patent abstracts and a bibliography of other Division publications related to night vision technology.

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night vision goggles, NVG, visual acuity, resolution, NVIS cockpit lighting compatibility, wide field of view, panoramic NVG, NVG measurement, aircraft integration

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INTRODUCTION

Night vision goggles (NVGs) were first developed and introduced by the US Army for use by ground forces. They were later adapted for use in rotary- and fixed-wing aircraft. The Human Engineering Division of the Armstrong Aerospace Medical Research Laboratory (later becoming the Crew Systems Interface Division of the Air Force Research Laboratory or AFRL/HEC) at Wright-Patterson AFB, Ohio first became involved in Air Force use of NVGs in the late 1970s. Using NVGs in aircraft presented a unique and challenging set of cockpit and human-system integration issues. These issues were the focus of much of AFRL/HEC's involvement in the research, development and use of NVGs. Some of these integration issues include: visual acuity, resolution, peripheral vision, weight, transparency effects (materials, coatings, geometry), cockpit lighting compatibility, laser eye protection, G effects, egress, NVG characterization (signal-to-noise ratio, gain, modulation transfer function, field of view, dark spots, distortion, magnification, image rotation), optical design and aircrew acceptance criteria. This document provides a summary of the night vision research and development efforts of AFRL/HEC over the past twenty-plus years. It includes the complete text of selected in-house publications addressing visual acuity, lighting and display compatibility, panoramic NVGs, the measurement of NVGs and their related components and human factors interface issues. Also, included is a listing of this Division's night vision related patents and a bibliography of other AFRL/HEC night vision articles.

I. SELECTED NIGHT VISION RELATED PUBLICATIONS

1. VISUAL ACUITY AND NIGHT VISION GOGGLES

One of the most frequently referenced parameters relating to the capability or quality of night vision goggles is visual acuity. This parameter is often mistakenly referred to as the *visual acuity of NVGs*. Since visual acuity is an attribute of human vision, this statement is incorrect. However, the intent of this statement is to convey a sense of the performance level that the NVGs can attain. When one is referring to an optical instrument or display, such as an NVG, the appropriate term to use is *resolution*. Resolution is the level of detail that an optical or display device can sense or resolve independent of whether or not the human eye can actually see the level of detail. Since both metrics can have the same units (such as cycles/mrad), it is easy to understand why these two different terms are often used interchangeably.

Several parameters can affect human visual acuity independently of the NVGs, such as luminance (how much light is getting into the eyes) and contrast (what is the difference or ratio between the bright and dark areas of the image that is used to test visual acuity). In general, as light level and contrast are reduced, visual acuity is degraded. Therefore, visual acuity obtained when viewing through NVGs tends to be worse when the light and contrast are reduced.

This section contains select publications that deal with the issue of assessing human visual acuity capability, while using NVGs. The first article, Pinkus & Task (1998), discusses the basics of measuring human visual acuity through night vision goggles. The second article, Pinkus, Task, Dixon & Goodyear (2000), investigates the variability associated with measuring visual acuity through NVGs. Task (2001) describes the results of an interagency test to determine the repeatability and reproducibility of NVG visual acuity. Each participating organization used their own NVG visual acuity test procedures on the same two pair of NVGs. Pinkus & Task (1997) demonstrates that visual acuity is reduced when viewing through aircraft transparencies that have lower night vision imaging system (NVIS) transmission coefficients (less available near infrared light). Different canopy coatings can have different transmission effects. Task, Riegler & Goodyear (1999) shows that the reduction in visual acuity due to light loss can be caused by transmission effects either at the eyepiece of the NVGs or at the objective lens. For example, aircraft transparencies cause a reduction of light entering the objective lens, while aircrew laser eye protection or glasses cause a reduction of light at the eyepiece side of the NVG. Riegler, Whiteley, Task & Schueren (1991) explores the effects of light level, contrast and the inherent signal/noise ratio of the image intensifier tube on visual acuity. Gleason & Riegler (2001) describes the impact of the diopter setting of the NVG eyepiece, on visual acuity for both short term and long term wear of the NVGs. The last article, Donohue-Perry, Task & Davis (1994), shows the effect of field of view (FOV) on visual acuity through NVGs. For a given image intensifier tube, the same number of pixels (picture elements or resolution elements) must be spread over a larger angular area to get a larger FOV. This spread increases the visual angle per resolution element, thereby reducing the device's resolution and the visual acuity that can be obtained.

These articles are reprinted to provide the reader with a reference and background to better understand NVG-aided visual acuity.

Pinkus, A. R., & Task, H. L. (1998). **Measuring observers' visual acuity through night vision goggles.** *Proceedings of the 36th Annual Symposium SAFE Association* (pp. 1-11).

Pinkus, A. R., Task, H. L., Dixon, S. A., & Goodyear, C. D. (2000). **Reproducibility limits of night vision goggle visual acuity measurements.** *SAFE Journal, 30(1),* 131-139.

Task, H. L. (2001). **Night vision goggle visual acuity assessment: results of an interagency test.** *Proceedings of SPIE – International Society for Optical Engineering Helmet- and Head-Mounted Displays VI, USA, 4361,* 130-137.

Pinkus, A. R., & Task, H. L. (1997). **The effects of aircraft transparencies on night vision goggle-mediated visual acuity.** *Proceedings of the 35th Annual Symposium SAFE Association,* (pp. 93-104).

Task, H. L., Riegler, J. T., & Goodyear, C. D. (1999). **Effects of laser eye protection and aircraft windscreens on visual acuity through night vision goggles.** *Proceedings of the 37th Annual Symposium SAFE Association,* http://www.safeassociation.com

Riegler, J. T., Whiteley, J. D., Task, H. L., & Schueren, J. (1991). ***The effect of signal-to-noise ratio on visual acuity through night vision goggles.*** (Report No. AL-TR-1991-0011). Wright-Patterson AFB, OH: Armstrong Laboratory. (DTIC No. A260579)

Gleason, G. A., & Riegler, J. T. (2001). ***The effect of eyepiece focus on visual acuity through ANVIS night vision goggles during short- and long-term wear.*** (Report No. AFRL-HE-WP-TR-2001-0033). Wright-Patterson AFB, OH: Air Force Research Laboratory.

Donohue-Perry, M. M., Task, H. L., & Davis, S. A. (1994). ***Visual acuity vs. field-of-view and light level for night vision goggles (NVG).*** (Report No. AL/CF-TR-1994-0076). Wright-Patterson AFB, OH: Armstrong Laboratory. (DTIC No. A284750)

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Pinkus, A. R., & Task, H. L. (1998). Measuring observers' visual acuity through night vision goggles. *Proceedings of the 36th Annual Symposium SAFE Association* (pp. 1-11).

Measuring Observers' Visual Acuity Through Night Vision Goggles

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ABSTRACT
Use of night vision goggles (NVGs) for military applications has grown steadily over the past 30 years. Each successive NVG model represents some kind of improvement in terms of size, weight, ruggedness, gain, noise, spectral sensitivity, field-of-view or resolution. The primary focus of this paper is the determination of NVG resolution. Many methods have been devised to measure the resolving power of NVGs and each method has with it an associated variance or accuracy of measurement. This variance is most likely caused by several sources including observer visual capability (since most methods involve visual observations and judgement to assess NVG resolution). The main purpose of this paper is to present the different methods that have been used to assess NVG resolution and to determine to what extent observer visual capability limits the accuracy of NVG resolution measurement. This study uses a methodology that measures an observer's psychometric function when viewing through NVGs (percent correct detection as a function of spatial separation) to determine their visual acuity using probit analysis.

INTRODUCTION and BACKGROUND

Night vision goggles (ITT) allow an observer to see objects that are illuminated by very low amounts of light energy by greatly amplifying the light level. Present generation NVGs have a gain (as measured by the Hoffman ANV-120) of 6000 or more which means that for an object illuminated by a 2856K color temperature light source the NVGs present a luminance that is 6000 times brighter than the object viewed directly. However, the image intensifier tubes that are the heart of the NVGs also have an automatic brightness control which limits the output luminance. For present generation NVGs this maximum average output luminance is on the order of 2 to 4 foot-Lamberts. Since visual acuity depends on light level it is apparent that the level of detail that can be seen through the NVGs depends on the illumination level on the target scene. This becomes a factor in determining the resolution of NVGs.

The term "resolution" is defined (the definition of interest to this topic) by Webster's Ninth New Collegiate Dictionary as "the process or capability of making distinguishable the individual parts of an object, closely adjacent optical images, or sources of light." The same dictionary defines "visual acuity" as "the relative ability of the visual organ to resolve detail that is usually expressed as the reciprocal of the minimum angular separation in minutes of two lines just resolvable as separate and that forms in the average human eye an angle of one minute." It is apparent from these two definitions that "resolution" and "visual acuity" are somewhat connected but are not quite the same thing, especially when we refer to the "resolution" of the NVGs. The primary reason for having a parameter such as resolution is to try to describe the capability of the NVG. However, all current widely used methods of measuring NVG resolution involve the use of human observers and vision. This has both good and bad points. The good point is that the NVGs are intended to be used with human vision in operation; so using vision as the means to assess NVG resolution seems to make sense. The bad point is that when one uses human visual capability as an integral part of a measurement procedure one may end up with increased variance due to individual differences or dynamic shifting of human visual threshold. The purpose of the research described herein is to determine the extent of human visual acuity variance when viewing through NVGs by using "frequency of seeing" curves. This is a time-consuming approach and is not suitable as a routine method for characterizing NVG resolution; but it does provide some insight into limitations of other methods used to measure NVG resolution.

There is a subtle but very real difference between "NVG resolution" and "visual acuity through NVGs." This can be demonstrated by the following example. Suppose that some day advanced technology produces a "super" NVG capable of presenting details down to a tenth of a minute of arc. If vision is used to assess these "super" NVGs we would get a reading of about 1 minute of arc since that is the limit of visual capability; even though the NVGs were presenting details one tenth of this size. Thus, in this case, what is being measured is actually "visual acuity through NVGs" and not the actual "NVG resolution." As long as NVG capability is worse than human visual capability there is not a significant difference between the two. However, even with today's NVGs the difference between "NVG resolution" and "NVG visual acuity" can be significant at low light levels. Although the measurement methods described in the following section are used to measure "NVG resolution" most of them actually measure "NVG visual acuity."

METHODS USED TO MEASURE NVG RESOLUTION

Snellen Letter Charts

The Snellen eye chart is frequently used by optometrists to assess patients' visual acuity. The chart displays rows of letters starting with a very large size (20/200) and stepping down to the smallest (20/10). A measured Snellen acuity of 20/40 means that the person sees certain chart letters at a 20 foot viewing distance as well as a person with normal sight sees the same chart letters at 40 feet. The visual acuity score can be converted to minutes of visual subtended angle by taking its reciprocal (for example 40/20) and then dividing to get (2) minutes of arc (MOA). Miller, Provines, Block, Miller and Tredici (1984) used the Snellen eye chart to measure visual acuity through NVGs. The tumbling E (used by Wiley, 1989; Levine and Rash, 1989) chart has also been used to measure visual acuity through NVGs. Some researchers (Kotulak and Rash, 1992) prefer to use the Bailey and Lovie (1976) eye chart which has logarithmically sized letters.

Limiting Resolution

Limiting resolution is defined as the spatial frequency at which the modulation transfer function (MTF) of the NVGs (Stefanik, 1994) and the visual threshold function or VTF (Campbell and Robson, 1968; Task, 1979) intersect (see Figure 1). This intersection point occurs at the highest spatial frequency that the NVG can transmit with sufficient contrast that the human eye can see it. This spatial frequency can be converted to an equivalent Snellen acuity or other convenient resolution unit. (Barfield and Furness, 1995). Though the concept itself is straightforward, there are underlying problems associated with its implementation. The MTF of an NVG is difficult to measure because of the low light level and the scintillation. Also, the VTF has a certain amount of variance associated with its measurement since it involves human vision. It order to accurately predict the limiting resolution using this approach one would need to measure the observers VTF for the same color, luminance levels, and noise levels that occur in the NVG. Both the VTF and the MTF measurements are time consuming processes and not suitable for routine testing. In addition, the variance associated with both the MTF and the VTF mean that there will be a corresponding uncertainty regarding the location of the intersection of these two. This results in a fairly significant variance in the final limiting resolution determination.

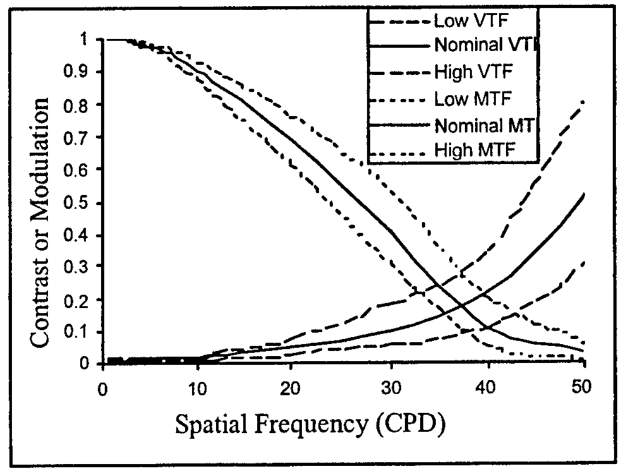

Figure 1. Idealized NVG MTF (upper thick solid line) and VTF (lower thick solid line); their intersection defines limiting resolution. Note the range (about 33 cpd to 43 cpd in this example) of possible limiting resolution values due to the variance (the upper and lower dashed lines) in the MTF and VTF measurements.

1951 AF Tri-Bar Target

One of the most frequently used resolution test standards is the 1951 Air Force tri-bar target (see Fig. 2) which was originally developed as a tool to evaluate the optical performance of airborne reconnaissance systems (MIL-HDBK-141). This target pattern contains seven groups having six elements each. Each element is comprised of a pair of three-bar patterns, one pattern is vertically oriented and the other is larger by a factor of the 6^{th} root of 2 (about 1.1225) than the next smaller element. This means the first element of each group is exactly twice as large as the first element of the next smaller group. The original 1951 USAF tri-bar target was designed with Group 0, Element 1 set to one line pair per millimeter. However, in order to use this pattern to evaluate NVGs the basic pattern has been greatly magnified as a wall chart. A conversion factor must be devised to convert from the Group and Element number to NVG resolution. Most of the time NVG resolution is given as a Snellen acuity equivalent with the conversion being 1 minute of arc angular subtense of a bar width corresponds to 20/20 Snellen visual acuity. A Snellen acuity of 20/40 would correspond to a bar width of 2 minutes of arc and so on.

NVG resolution is determined by having a trained observer view the tri-bar pattern under specified illumination conditions (which may be between overcast starlight up to full moon illumination equivalent) and then state which Group and Element number he/she can "resolve." This is then converted to a Snellen acuity equivalent using the conversion assumptions stated above. When doing NVG evaluations agencies may have 3 trained observers whose responses to this test are averaged to determine the "resolution" of the night vision goggles. Although the 1951 tri-bar target pattern has proved to be very useful over the years in comparing lens systems it still has a certain amount of variance due to differences in observer criteria as to when the tri-bars are "resolved" (Farrell and Booth, 1984, p. 3.1-41, item 18). Studies using the tri-bar pattern have shown observer "resolution" discrepancies of as much as 60%. (Farrell and Booth, 1984, p. 3.1-41 item 18).

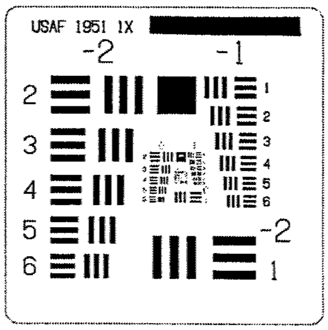

Figure 2. US Air Force 1951 tri-bar resolution chart.

3X3 Square-Wave Target Array
The 3x3 square-wave target array (Task and Genco, 1986) was developed about 1989 as a means for pilots to do a quick verification that their NVGs were operating correctly and were capable of resolving detail to a specified level. This chart has several features that set it apart from the 1951 AF target. The chart has nine square-wave patterns, arranged in a 3x3 array as shown in Figure 3. For its standardized viewing distance of 20 ft., each pattern was sized to equal specific Snellen values of 20/20 through 20/60 in increments of five. Their locations and orientations within the array were randomized. To increase the number of randomized grating orientations for a repeated measurements test, the chart is simply rotated to any one of its four orientations which has the effect of quickly changing grating locations and orientations within the 3x3 array. Each chart orientation was numbered one, two, three and four which keyed it to legends on the back of the chart for quick acuity reference. Charts having different levels of contrast were also made.

The chart was placed at a 20 ft. viewing distance and illuminated with a 2856K color temperature illumination source that could be adjusted to various desired illumination levels. After adjusting the NVGs, the trained observer examines pattern, reporting which grating structure could be resolved and its orientation (vertical or horizontal). After all of the rows are viewed, the chart is rotated to a new orientation and the test is repeated. With this kind of chart, repeated measurements can be quickly made and the results, which are in Snellen acuity, can be directly compared to what the NVGs should be capable of resolving. This method has been successfully used for many years and has been adopted as the standard test chart that squadrons use to perform preflight NVG adjustments and to insure that the goggles are performing optimally. However, the step sizes between patterns are relatively large making this pattern unsuitable for comparing the capability of different NVGs that are somewhat close in their resolving power.

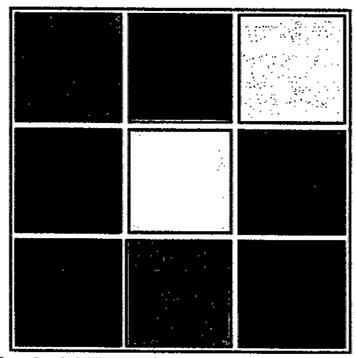

Figure 3. The 3x3 NVG chart (US Patent 4,607,923).

Step-Back Method
In an effort to refine the square-wave grating pattern to obtain smaller step sizes between resolutions a variation was developed and constructed (see Figure 4) containing six pairs of vertically and horizontally oriented square-wave gratings (Donohue-Perry, Task and Dixon, 1994). While looking through the NVGs at the pattern from a distance of 30 ft, the observer selected the smallest resolvable target pair. Then the observer would slowly step backwards until the selected target pair was no longer resolvable. The observer then stepped forward until the square-wave pair could barely be resolved. This final viewing distance was then used to calculate the exact Snellen acuity of the selected target pattern. The spatial frequencies of the square-wave patterns were sufficiently close together in spatial frequency that the observer would not have to step back more than 3 ft (10% of the baseline viewing distance) thereby minimizing the effect of possible objective lens misfocus.

The step-back method eliminated the problem of step sizes between target patterns by making the angular subtense of the square-wave pattern a continuous variable. When doing an NVG resolution evaluation measurements were typically repeated several times (e.g. 5) for 3 trained observers and then averaged to determine the final value.

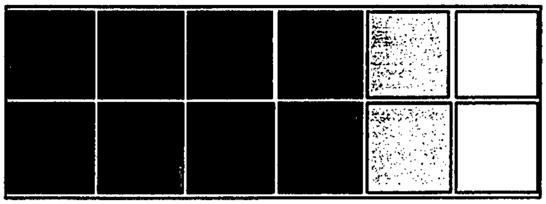

Figure 4. Example of the square-wave chart used in the step-back method.

Landolt C

Another assessment method uses Landolt C stimuli (National Academy of Sciences, 1980). The Landolt C is a perfectly circular C (no serifs) that has a specified contrast and gap size. The gap size is varied as is the orientation. The observer's task is to detect the orientation of the gap. Pinkus and Task (1997) used closely sized Landolt C stimuli in a two-alternative, forced-choice (2AFC) method to determine visual acuity through NVGs as a function of night-time ambient illumination levels. A computer executed the 2AFC (gap seen up or down), Step Program adapted from Simpson (1989). Based on the observer's last response, the program selected the specific gap size (smaller or larger) of the next Landolt C to be presented, according to *a priori* rules inherent in the algorithm. This method allowed relatively efficient convergence to a threshold acuity usually within 10 to 35 trials. The step method yielded reasonable results but informal repeatability tests found that the observer's scores varied from day to day. These variations could be due to a number of variables: working at threshold levels, NVG drift, good guessing in the 2AFC method, fatigue, eye strain, sinus headaches and so on.

METHOD

Psychometric Function of Acuity Through NVGs

Probit analysis (Finney, 1980) provides a method by which to fit a smooth s-curve through empirically derived probabilistic data. The threshold acuity of a trained observer may be determined by first measuring the probability of correct responses (the location of a Landolt C's gap) as a function of gap size. In order to reduce the effects of "good guessing", we used a four-alternative, forced-choice (4AFC) presentation of Landolt C's where the observer had to state if the gap was oriented up, down, left or right. The probabilities of the resulting s-curve, or ogive function, were then converted to z-scores and a straight line was fit to the data. When the z-score data were converted back to their equivalent probabilities and replotted, the line formed a smooth, s-shaped curve through the data. Depending on the number of possible outcomes in a particular forced-choice paradigm, the floor of the curve was usually near chance levels (25% for 4AFC). As gap size increased, the probability of correct detection of its orientation increased until it asymptotes at the 100% correct level. Though arbitrarily selected, the acuity (or any other quantity) is conventionally defined as the value that corresponds with the probability point that is half way between chance and 100% correct (Brown, Galanter, Hess and Mandler, 1962). This point is at the 62.5% probability level for the 4AFC presentation. The present study derived visual acuity through NVGs by measuring this psychometric function.

Participants

The three participants in this study were highly trained psychophysical observers, two males and one female, ranging in ages from 36 to 47 years.

Apparatus and Stimuli

The study utilized a set of ITT Model F4949C (serial #0356) NVGs that had P-43 phosphor (green) image intensifier tubes. The goggles had a gain (Hoffman) of about 5000 as measured by a Hoffman ANV-120 Night Vision Goggle Test Set. With the room lights off and the NVGs on, the observer first adjusted the interpupillary distance (IPD) of the goggles. Next they adjusted the eyepiece lenses by looking at the dark ceiling with the goggles and focusing until the scintillation looked sharp. Objective lenses were then focused by viewing an approximately one-half moon illuminated NVG resolution chart (see Fig. 2) composed of square-wave gratings (Task and Genco, 1986).

All observations were made in a light-tight room. The observer sat in a chair behind a table with their eyes 9.14 m (30 ft) from the stimulus target. The NVGs were held in a mount at the proper height for viewing while the observer was seated. The goggles were powered using a regulated external power supply.

The stimuli were high contrast (70% Michelson) Landolt C's (National Academy of Sciences, 1980) printed using a high resolution photo-grade laser printer. After the study, the observers' data were converted to Snellen acuity (20/xx). The C's were mounted on 18 x 18 cm (7 x 7 in.) foam board. For presentation, the C was placed onto a larger surround board 61 x 61 cm (24 x 24 in.) that matched the high contrast Landolt C background reflectance. The background board was held on an easel and had a small ledge that held the letter C in the center. This ledge was invisible when viewed through NVGs. The C was then placed by the experimenter onto the ledge with the gap oriented either up, down, left or right. The experimenter's station was to the side of the stimulus easel.

An adjustable 2856K color temperature incandescent lamp (MIL-L-8576A, 1986) was used to produce the different illumination levels. Apertures were used to vary illumination intensity without affecting the color temperature. Table 1 shows the five illumination levels and the five corresponding luminance outputs from the NVG eyepieces used for the study. The lowest level is approximately equivalent to 1/100th full moon (RCA Electro-Optics Handbook, 1974). Each succeeding level is approximately double that of the previous level to form the five illumination levels. Another lamp, set to about one-half moon illumination of $1.3x10^{-1}$ lux ($1.2x10^{-2}$ fc) was used to illuminate an NVG resolution target (Task and Genco, 1986) during pretest goggle focusing.

Table 1. The five illumination levels used in the study and their corresponding NVG output luminances.

Illumination on Landolt C	NVG Output Luminance
$8.61x10^{-4}$ lux ($8.00x10^{-5}$ fc)	0.356 nit (0.104 fL)
$1.72x10^{-3}$ lux ($1.60x10^{-4}$ fc)	0.709 nit (0.207 fL)
$3.44x10^{-3}$ lux ($3.20x10^{-4}$ fc)	1.398 nit (0.408 fL)
$6.89x10^{-3}$ lux ($6.40x10^{-4}$ fc)	2.720 nit (0.794 fL)
$1.38x10^{-2}$ lux ($1.28x10^{-3}$ fc)	4.324 nit (1.262 fL)

Procedure

First the observer was partially dark adapted to the goggle output luminance for about 10 minutes. The stimulus was blocked from the observer's view by the experimenter when the stimulus was placement onto the easel. The experimenter asked the observer if he or she was ready, unblocked the stimulus for about 4 seconds, then blocked it again. The observer had to respond either "up, down, left, right" to indicate the orientation of the C. No feedback was given to the observer. The experimenter then removed the stimulus and placed the next stimulus size, at a randomized orientation, onto the easel. The procedure was repeated until all 112 stimuli were presented requiring about 55 minutes. One lighting level was tested per day for each observer.

RESULTS

Each of the four Landolt C orientations was repeated four times yielding 16 trials per Landolt C size. Each observer performed 16 trials for each combination of Snellen acuity and illuminance ($8.61x10^{-4}$, $1.72x10^{-3}$, $3.44x10^{-3}$, $6.89x10^{-3}$ and $1.38x10^{-2}$ lux). There were seven levels of Landolt C sizes used for each level of illuminance. The acuity ranges (Landolt C sizes) used for each illumination level were selected from pilot data. Four orientations, repeated four times, for seven gap size values, over five levels of illuminance and using three observers yielded a total of 1680 data points for the study. The percent of trials correctly identified was determined for each combination of observer, illuminance and acuity (N=16).

Chance alone would result in 25% correctly identified trials. It is assumed that percents that are less than 25% would approach 25% given a sufficient number of trials. The percents were transformed to adjust for chance. The procedure for this transformation is as follows:

Let: P = percent of correct trials
P_A = percent of correct trials adjusted for chance

(1) if $P < 25$ then $P = 25$
(2) $P_A = (P-25)*100/75$

Certain percents were not used for modeling. The rational for selecting percents used for modeling was to start with the *last value = 0* (if applicable) and end with the *first value = 100* (if applicable).

These percents were converted to normal equivalent deviates[10] (NED). An NED is the value of a standard normal variable whose cumulative probability (expressed as a percent) would equal the percent adjusted for chance. Since an NED can not be computed for 0% or 100%, 0% was set equal to 1% and 100% was set equal to 99%. The NED values were used as the dependent variable in a linear regression with acuity (gap size) as the independent variable (a linear relationship is assumed).

The estimated linear equation, $NED = b_0+b_1*acuity$, was expanded to the full range of acuity used for each illuminance. The predicted NED was then transformed back to percents. For each illuminance and observer, the acuity that corresponded with predicted 50, 75 and 95 percent correct trials adjusted for chance were determined. Results are shown in Table 2.

Table 2. Snellen acuity values (20/xx) corresponding to predicted 50, 75, and 95 percent correct trials adjusted for chance, for each illuminance and observer.

Illuminance (lux)	Obs	50%	75%	95%
$8.61x10^{-4}$	S1	30.6	36.1	44.0
	S2	35.0	40.0	47.2
	S3	32.1	36.0	41.6
$1.72x10^{-3}$	S1	26.0	29.0	33.3
	S2	23.2	26.0	30.1
	S3	27.7	30.4	34.2
$3.44x10^{-3}$	S1	24.8	27.9	32.4
	S2	21.8	25.8	31.5
	S3	23.9	27.8	33.3
$6.89x10^{-3}$	S1	22.0	26.1	32.1
	S2	23.5	27.4	33.0
	S3	22.5	24.0	26.2
$1.38x10^{-2}$	S1	23.0	25.1	28.0
	S2	21.1	23.3	26.5
	S3	21.1	23.7	27.4

The same procedure for determining the predicted percent of correct trials adjusted for chance that was performed for each illuminance and observer was also performed for each illuminance averaged across observers. Table 3 contains the percent of trials correctly identified for each combination of illuminance and acuity. Table 4 contains the percent of correct trials adjusted for chance. Table 5 contains the acuity values corresponding to predicted 50, 75 and 95 percent correct trials adjusted for chance. Figure 5 contains plots of NED regressed n acuity for each illuminance and Figure 6 contains plots of the predicted percents.

Table 3. Percent of correct trials (N=48) for each illuminance and Snellen acuity (20/xx).

Illuminance (lux)	Acuity (20/xx)	Percent Correct
$8.61x10^{-4}$	30.6	58
	32.5	54
	34.4	77
	36.3	77
	38.2	83
	40.1	79
	42.0	96
$1.72x10^{-3}$	19.1	29
	22.9	54
	26.7	65
	28.6	75
	32.5	96
	36.3	100
	38.2	98
$3.44x10^{-3}$	19.1	42
	22.9	56
	26.7	83
	28.6	81
	32.5	96
	36.3	100
	38.2	100
$6.89x10^{-3}$	19.1	46
	21.0	48
	22.9	65
	24.8	71
	26.7	83
	28.6	92
	30.6	96
$1.38x10^{-2}$	19.1	40
	21.0	69
	22.9	71
	24.8	85
	26.7	92
	28.6	98
	30.6	98

Table 4. Percent of correct trials (N=48) adjusted for chance, for each illuminance and Snellen acuity (20/xx). Percents in *italics* were not used for modeling.

Illuminance (lux)	Acuity (20/xx)	Percent Correct
$8.61x10^{-4}$	30.6	44
	32.5	39
	34.4	69
	36.3	69
	38.2	78
	40.1	72
	42.0	94
$1.72x10^{-3}$	19.1	6
	22.9	39
	26.7	53
	28.6	67
	32.5	94
	36.3	100
	38.2	*97*
$3.44x10^{-3}$	19.1	22
	22.9	42
	26.7	78
	28.6	75
	32.5	94
	36.3	100
	38.2	*100*
$6.89x10^{-3}$	19.1	28
	21.0	31
	22.9	53
	24.8	61
	26.7	78
	28.6	89
	30.6	94
$1.38x10^{-2}$	19.1	19
	21.0	58
	22.9	61
	24.8	81
	26.7	89
	28.6	97
	30.6	97

Table 5. Snellen acuity values (20/xx) corresponding to predicted 50, 75, and 95 percent correct trials adjusted for chance, for each illuminance.

Illuminance (lux)	50%	75%	95%
$8.61x10^{-4}$	32.6	37.5	44.7
$1.72x10^{-3}$	25.8	28.8	33.2
$3.44x10^{-3}$	23.6	27.4	32.8
$6.89x10^{-3}$	22.8	26.2	31.0
$1.38x10^{-2}$	21.5	24.3	28.4

The data presented in this results section up to this point were all collected as part of experiment 2 which used 3 trained observers. In preparation for experiment 2, data were collected on 2 observers using the same methodology. Table 6 and Figure 7 shows the data for these 2 observers for the 2 data collection sessions. This provides some indication of the repeatability of the procedures described herein.

Table 6. Visual acuity results for 50% probability level for 2 observers and 2 experiments.

		Illumination Level (lux)			
Observer	8.61E-04	1.72E-03	3.44E-03	6.89E-03	1.38E-02
O2-1	35.2	25.6	24	23.3	21.2
O2-2	35.0	23.2	21.8	23.5	21.1
O3-1	36.1	28.3	28.5	23.8	20.5
O3-2	32.1	27.7	23.9	22.5	21.1

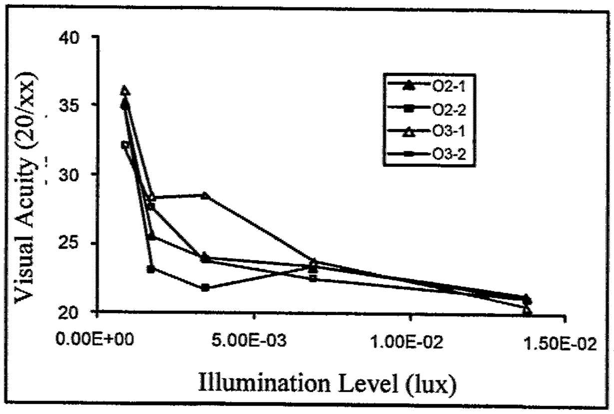

Figure 7. Comparison of visual acuity vs. illumination for 2 observers (S2 and S3) for two experiments.

DISCUSSION

The results of Table 5 showing averaged (across the 3 observers) visual acuity data for the 5 illumination levels does indicate the satisfying result that one would expect: namely, that visual acuity gets worse (higher number) as illumination level is reduced. This result holds for the 3 different probability levels shown in Table 5 (50%, 75%, and 95%). However, this does mask the difference in visual acuity measured for the different observers. Table 6 shows a comparison of the 50% probability visual acuity for 2 of the observers that participated in both this main experiment and a pilot experiment done earlier to establish procedures. It is apparent from Table 6 that there is a fairly large difference between the 2 observers at the lower illumination levels. At higher illumination levels the observer's performance converges both between the observers and between the two data collection sessions (experiment 1 and 2) graphically shown in Figure 7.

It is apparent from the graphs of Figures 5 and 6 that more presentation trials are needed to improve the smoothness of the "frequency-of-seeing" curves. However, the basic approach appears to be sound and should provide a good baseline for assessing visual acuity using other, less time-consuming, methodologies. Equipment and procedures are being designed to semi-automate data collection to obtain the "frequency-of-seeing" curves faster. Once this is done, we expect to compare NVG visual acuity using some of the widely used methodologies, such as the tri-bar chart and the square-wave chart, to specific probability levels on the frequency-of-seeing curves. The procedure would be to establish a frequency-of-seeing curve for a particular observer using a particular NVG. Then measure the NVG visual acuity of the same observer using the tri-bar chart and the square-wave chart. By comparing each of these NVG visual acuities to the frequency-of-seeing curve it should be possible to determine what probability level equates to the tri-bar chart procedure and the square-wave chart procedure.

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BIOGRAPHIES

Alan Pinkus has been a US Air Force psychologist since 1982. As a human factors engineer, he has worked on major systems including Royal Saudi Air Force KE-3 tanker, Gunship 2, LANTIRN, Air Force One and Joint-Stars. As a researcher, he has worked in the areas of image display metrics, night vision goggles, apparent motion, aircraft lighting, transparency analysis, vision from space, workload assessment and has lectured for NATO AGARD in Europe. Alan has a BS Degree (Wright State, 1974), an MA (University of Dayton, 1980) and a PhD (Miami University, 1992), all in Experimental Psychology. He holds seven patents (or pending) in the area of night vision goggle ancillary devices and has over 20 publications. He is a member of the Human Factors and Ergonomics Society (Southern Ohio Chapter), SAFE, Association of Aviation Psychologists and is active in the American Society for Testing and Materials Subcommittee F7.08 on Transparent Enclosures and Materials.

H. Lee Task has been employed as a research scientist for the US Air Force since 1971. He has served as chief scientist for the Armstrong Aerospace Medical Research Laboratory (prior to its reorganization and disestablishment in 1991) and is presently a senior scientist at the Visual Display Systems Branch of the Human Engineering Division, in the Armstrong Laboratory's Crew Systems Directorate, at Wright-Patterson AFB, Ohio. He is currently involved in research and development in the areas of helmet-mounted displays, vision through night vision goggles, optical characteristics of aircraft windscreens, vision, and display systems. He has a BS Degree in Physics (Ohio University), MS degrees in Solid State Physics (Purdue, 1971), Optical Sciences (University of Arizona, 1978), and Management of Technology (MIT, 1985) and a PhD in Optical Sciences from the University of Arizona Optical Sciences Center (1978). During his career he has earned 36 patents and has published more than 80 journal articles, proceedings papers, technical reports, and other technical publications. He is a member of the Human Factors and Ergonomics Society (HFES), the American Society for Testing and Materials (where he is chairman of Subcommittee F7.08 on Aerospace Transparencies and is a Fellow of the Society), the Association of Aviation Psychologists, SAFE association, the Society for Information Display (SID), and SPIE (the optical engineering society). He has served as reviewer for papers in SID, and HFES. Lee is currently the Editor of the *SAFE Journal.*

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Reproducibility Limits of Night Vision Goggle Visual Acuity Measurements

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ABSTRACT

The main purpose of the study was to determine reproducibility limits of night vision goggle (NVG) visual acuity measurement under relatively high and low illumination levels. Psychometric acuity functions of three observers were repeatedly measured using Landolt C's as stimuli. The reproducibility limits of the Snellen acuity value (20/xx) relating to 50, 75 and 95% correct (adjusted for chance) were then determined. Reproducibility limit is defined as approximately 95% of all pairs of replications (20/xx) from the same illuminance and same observer, generated on different days, should differ in absolute value by less than the reproducibility limit. It was determined that for the lower illumination (8.61E-4 lux) at 50% corrected for chance probability level, the reproducibility limit was 5.1 Snellen acuity (20/xx) and for the higher illumination (1.38E-2 lux), 2.5 Snellen acuity. These limits were 17% and 13% of mean acuity, respectively.

INTRODUCTION and BACKGROUND

There are numerous methods used to determine night vision goggle (NVG) visual acuity (Pinkus & Task, 1998); limiting resolution (Stefanik, 1994; Task, 1979), Snellen Acuity (Bailey & Lovie, 1976; Wiley, 1989; Miller, Provines, Block, Miller & Tredici, 1984), square-wave targets (Task & Genco, 1986), Landolt C's (Pinkus & Task, 1997), adaptive psychophysical (Simpson, 1989) and directly measuring the psychometric function (Pinkus & Task, 1998; Brown, Galanter, Hess, & Mandler, 1962). Each method produces a number that is composed of the actual acuity value plus error. There can be many sources of error but the largest are the method itself and the inherent variability of the observer while working under threshold conditions. Observer variability is reduced to a minimum through extensive training, testing the same time everyday and shortened sessions in order to reduce eye fatigue. Additionally, even though observers are given specific instructions, response criteria also vary among or within observers; even over the course of a single experimental session. To eliminate the *criteria problem*, Pinkus & Task (1998) used Landolt C's in a four-alternative forced-choice (4AFC) paradigm to measure the entire psychometric function. This paradigm allowed for any desired response criterion level (e.g., 50% or 75% corrected for chance, probability of detection) to be selected for the prediction of NVG visual acuity performance.

The goal in this study was to select a stable method and then determine its reproducibility (ASTM Practice E 691). Reproducibility represents observation-to-observation variability under a given set of viewing conditions. Directly measuring the psychometric function should keep variability due to the test method to a minimum. Determining reproducibility will allow the use of this test method to determine NVG visual acuity with a known error tolerance. The interpretation of visual acuity data is investigated in the discussion section.

METHOD

Participants

The trained observers were one female and two males highly experienced with the operation of NVGs. They ranged in age from 37 to 47 years, each having normal (20/20) or corrected-to-normal binocular visual acuity.

Apparatus and Stimuli

NVGs - Participants viewed the target stimuli using a pair of ITT model F4949D (SN 3872) NVGs. The goggles had a gain of approximately 5600 as measured using the Hoffman ANV-120 NVG Test Set. Before the start of each test session, the optical alignment of the NVGs was verified using the Hoffman ANV-126 Night Vision Tester.

Each test session was conducted in a light-tight laboratory. The observer was seated at an optical table with the NVGs secured in a stationary mount directly in front of them. The observer was able to adjust their seat to the proper height for viewing through the NVGs. An external regulated power supply was used to energize the goggles.

At the beginning of each test session the observer would set up and pre-focus the NVGs using the following procedure. After dark-adapting for 15 minutes, the NVGs were powered on and the observer adjusted the inter-pupillary distance until a fused circular image was visible. The observer (using their dominant eye) focused one channel at a time. The observer first focused on the green scintillation by looking at the ceiling and adjusting the eyepiece until the focus of the scintillation was as sharp as possible. Next, the observer focused the corresponding objective lens by viewing the 3 x 3A, NVG high-contrast square-wave resolution chart (Task and Genco, 1986) located at a 30 ft distance (optical infinity). The objective lenses were pre-focused using the highest illumination level (1.38 x 10-2 lux). A higher illumination level allows the observer finer, low noise focusing. The observer chose the finest grating clearly resolvable and adjusted the objective lens to the sharpest focus possible. If necessary, the observer fine tuned the eyepiece while viewing the chart. These steps were repeated for the second channel.

Illumination source and Illumination levels - Table 1 shows the illumination levels and corresponding NVG eyepiece luminance outputs. The lowest illumination level is approximately equivalent to 1/300th full moon (RCA Electro-Optics Handbook, 1974, p. 65) while the highest illumination level is 16 times brighter. The low illumination level corresponds to a practical lower limit under which goggles are used in the field. The higher level corresponds to an approximate ¼ moon level. Target stimuli were illuminated by one or two moon illumination lamps outfitted with adjustable 2856K color temperature incandescent bulbs (MIL-L-8576A, 1986). Metal apertures were used to achieve the two illumination levels. Using apertures to vary illumination intensity did not affect the 2856K color temperature. The target illumination levels were measured and adjusted prior to each test session. The goggle output luminances were measured using a NVG photometer (Pinkus, 1991).

Table 1. The two illumination levels (average) and corresponding NVG output luminances (average) for this study.

ILLUMINATION ON LANDOLT C	NVG OUTPUT LUMINANCE
8.61×10^{-4} lux (8.00×10^{-5} fc)	0.356 nit (0.104 fL)
1.38×10^{-2} lux (1.28×10^{-3} fc)	4.324 nit (1.262 fL)

Landolt C test stimuli and automated data recording device - Test stimuli were Landolt C's. The C's were printed using a high resolution, photo-grade laser printer. They were high contrast (67% photopic, Michelson; Farrell & Booth, 1984) Landolt C's (National Academy of Sciences, 1980) printed using a high resolution, photo-grade laser printer. The print out of each target was mounted on 18 cm x 18 cm (7" x 7") squares of foam board. Each target varied in gap size and represented, when converted, a specific Snellen visual acuity value (20/xx). The back of each target was labeled with four different bar code patterns. Each bar code contained identification information such as target number, type, contrast, gap orientation and corresponding visual acuity (20/xx). On each experimental trial, a Landolt C was placed in the center of a larger foam board surround 56 cm x 56 cm (22" H x 22" L). The surround had the same reflectance as the background of the Landolt C's. This surround was secured to the front of a black light-tight wooden box. The box measured 66 cm H x 56 cm W x 36 cm L (26 H x 22" W x 14" L) and sat on top of a stand. This box housed a bar code scanner/reader used to automate the recording of Landolt C target information. The light-tight box prevented the incompatible red laser beam from the bar code scanner from affecting the NVGs. The bar code reader connected directly to a computer at the experimenter's station. The entire set up was positioned at 914 cm (30 feet) or optical infinity from the observer. A four button response box located next to the observer was also connected to the computer. The observer used the buttons to indicate the orientation of the Landolt C gap (up, down, left or right). The computer recorded the button press response and Landolt C bar code information as well as other pertinent information.

Procedure

Three trained observers participated in this study. Each observer completed 2 sessions per day on each of 3 days. Each session (140 randomized trials) used an illumination level of either 8.61E-04 or 1.38E-2 lux (target background reflectance's were 5.64E-5 and 9.03E-4 lux, respectively). At the beginning of each test session, the observer dark-adapted for approximately 15 minutes. The observer then turned on and focused the NVGs. For each trial, the experimenter, using pre-determined randomized stimuli ordering, placed a Landolt C onto a small ledge on the surround and kept it blocked from the observer's view. This ledge centered the 'C' and was not noticeably visible when viewed through the NVGs. The experimenter pressed a switch to scan the bar code on the back of the target. The experimenter would then move away from the Landolt C and the observer had about four seconds to view the stimulus. At the end of the four-second interval the computer would beep an alarm and the experimenter would immediately block the stimulus from the observer's view. The observer would press the appropriate button on the response box to indicate what direction the gap was oriented: up, down, left or right. The observer was not provided with any feedback on their performance. This sequence of events was repeated until 140 trials were completed (7 Landolt C target sizes x 4 orientations x 5 repetitions of each orientation). The 7 target sizes are Snellen acuity values (i.e., 20/xx).

RESULTS

Probit analysis was used to determine the observer's acuity, for each replication, that corresponded with 50%, 75%, and 95% correct adjusted for chance. These acuity values were then used to determine the reproducibility limit as previously defined.

Table 2 contains the percent of correctly identified orientations out of the 20 trials (4 orientations x 5 repetitions) for each combination of illuminance, observer, acuity, and replication. Chance alone would result in 25% correctly identified trials. It is assumed that percents that are less than 25% would approach 25% with a sufficient number of trials. The percents were transformed to adjust for chance. The procedure for this transformation was as follows:

Let: P = percent correct trials

P_A = percent correct trials adjusted for chance

(1) if $P < 25$ then $P = 25$

(2) $P_A = (P-25) * 100/75$

For probit analysis, adjusted percents are converted to normal equivalent deviates (NED). An NED is the value of a standard normal variable whose cumulative probability (expressed as a percent) would equal the percent correct adjusted for chance. The NED values are then used as the dependent variable in a linear regression with acuity as the independent variable, where a linear relationship is assumed (Finney, 1980). The estimated $NED=b_0+b_1*acuity$ is then transformed back to percents. The resulting estimates of P_A form a curvilinear function.

If there is a range of acuity values where P_A is near 0 or P_A is near 100, the relationship between NED and acuity will not be linear. The rationale for selecting percents used for modeling was to start with the largest acuity value where the observer was guessing (correct ≤ 7 out of 20 was used) if applicable, and end with the smallest acuity value where P_A=100, if applicable. Since an NED cannot be computed for 0% or 100%, 0% was set to 1% and 100% was set to 99%. Correct ≤ 7 was used as a 'guessing' cutoff since the probability of $8 \leq$ Correct is 0.10 by chance alone. Table 3 contains the percent of correctly identified orientations out of the 20 trials (4 orientations x 5 repetitions), adjusted for chance, for each combination of illuminance, observer, acuity, and replication. Results of NED regressed on acuity are shown in Figures 1a and 1b.

Table 2. Percent correct trials (N=20) for each illuminance, observer, acuity, and replication.

	Observer #1				**Observer #2**				**Observer #3**			
	Snellen	**% Correct**			**Snellen**	**%Correct**			**Snellen**	**%Correct**		
Illuminance	**Acuity**	**Replication**			**Acuity**	**Replication**			**Acuity**	**Replication**		
(lux)	**(20/xx)**	**1**	**2**	**3**	**(20/xx)**	**1**	**2**	**3**	**(20/xx)**	**1**	**2**	**3**
8.61E-4	24.8	55	35	45	24.8	35	65	45	26.7	35	50	47
	26.7	20	50	45	26.7	45	45	55	28.6	15	45	48
	28.6	65	37	75	28.6	50	60	70	30.6	50	70	55
	30.6	65	45	85	30.6	90	70	80	32.5	60	85	90
	32.5	90	58	90	32.5	80	80	85	34.4	75	80	89
	34.4	100	85	95	34.4	70	95	75	36.3	90	75	95
	36.3	100	75	100	36.3	90	85	90	38.2	100	95	95
1.38E-2	13.4	30	45	20	13.4	25	20	20	13.4	35	15	30
	15.3	20	30	45	15.3	30	40	50	15.3	35	25	30
	17.2	35	55	45	17.2	50	50	60	17.2	35	55	45
	19.1	70	75	45	19.1	80	45	85	19.1	75	80	70
	21.0	75	85	85	21.0	95	80	65	21.0	90	100	100
	22.9	65	85	100	22.9	100	95	80	22.9	90	100	100
	24.8	85	85	95	24.8	100	80	80	24.8	100	100	100

Table 3. Percent correct trials (N=20), adjusted for chance, for each illuminance, observer, acuity, and replication. Percents in italic were not used for modeling.

	Observer #1				**Observer #2**				**Observer #3**			
	Snellen	**% Correct**			**Snellen**	**%Correct**			**Snellen**	**%Correct**		
Illuminance	**Acuity**	**Replication**			**Acuity**	**Replication**			**Acuity**	**Replication**		
(lux)	**(20/xx)**	**1**	**2**	**3**	**(20/xx)**	**1**	**2**	**3**	**(20/xx)**	**1**	**2**	**3**
8.61E-4	24.8	40	13	27	24.8	13	53	27	26.7	*13*	33	30
	26.7	0	33	27	26.7	27	27	40	28.6	0	27	30
	28.6	53	16	67	28.6	33	47	60	30.6	33	60	40
	30.6	53	27	80	30.6	87	60	73	32.5	47	80	87
	32.5	87	44	87	32.5	73	73	80	34.4	67	73	86
	34.4	100	80	93	34.4	60	93	67	36.3	87	67	93
	36.3	*100*	67	100	36.3	87	80	87	38.2	100	93	93
1.38E-2	13.4	*7*	27	0	13.4	*0*	0	0	13.4	*13*	*0*	*7*
	15.3	*0*	7	27	15.3	7	20	33	15.3	*13*	0	7
	17.2	13	40	27	17.2	33	33	47	17.2	13	40	27
	19.1	60	67	27	19.1	73	27	80	19.1	67	73	60
	21.0	67	80	80	21.0	93	73	53	21.0	87	100	100
	22.9	53	80	100	22.9	100	93	73	22.9	87	*100*	*100*
	24.8	80	80	*93*	24.8	*100*	73	73	24.8	100	*100*	*100*

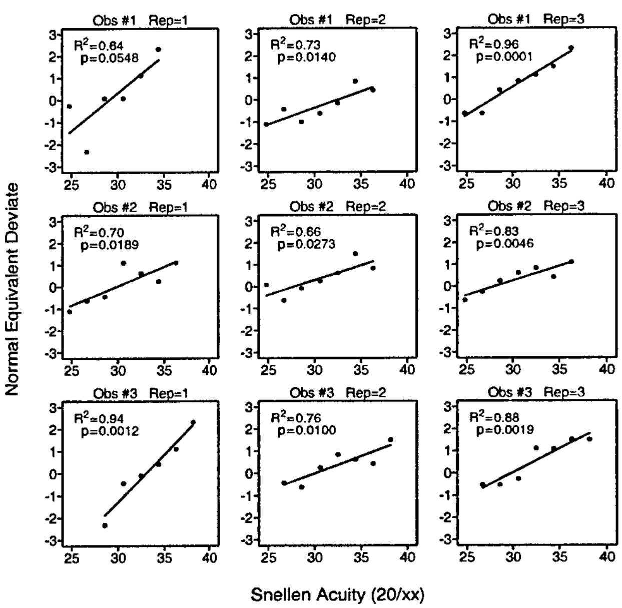

Figure 1a. For illuminance = 8.61E-4 lux, results of NED regressed on acuity for each observer and replication.

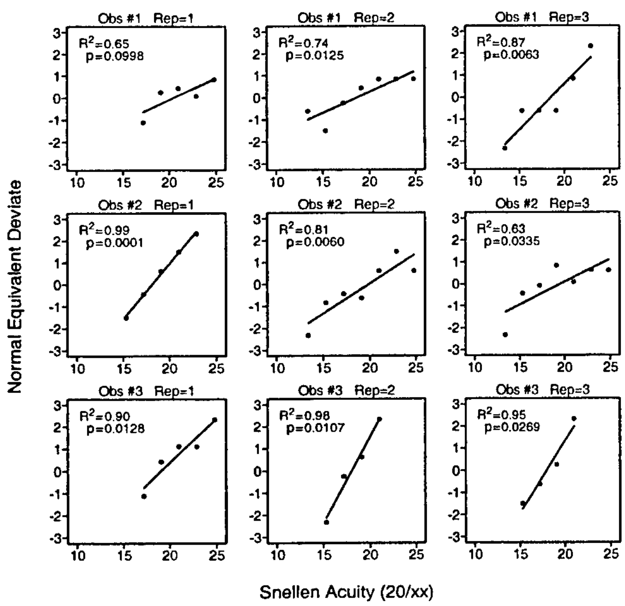

Figure 1b. For illuminance = 1.38E-2 lux, results of NED regressed on acuity for each observer and replication.

The estimated NED = b_0+b_1*acuity, as shown in Figures 1a and 1b, was transformed back to percents. For each illuminance, observer, and replication, the acuity that related to predicted 50, 75, and 95 percent correct adjusted for chance was determined. Plots of the predicted percents are shown in Figures 2a and 2b. Results are shown in Table 4. The reproducibility limits of the acuity value (20/xx) relating to 50, 75, and 95 percent correct adjusted for chance were determined. Reproducibility limit is defined as: approximately 95% of all pairs of replications (20/xx) from the same illuminance and same observer, generated on different days, should differ in absolute value by less than the reproducibility limit. Table 5 contains the reproducibility limits.

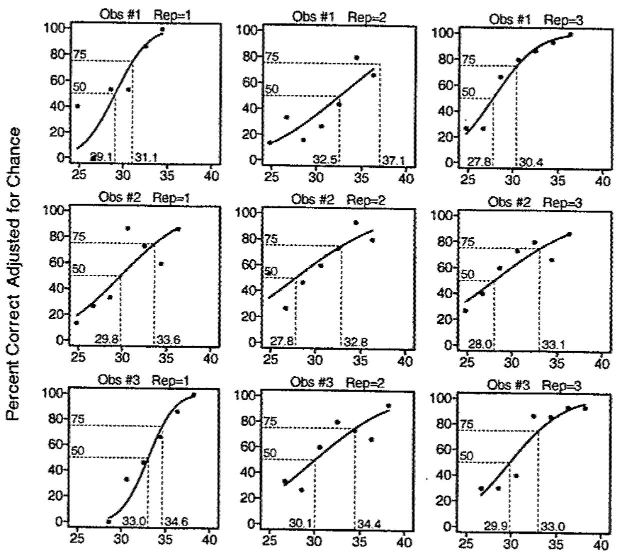

Figure 2a. For illuminance = 8.61E-4 lux, predicted percent correct adjusted for chance, for each observer and replication. Acuity values are given that relate to 50 and 75 percent correct adjusted for chance.

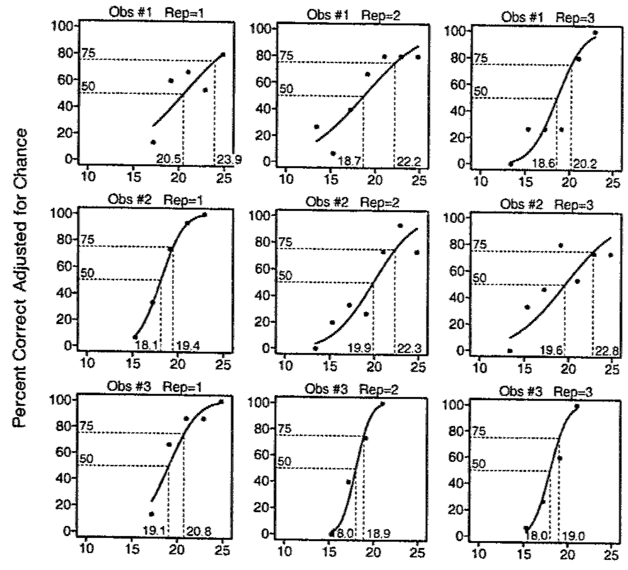

Figure 2b. For illuminance = 1.38E-2 lux, predicted percent correct adjusted for chance, for each observer and replication. Acuity values are given that relate to 50 and 75 percent correct adjusted for chance.

Table 4. Snellen acuity values (20/xx) relating to predicted 50, 75, and 95 percent correct adjusted for chance, for each illuminance, observer, and replication.

Illuminance (lux)	Observer	50% Replication 1	50% 2	50% 3	75% Replication 1	75% 2	75% 3	95% Replication 1	95% 2	95% 3
8.61E-4	#1	29.1	32.5	27.8	31.1	37.1	30.4	33.9	43.6	34.2
	#2	29.8	27.8	28.0	33.6	32.8	33.1	39.1	40.0	40.4
	#3	33.0	30.1	29.9	34.6	34.4	33.0	36.9	40.7	37.6
1.38E-2	#1	20.5	18.7	18.6	23.9	22.2	20.2	28.9	27.3	22.5
	#2	18.1	19.9	19.6	19.4	22.3	22.8	21.4	25.9	27.4
	#3	19.1	18.0	18.0	20.8	18.9	19.0	23.2	20.1	20.5

Table 5. Snellen acuity reproducibility limits (20/xx) for each illuminance and percent correct adjusted for chance.

Illuminance (lux)	% Correct (Adjusted)	Mean Acuity (20/xx)	RL (20/xx)	RL % of Mean
8.61E-04	50	29.8	5.1	17
	75	33.3	6.1	18
	95	38.5	9.4	24
1.38E-02	50	18.9	2.5	13
	75	21.1	4.5	21
	95	24.1	7.8	32

The same procedure for determining the predicted percent correct adjusted for chance that was performed for each illuminance, observer, and replication was also performed for each illuminance and observer, summed across replications. Table 6 contains the percent of trials correctly identified for each combination of illuminance, observer, and acuity. Figure 3 contains NED regressed on acuity. Figure 4 contains plots of the predicted percents. Table 7 contains the acuity values corresponding to predicted 50, 75, and 95 percent correct adjusted for chance.

Table 6. Percent correct trials (P) and percent correct trials adjusted for chance (P_A), for each illuminance, observer, and acuity. Trials have been summed across replications (N = 60). P_A in italics were not used for modeling.

	Observer #1			Observer #2			Observer #3		
Illuminance (lux)	Snellen Acuity (20/xx)	Percent Correct P	Percent Correct P_A	Snellen Acuity (20/xx)	Percent Correct P	Percent Correct P_A	Snellen Acuity (20/xx)	Percent Correct P	Percent Correct P_A
8.61E-4	24.8	45	27	24.8	48	31	26.7	44	25
8.61E-4	26.7	38	18	26.7	48	31	28.6	36	15
8.61E-4	28.6	59	46	28.6	60	47	30.6	58	44
8.61E-4	30.6	65	53	30.6	80	73	32.5	78	71
8.61E-4	32.5	80	73	32.5	82	76	34.4	81	75
8.61E-4	34.4	93	91	34.4	80	73	36.3	87	82
8.61E-4	36.3	92	89	36.3	88	84	38.2	97	96
1.38E-2	13.4	32	9	13.4	22	0	13.4	27	2
1.38E-2	15.3	32	9	15.3	40	20	15.3	30	7
1.38E-2	17.2	45	27	17.2	53	38	17.2	45	27
1.38E-2	19.1	63	51	19.1	70	60	19.1	75	67
1.38E-2	21.0	82	76	21.0	80	73	21.0	97	96
1.38E-2	22.9	83	78	22.9	92	89	22.9	97	96
1.38E-2	24.8	88	84	24.8	87	82	24.8	100	100

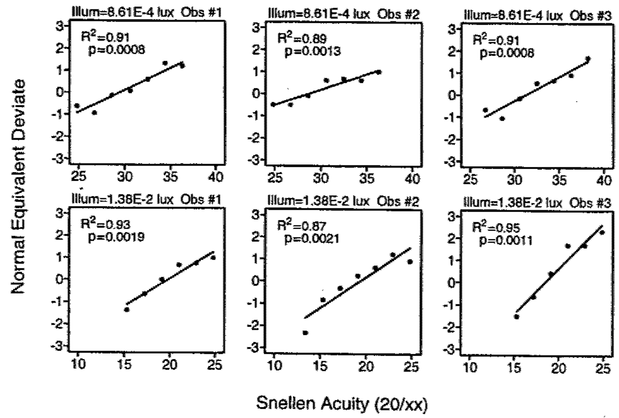

Figure 3. Results of NED regressed on acuity for each illuminance and observer.

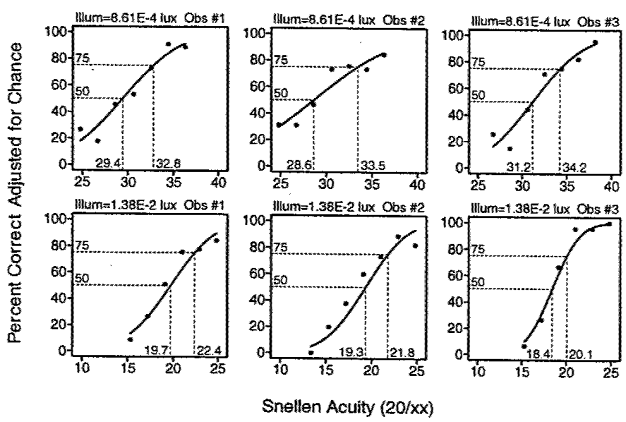

Figure 4. Predicted percent correct adjusted for chance, for each illuminance and observer. Acuity values are given that correspond to 50 and 75 percent correct adjusted for chance.

Table 7. Snellen acuity values (20/xx) corresponding to predicted 50, 75, and 95 percent correct adjusted for chance, for each illuminance and observer.

Illuminance (lux)	Observer	50%	75%	95%
8.61E-4	#1	29.4	32.8	37.6
	#2	28.6	33.5	40.4
	#3	31.2	34.2	38.6
1.38E-2	#1	19.7	22.4	26.3
	#2	19.3	21.8	25.2
	#3	18.4	20.1	22.4

DISCUSSION

Table 5 summarizes the Snellen acuity reproducibility limits at the two illumination levels for three levels of percent correct (adjusted for chance). The 50%, 75% and 95% percent levels represent threshold, a just-noticeable-difference (JND) above threshold and a conservative, high-confidence gap detection, respectively. The reproducibility limits, when taken as a percent of the mean, show similar variability at both the lower and higher illuminance conditions.

One way to apply the reproducibility limit is to use it to assign a range for a given NVG visual acuity measurement. Many times, the interactions between NVGs and other cockpit subsystems such as a gold-coated canopy or an incompatible light source, are evaluated by making only a few NVG visual acuity measurements (baseline versus a test condition) using just a couple of observers. The problem with this approach is that the variability that is inherent in both the test method and the observer can easily mask the true NVG acuity effects. The reproducibility limits at the 50% correct were approximately 15% of the mean acuity values (for this specific lab methodology only). When interpreting field data acuity results, 95% of all absolute differences in observations should differ by less than 15% of the mean acuity if variability is due solely to experimental error. If the data varies more than 15% than there are additional sources of variability such as the infrared-attenuating effects of canopy coating on NVG visual acuity. For example, if, under low light levels, an observer reports an NVG visual acuity baseline of 20/30 and then 20/35 while looking through a coated canopy, one might (erroneously) conclude that the canopy caused a large loss of acuity which translates into a loss of target acquisition slant range. The difference between 20/30 and 20/35 is 5 which when divided by their average of 32.5 equals 0.15 or 15%. A difference of five then is approximately at the 95 percentile of acuity differences under the same viewing conditions. Therefore, these example data are at the outer limit of variability due solely to experimental error implying that small differences found in field measurements are questionable. The reproducibility value of 15% of the mean acuity value is a good estimate for field tests. If the tests are conducted under more conservative criteria (75% correct), then about 20% applies.

CONCLUSIONS

One problem we have observed in this and other studies is that of interpretability. Observers reliably report seeing Landolt C gaps at relatively high visual acuity's of 20/20 and better, even under degraded viewing conditions such as low-light levels or noisy (scintillation) conditions. But does the observer really see the gap? When working at noisy threshold levels the gap can appear to move around to the four different locations or alternately open and close. Sometimes no gap is seen at all, maybe just a lighter area or a circle having a flat side. When the observer *correctly* responds to this flat side, we interpret the correct response as a seen gap having a specific size indicating a specific visual acuity which may explain higher than expected visual acuity's. This problem underlies all acuity measurements thus affecting interpretability and conclusions of studies' findings. To try to reduce this effect the stimulus duration was held to four seconds. The current method of stimulus presentation makes shorter, precise duration's difficult. A tachistoscope-type apparatus suited for NVG optics will have to be designed for the next study that will examine the effects of short-duration stimulus presentations on NVG acuity.

ACKNOWLEDGEMENTS

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BIOGRAPHIES

Alan Pinkus has been a US Air Force research psychologist since 1982. As a human factors engineer, he has worked on major systems including the Royal Saudi Air Force KE-3 tanker, Gunship 2, LANTIRN, Air Force One and Joint-Stars. As a researcher, he has worked in the areas of image display metrics, night vision goggles, apparent motion, aircraft lighting, transparency analysis, vision from space, workload assessment and has lectured for NATO AGARD in Europe. Alan has a BS Degree (Wright State University, 1974), an MA (University of Dayton, 1980) and a PhD (Miami University, 1992), all in Experimental Psychology. He holds nine patents in the area of night vision goggle ancillary devices and has over 25 publications. He is a member of SAFE, Association of Aviation Psychologists, the Human Factors and Ergonomics Society (Southern Ohio Chapter) and is the vice-chairman of the American Society for Testing and Materials Subcommittee (ASTM) F7.08 on Transparent Enclosures and Materials.

H. Lee Task has been employed as a research scientist for the US Air Force since 1971. He has served as chief scientist for the Armstrong Aerospace Medical Research Laboratory (prior to its reorganization and disestablishment in 1991) and is presently a senior scientist at the Visual Display Systems Branch of the Human Engineering Division, in the Armstrong Laboratory's Crew Systems Directorate, at Wright-Patterson AFB, Ohio. He is currently involved in research and development in the areas of helmet-mounted displays, vision through night vision goggles, optical characteristics of aircraft canopies, vision, and display systems. He has a BS Degree in Physics (Ohio University), MS degrees in Solid State Physics (Purdue, 1971), Optical Sciences (University of Arizona, 1978), and Management of Technology (MIT, 1985) and a PhD in Optical Sciences from the University of Arizona Optical Sciences Center (1978). During his career he has earned 36 patents and has published more than 80 journal articles, proceedings papers, technical reports, and other technical publications. He is a member of the Human Factors and Ergonomics Society (HFES), the American Society for Testing and Materials (where he is chairman of Subcommittee F7.08 on Aerospace Transparencies and is a Fellow of the Society), the Association of Aviation Psychologists, SAFE association, the Society for Information Display (SID), and SPIE (the optical engineering society). He has served as reviewer for papers in SID, and HFES. Lee is currently the Editor of the *SAFE Journal*.

Sharon Dixon is a contractor with Sytronics, Inc., with eleven years experience as a human factors psychologist. As a research assistant, she has worked in the areas of subjective mental workload, cognition, situation awareness, NVG-weighted canopy transmissivity, night vision goggles and panoramic night vision goggles. She has nine publications. Sharon has a BS degree in Human Factors Psychology from Wright State University (1987).

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* Night Vision Goggle Visual Acuity Assessment: Results of an Interagency Test

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ABSTRACT

There are several parameters that are used to characterize the quality of a night vision goggle (NVG) such as resolution, gain, field-of-view, visual acuity, etc. One of the primary parameters is visual acuity or resolution of the NVG. These two terms are often used interchangeably primarily because of the measurement methods employed. The objectives of this paper are to present: 1) an argument as to why NVG visual acuity and resolution should be considered as distinctly different parameters, 2) descriptions of different methods of measuring visual acuity and resolution, and 3) the results of a blind test by several agencies to measure the resolution of the same two NVGs (four oculars).

1.0 INTRODUCTION

Visual acuity (VA), or more properly, resolution, is probably the most important and frequently stated characteristic of night vision goggles (NVGs). It is often used as the main parameter to compare the quality of one NVG with another. However, even with this level of importance, there is no single, standardized method by which NVG resolution is assessed. The primary objective of this paper is to present several methods to assess NVG resolution that are currently in use by different organizations and compare the results obtained from each. This was accomplished by having two NVGs (a total of four oculars) measured by seven different organizations that are regular participants in the night vision goggle arena. Participants are not identified specifically in this paper but they include organizations within the US Army, US Air Force, US Navy, and industry. It should be noted that it is not an objective of this paper to endorse one measurement method over another; they each have their strengths and weaknesses, which will be discussed. It is a further objective of this paper to provide an indication of the level of reproducibility of results that one can expect due to the different measurement methods and organizations.

2.0 RESOLUTION VS VISUAL ACUITY

As indicated earlier, the two terms "resolution" and "visual acuity" are often used interchangeably in characterizing the level of image quality of the NVGs. I would suggest that resolution is primarily a characteristic of the NVG itself (independent of vision) and visual acuity is the resulting visual capability obtained when viewing through an NVG. So the phrase "NVG visual acuity" actually means the latter since NVGs really don't have a visual acuity *per se*. To try to further clarify this subtle, but important, difference it is probably worthwhile to refer to the dictionary definitions of the two terms. The dictionary defines resolution as: "...the process or capability of making distinguishable the individual parts of an object, closely adjacent optical images, or sources of light." The dictionary definition of visual acuity is: "...the relative ability of the visual organ to resolve detail that is usually expressed as the reciprocal of the minimum angular separation, in minutes (of arc), of two lines just resolvable as separate and that forms in the average human eye an angle of one minute." In general, I believe the problem arises from the fact that all methods of assessing the visual quality of the NVGs (in terms of resolution) involve observations and judgements made using the human eye (see following section). When lighting levels and NVG quality are such that the human eye visual acuity far exceeds the resolution capability of the NVGs then the resulting measurements of visual acuity through the NVGs represent the resolution of the NVGs. That is to say the visual acuity obtained viewing through the NVGs is actually also the resolution of the NVGs. The problem occurs when the viewing conditions (light level) or actual resolution of the NVGs are such that they exceed the visual acuity ability of the eye. Under low light level conditions the resolving power of the NVGs is essentially unchanged, but due to the decreased light level and the noise in the NVG the human eye does not have a long enough integration time to perceived the true resolving power of the NVGs. Under this condition one obtains a visual acuity viewing through the NVGs that is primarily the result of limitations in the eye. In this situation one is not so much measuring the capability of the NVG as one is measuring the capability of the particular human eye that made the observations.

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Where this distinction between visual acuity and NVG resolution becomes important is in the assessment of NVG capability at low light levels. If one uses the typical test procedure involving observations made by the human eye of a resolution target under low light level, then one is measuring the visual capability of that particular observer as much as they are measuring the capability of the NVG. For this reason, low light "resolution" (really should be visual acuity through NVGs) measurements of NVGs tend to have a higher degree of variability since they are more dependent on the low light level acuity of the particular observer.

For the results presented in this paper only "optimum" light level measurements of NVG resolution were analyzed and included. Some participating organizations made lower light level assessments but the means of characterizing the light level were sufficiently varied as to make it impossible to determine comparability between different organizations with respect to the light levels they used. In any event, the following section presents the different methods and target types that have been used to assess NVG resolution.

3.0 MEASUREMENT TECHNIQUES

Each of the seven participating organizations used a slightly different procedure to make NVG resolution measurements of the four oculars. This section describes some of the main procedures but does not necessarily cover each organization's specific procedures. Target types that have been used to make NVG resolution measurements include tumbling "E", Landolt "C", USAF 1951 tri-bar resolution pattern, and square-wave gratings. Procedures have included using a single trained observer or taking the average of three trained observers. Procedures have also involved making subjective judgements (as in whether or not the USAF tri-bars are "resolved" or not) or are completely objective requiring the observer to state the orientation of a target. The following specific procedures are a sample of the NVG resolution procedures that have been or are being used. Please note that the title used for each procedure is not necessarily standardized but was selected to emphasize a particular feature of the procedure.

3.1 USAF 1951 Tri-Bar Resolution Chart

The USAF 1951 Tri-Bar Resolution Chart has a very specific format as shown in Figure 1a. This chart is composed of multiple sets of "Tri-Bars" of different sizes oriented both vertically and horizontally. The bars are organized into Groups and Elements such that there are 6 different elements (different sized bars) within each Group. The bars in each Element vary in size by the sixth-root of 2 such that the size of the bars in the first Element of each Group is exactly twice the size of the first element in the following (smaller) Group. This means that each bar pattern is about 12.25% larger than the next smaller bar size. The original USAF 1951 Tri-Bar Chart (Figure 1a) was designed such that the Group 0, Element 1 bar size was exactly 1/2 mm in width. Since that time variations in the original chart have been devised that still use the sixth-root of 2 design concept but are of a different basic size so that they can be used as a large wall chart. Figure 1b shows a picture of such a chart as photographed through one of the NVG oculars used in this study (photo courtesy of Bill McLean, US Army).

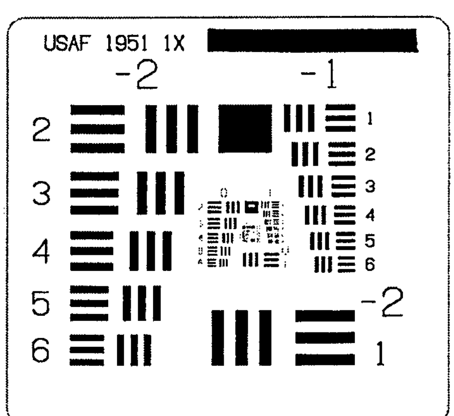

Figure 1a. USAF 1951 Tri-Bar Chart

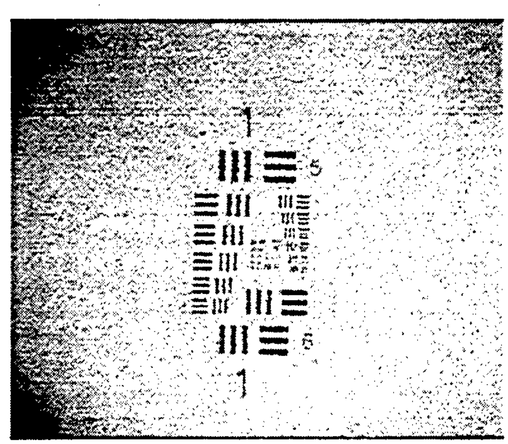

Figure 1b. Variation of USAF 1951 Tri-Bar Chart

The Tri-Bar target sizes can be converted to equivalent Snellen Acuity (SA) values by determining the angular subtense of the bar sizes as measured from the viewing distance. An angular subtense of 1 minute of arc corresponds to a Snellen acuity of 20/20; 2 minutes of arc is 20/40, 3 minutes of arc is 20/60, and so forth. The angular subtense is calculated by taking the arc tangent of the width of the bar divided by the viewing distance. Visual acuity obtained looking through an NVG ocular may be determined by a single observer or by averaging the observations made by a panel of observers (typically 3 observers).

One potential disadvantage of this target type is that the steps between bar sizes are relatively large. For example, if a bar pattern were of a size such that the Snellen acuity was 20/40 then the next larger size would be 20/44.9 and the next smaller size would be 20/35.6 (12.25% differences between sizes going up and 10.9% difference in sizes going down). This relatively large "least-count" for this procedure limits the precision with which one can determine the resolution of an NVG ocular; especially if only one observer is used. On the other hand, visual acuity is a relatively difficult parameter to precisely measure, so one could argue that a precision of 12.25% or 10.9% is all that is required.

3.2 Hoffman 20/20 Test Set

Prior to flying with NVGs aircrew in the US Air Force are required to pre-flight their NVGs. This includes making adjustments so that the NVGs line up with the individual's eyes and checking visual acuity, usually using the Hoffman ANV-20/20 test set shown in Figure 2. This device provides a collimated image (image at infinity) for the aircrew to focus their objective lenses and to check for visual acuity level. The target pattern used to check visual acuity is shown in the upper left of Figure 2. The pattern consists of 9 target sizes corresponding to 9 different visual acuities. The patterns are patches of square-waves (alternating light and dark bars of equal size) in both vertical and horizontal directions. The legend under the target picture in Figure 2 shows the corresponding VA target sizes, which range from 20/20 to 20/70.

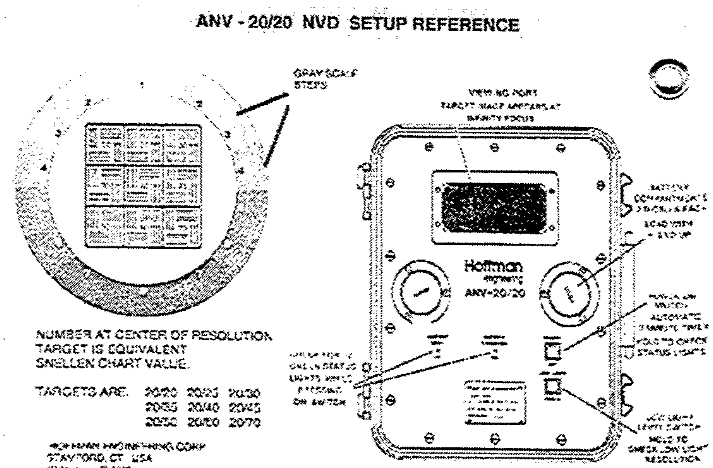

Figure 2. Hoffman ANV-20/20 NVD tester used to pre-flight NVGs (photo courtesy of Hoffman Engineering).

While this device makes an excellent pre-flight instrument, it is not very well suited for making precise measurements of NVG ocular resolution because of the relatively large step sizes. The highest resolution pattern is 20/20 and the next highest is 20/25, which is a large 25% decrease. Its main advantages are that it produces a distant image (using an optical system) within a small space and it can control lighting on the target.

3.3. Walk-Back Procedure Using Square-Wave Gratings

This technique was developed as a means to shift from a discontinuous dependent variable to a continuous dependent variable. In other words, one is not limited to specific, quantized levels of visual acuity but, instead, is afforded a complete continuum. The target patterns chosen for this technique are square-wave patches of different spatial frequencies (light and dark bar widths) organized in a pattern shown in Figure 3. A total of 3 charts were used with six grating patch sizes each. The spatial frequency was lower (wider bar widths) on the left side and progressed to higher frequencies (narrower bars) moving to the right. A vertical bar pattern and a horizontal bar pattern were provided for each spatial frequency. These charts were placed a distance of 30 feet from the observer and illuminated with a 2856K light source that could be adjusted. The patches were sized such as to produce whole number Snellen visual acuities at the 30 ft distance such as 20/25 or 20/30. The observer would select the highest spatial frequency grating that he/she could see and inform the experimenter of their selection. Then the observer would slowly step backward until that pattern became a uniform green indicating the NVG could no longer resolve the grating pattern. By using the increased distance, one could calculate the new resolution (Snellen acuity) that corresponded to that particular pattern. For example, if the observer had selected the 20/30 pattern and then walked back 2 feet the resolution of that pattern at the new distance would be 20/[30*(30/32)] = 20/28.1. The grating sizes were selected such that the observer should never have to walk back more than about 3 feet (10%). If they did walk back more than the maximum that meant they should have been able to resolve the next higher resolution pattern at the 30-ft distance. So, if they did walk back past the maximum they were asked to return to the 30 ft distance and look at the next higher spatial frequency patch to see if they could resolve it. The 30 ft distance was selected to minimize possible blur effects caused by focusing the NVGs at 30 feet and then viewing the pattern at distances slightly farther than 30 ft (out to 33 ft). This depth of focus issue is the major disadvantage of this procedure although tests allowing subjects to refocus their NVGs at the longer distances once they had moved back did not produce any noticeably different results.

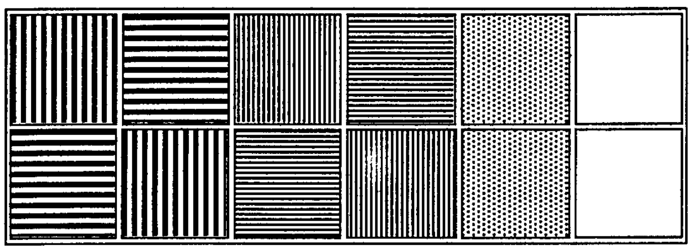

Figure 3. Drawing of the square-wave grating patches used to measure NVG visual acuity using the "walk-back" method.

The major advantage of this technique is to provide a continuum of values that could be obtained for visual acuity. In practice, this procedure normally used 3 trained observers and collected 3 to 5 repeated measures each. The results were then the grand average for all observers and repetitions.

3.4 Rotating Grating Technique

A variation of the walk-back technique is the rotating grating method. This technique uses a square-wave grating pattern with the lines running vertically. The grating patch is a rectangle that is about 1.5 times wider than high. This target is placed on a rotating table such that it rotates about an axis that corresponds to the center bar of the pattern. As the pattern is rotated the apparent spatial frequency increases as the view of the pattern is "fore-shortened." The advantage of this technique is that it provides a continuum of values for Snellen acuity. The disadvantage is the same as the walk-back technique in that the focus distance is different for the side of the chart that is closest to the observer compared to the opposite side. However, compared to the walk-back technique, this technique does not require the observer to move and data can be gathered relatively quickly. Initial results indicate the procedure is reasonably repeatable. The base distance (distance from observer to center of the chart) should be 30 feet or greater to minimize the focus disparity between the left and right side of the chart in its rotated position.

3.5 Multiple Observations, Multiple Orientation Gratings

Another VA measurement technique to assess NVG oculars uses circular grating patches arranged in rows. In one specific implementation of this procedure the circular target patches were organized into two rows of six gratings each. All of the gratings in a given row were of the same spatial frequency. The gratings were oriented in 4 directions: vertical, horizontal, slanted 45degrees left, and 45 degrees right. Observers were required to state the direction of the grating, making this an objective test. In this particular case, the gratings were designed to be viewed at a distance of 20 feet and the sizes were selected such that each pattern was approximately 12.2 percent larger than the preceding pattern. This corresponds to a size spacing of 0.05 log minimum angle of resolution or 0.05 log MAR. One difficulty with this type of procedure is how to score an individual who gets all of a particular row correct, then misses 2 in the next smaller size row, but then gets all of the next smaller size correct. Some guide must be adopted to determine what score is to be given to an observer who misses one or more orientations in a particular row. For this specific version of this technique a criterion level of achieving 5 of 6 correct orientations in a row was established. The observer was given the Snellen acuity score corresponding to the row in which he/she got 5 of the 6 correct, with a minor modification. If they provided some correct responses on the following row as well, then they were awarded an additional acuity increment of 0.008 log MAR units per correct response. For example, if an observer correctly resolved 5 of 6 patterns on the 20/40.2 (log MAR 0.303) line and resolved 2 patterns on the 20/35.8 line, his/her VA would be scored as 0.303 - 0.016 = 0.287 log MAR or 20/38.7 Snellen). Three observers were used and their average score was recorded as the resultant visual acuity.

4.0 RESULTS OF ROUND ROBIN TEST

Two NVGs were selected for this interlaboratory study: one was an older AN/AVS-6 NVG and the other was a more recently produced AN/AVS-9 NVG. The two NVGs were supplied to each organization for testing with the instructions to conduct their normal test procedures for visual acuity (resolution) under two lighting conditions: optimum lighting for best resolution and starlight level lighting. The organizations were directed to measure each ocular (a total of 4 oculars) independently and provide their visual acuity (resolution) results for each of the two lighting levels; a total of 8 numbers. Not all organizations conducted the lower light level measurements and, of those that did, not all of them stated what lighting level was used (in quantitative terms) to simulate the starlight level. For this reason only the "optimum" light level data is included here and analyzed.

Some organizations provided their data in the form of Snellen Acuity values, others submitted their results in terms of cycles per milliradian. In order to make it easy to compare the results between the organizations all data were converted to Snellen Acuity and to cycles per milliradian (Tables 1 and 2). One organization measured the NVGs using two different procedures/devices but their results for the two were identical so only one was used in the analysis. In addition, another organization was the first to measure the NVGs and then measured them again after all of the other organizations had conducted their tests. The results from these two sets of measurements from this organization (using the same procedure both times) were very close so the results from the two were averaged and included in the analysis. A third organization provided raw visual acuity data for two observers (who had significantly different results) so their data was averaged to provide single resolution numbers for their organization. Tables 1 and 2 are a summary of the optimum light level visual acuity data for the seven organizations that participated.

Table 1. Visual acuity results obtained from 7 organizations measuring the same NVGs (results in Snellen acuity-20/xx).

	AN/AVS-6		**AN/AVS-9**		**AN/AVS-6**	**AN/AVS-9**
Lab	**Left**	**Right**	**Left**	**Right**	**Right-Left**	**Right-Left**
A	33.8	35.0	26.1	26.7	1.2	0.6
B	40.0	45.0	32.0	32.0	5.0	0.0
C	33.4	41.9	26.4	29.6	8.5	3.2
D	31.4	31.4	23.2	23.2	0.0	0.0
E	34.7	38.2	27.5	28.6	3.5	1.1
F	38.1	39.6	30.2	33.0	1.5	2.8
G	40.0	39.0	31.0	32.3	-1.0	1.3
Mean	35.9	38.6	28.1	29.4	2.7	1.3
Std	3.4	4.4	3.1	3.5	3.3	1.3
t-test p-value for Ho: Mean Difference = 0					0.0743	0.0368

There are two observations that are apparent from Table 1: 1) the standard deviations for each ocular across organizations are relatively large (on the order of 10-12 percent of mean value) and 2) within each NVG type the determination of which ocular of the two had the better resolution was fairly consistent (right-left columns) although they were not statistically significant at the p=0.01 level (see last row of Table 1). The primary objective of this effort was to determine a reproducibility limit for NVG resolution/visual acuity measurement. The reproducibility limit is defined in ASTM E 691 along with the statistical procedures to calculate it. Basically, if two organizations measure the same NVG ocular there is a 95% probability that their results will differ by no more than the reproducibility limit. This is an indicator of how reproducible the measurement results are and should not be confused with repeatability. Repeatability is an indication of how consistent a single organization's results are when making the same measurement on the same NVG multiple times, whereas the reproducibility limit treats the issue of measurements made by different organizations. Since we collected only one assessment of resolution from each organization for each NVG ocular (at the high light level) we do not have sufficient data to calculate repeatability (which could well be different for the different organizations).

All remaining analyses were accomplished after converting all of the data to resolution in cycles per milliradian (see Table 2) using the conversion equation:

$$\text{Res (c/mrad)} = 34.3775/\text{Snellen (20/xx)} \quad (1)$$

Table 2 lists the NVG ocular resolutions converted to cycles/milliradian (c/mrad). At the bottom of Table 2 is a summary of the Reproducibility Limit (RL) as calculated using ASTM E 691 procedures. The RL was calculated for each type of NVG (AN/AVS-6 and the AN/AVS-9) and for all the oculars as a group. For the levels of resolution of these NVGs, the reproducibility limit was a relatively large 33% (0.35 c/mrad). This means that if we selected a single NVG ocular and randomly selected 2 organizations to measure its high-light-level resolution there is a 95% probability that their answers would agree within 0.35 c/mrad. Another way to look at this is if one randomly selected organization measured the resolution of an NVG ocular and then another (different) randomly selected organization measured a different ocular, then the difference in resolution measurements between the two would have to be greater by 0.35 c/mrad before we would be at least 95% confident that the two oculars were, indeed, different. Note that if we had supplied the two NVG oculars to the same organization then the appropriate confidence parameter would be repeatability and not reproducibility. Although this reproducibility value seems somewhat large it is apparent from the data in Table 2 that there is a wide spread in resolution results between organizations. Looking at the "Right" column of the AN/AVS-9 we see that the highest resolution obtained was 1.48 c/mrad and the lowest was 1.04 c/mrad; a huge 0.41 c/mrad difference!

Table 2. Resolution in cycles/mrad for each lab and ocular. Reproducibility Limits (RL) are given for each goggle separately and across all 4 oculars.

	AN/AVS-6		**AN/AVS-9**		**AN/AVS-6**	**AN/AVS-9**
Lab	**Left**	**Right**	**Left**	**Right**	**Right-Left**	**Right-Left**
A	1.02	0.98	1.32	1.29	-0.04	-0.03
B	0.86	0.76	1.07	1.07	-0.10	0.00
C	1.03	0.82	1.30	1.16	-0.21	-0.14
D	1.09	1.09	1.48	1.48	0.00	0.00
E	0.99	0.90	1.25	1.20	-0.09	-0.05
F	0.90	0.87	1.14	1.04	-0.03	-0.10
G	0.86	0.88	1.11	1.06	0.02	-0.04
Mean	0.96	0.90	1.24	1.19	-0.06	-0.05
Std	0.09	0.11	0.14	0.16	0.08	0.05
RL	0.28 (30%)		0.41 (34%)		0.22	0.14
(% of Mean)	0.35 (33%)				0.18	

It is apparent from an inspection of the data in Table 2 that there is some pattern to the variance in resolutions obtained. Specifically, some organizations tended to consistently obtain higher overall resolutions that other organizations. This could be due to the specific type resolution target that was used, the visual capability of the observers, or some other factor. In any event, it is possible to do an analysis to see how much the reproducibility limit could be improved (made smaller) if the differences between organizations were not only consistent but also invariant with time. That is to say, if we were to repeat this effort we would find that the same organizations that tended to obtain higher resolutions in the first effort obtain higher resolutions in the repeat. In order to explore the effects on the reproducibility limit if we could "handicap" labs according to the results of Table 2 we devised a "correction factor" to adjust the scores in Table 2 such that the average for the 4 scores of each lab are the same. This was done by dividing each of the 4 data points for a single lab by a ratio that was calculated by dividing that particular lab's average of the 4 readings by the overall average of the 28 data points. The results of this adjustment are listed in Table 3. The numbers in the second column of Table 3 are the adjustment ratios by which each corresponding row of numbers in Table 2 was divided. Note that the reproducibility limits calculated for Table 3 are greatly reduced from those calculated in Table 2; on the order of 10% instead of 33%.

Table 3. Adjusted Resolution values (cycles\mrad) for each lab and ocular. The resolution values of Table 2 were "adjusted" by dividing each lab's 4 values by an adjustment ratio (Adj. Ratio) that was equal to that lab's average (of the 4 numbers in Table 2) divided by the average of all 28 data points.

		AN/AVS-6		AN/AVS-9		AN/AVS-6	AN/AVS-9
Lab	Ratio	Left	Right	Left	Right	Right-Left	Right-Left
A	1.07	0.95	0.92	1.23	1.20	-0.03	-0.03
B	0.88	0.98	0.87	1.22	1.22	-0.11	0.00
C	1.00	1.03	0.82	1.29	1.15	-0.21	-0.14
D	1.20	0.91	0.91	1.23	1.23	0.00	0.00
E	1.01	0.98	0.89	1.24	1.19	-0.09	-0.05
F	0.92	0.98	0.94	1.24	1.13	-0.04	-0.10
G	0.91	0.94	0.97	1.22	1.17	0.02	-0.05
	Mean	0.97	0.90	1.24	1.19	-0.06	-0.05
	Std	0.04	0.05	0.03	0.04	0.08	0.05
	RL	0.12 (13%)		0.09 (7%)		0.22	0.15
	(% of Mean)	0.11 (10%)				0.19	

DISCUSSION/CONCLUSION

The rather large reproducibility limit (33%) found as a result of analyzing the data of Table 2 is somewhat disturbing but should serve as a major caution flag for any organization making and reporting NVG resolution results. Each of the participating organizations used slightly different procedures to arrive at a resolution number. Some used grating patterns (A and G) and some used tri-bar targets (B through F) as the resolution target. Some used a subjective assessment by observers and some used objective methods. Some used a single observer others used up to 3 observers and averaged the results. All of these differences could contribute to the consistent differences between organizations. However, having looked at the raw data from the 3 observers from our laboratory and the 2 observers from one of the other organizations it is apparent that one of the highest sources of difference is the particular individual(s) that participate in the measurement.

Table 4. Summary of NVG resolution measurement procedures used by the 7 labs.

Lab	Target	Observers	Procedure	Units
A	Grating	3	Subjective	Snellen
B	Tri-bar	1	Subjective	Snellen
C	Tri-bar	1	Subjective	c/mrad
D	Tri-bar	2	Subjective	c/mrad
E	Tri-bar	3	Subjective	Snellen
F	Tri-bar	3	Subjective	Snellen
G	Grating	3	Objective	Snellen

The analysis done for Table 3 on the "adjusted" data provides for the most optimistic reproducibility limit we could expect. The *ex post facto* analysis undoubtedly removed some systematic and some random variance from the data, which resulted in a fairly modest reproducibility limit (about 10%). It is highly unlikely the Adjustment Ratios calculated for each organization would remain exactly the same if we were to conduct this study again. However, there would probably still be a similar general ranking of organizations as to relative level of resolution measured (assuming the same personnel were involved at each location). There may also be some bias due to the type of organization: the highest resolutions were obtained from a vendor of NVGs and the lowest resolutions were obtained from a purchaser of NVGs. The real, practical reproducibility limit probably resides somewhere between the two values calculated from the data in Tables 2 and 3 but we have no way of determining where in between. Suffice it to say that the results of this study serve as a caution to any organization that is involved in NVG resolution measurements that would like to make a statement about the relative quality of a particular NVG compared to one assessed by another organization. The results also indicate that the NVG community should work on standarding NVG resolution measurement procedures in an effort to improve the reproducibility limit.

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BIOGRAPHY

H. Lee Task has been employed as a research scientist for the US Air Force since 1971. He has served as chief scientist for the Armstrong Aerospace Medical Research Laboratory and in March of 1997 was selected as the Senior Scientist for Human-Systems Interface of the new Air Force Research Laboratory at Wright-Patterson AFB, Ohio. He is currently involved in research and development in the areas of helmet-mounted displays, vision through night vision goggles, optical characteristics of aircraft windscreens, vision, and display systems. He has a BS Degree in Physics (Ohio University), MS degrees in Solid State Physics (Purdue, 1971), Optical Sciences (University of Arizona, 1978), and Management of Technology (MIT, 1985) and a Ph.D. in Optical Sciences from the University of Arizona Optical Sciences Center (1978). During his career he has earned 42 patents and has published more than 100 journal articles, proceedings papers, technical reports, and other technical publications.

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THE EFFECTS OF AIRCRAFT TRANSPARENCIES ON NIGHT VISION GOGGLE-MEDIATED VISUAL ACUITY

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ABSTRACT

Night vision goggles (NVGs) are currently used in a wide variety of military aircraft that were not originally designed for NVGs. Likewise, the windscreens and canopies on these aircraft were not designed with NVGs in mind. Present day windscreens and canopies typically have one or more specialized coatings applied to them. These may be reasonably transparent for visible wavelengths but not so transparent for near infrared light to which the NVGs are sensitive. It was hypothesized that the major mechanism by which aircraft transparencies affect the operation of NVGs is through reduced light levels. This would mean that the key characteristic of interest for determining the effect of an aircraft transparency on the operation of the NVGs would be its transmission coefficient calculated using the spectral sensitivity of the NVGs. This hypothesis was tested by investigating visual acuity performance of trained observers viewing through NVGs for three levels of ambient illumination (1, 2 and 5 times starlight) and three levels of NVG- weighted windscreen transmissivities (58, 76 and 100%). In addition, two levels of contrast were included in the study (20 and 70% modulation contrast). Three trained observers determined the orientation of a Landolt C using a two-alternative, forced-choice step paradigm. A luminance-based model was developed to smoothly combine the effects of illumination level and transmission level for each contrast thus supporting the hypothesis. In addition, the results demonstrate the significant difference between individual observer's performance level and the increased difficulty (higher variability) of performance at lower contrast levels.

INTRODUCTION AND BACKGROUND

Night vision goggles provide observers with the ability to see very dimly illuminated nighttime scenes by amplifying ambient light from the red and near infrared spectral energy region (600 through 950 nm; see Fig. 1). Anything that reduces the light level getting to the NVGs will tend to reduce the output luminance while at the same time decreasing the signal-to-noise ratio. This, in turn, tends to reduce the visual acuity of observers using the NVGs. These effects are most apparent at very low ambient light levels such as starlight illumination conditions. The basic hypothesis of this study is that it should not matter whether the light level is reduced by lowering the illumination level on the target area or by attenuating the light level getting to the NVGs by viewing through a transparency. This leads to the concept of equivalent illumination. For purposes of this study, equivalent illumination is the product of the actual illumination level and the transmission coefficient of the transparency through which one is viewing. As a specific example, the equivalent illumination for 2 times starlight actual illumination viewing through a 50% transmitting windscreen would be 1.0 starlight (2 times 0.5). This is the same equivalent illumination obtained for an actual illumination of 1 times starlight viewing through the NVGs with no intervening transparency (1 times 1.0). If the hypothesis is correct one would expect the visual acuity for these two conditions to be essentially the same (within the variability expected for human observations).

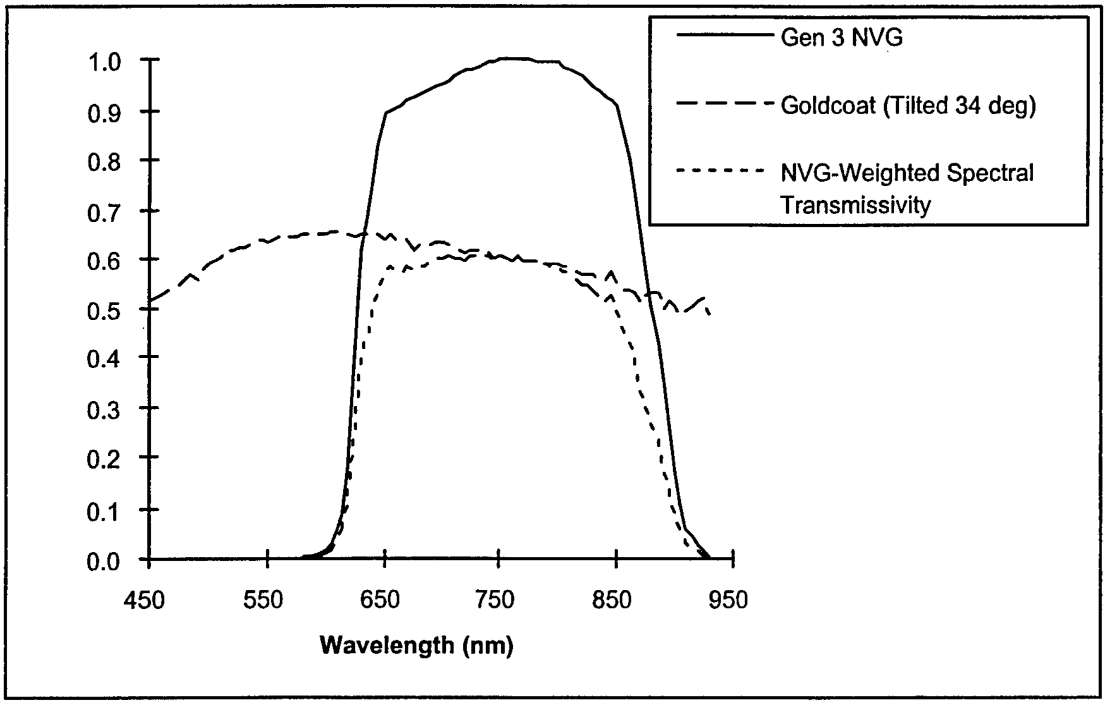

Figure 1. The relative value of a third-generation NVG, a gold-coated transparent sample (34 deg tilt) and its corresponding NVG-weighted spectral transmissivity plotted as a function of wavelength.

In order to determine how much an aircraft windscreen or canopy will reduce the light level by, it is necessary to measure or calculate the NVG-weighted transmission coefficient (T_{NVG}). This is done by using the spectral sensitivity of a given NVG[1,2,3]. Equation 1 describes the calculation for NVG-weighted transmissivity. T_{NVG} equals the integral with respect to wavelength, of the transparent part's spectral transmissivity [$P(\lambda)$] times the spectral energy distribution of the light source [$S(\lambda)$] times the NVG spectral sensitivity [$G(\lambda)$] divided by the integral with respect to wavelength, of the spectral energy distribution of the light source times the NVG spectral sensitivity. Since the specific spectral energy distribution of the light source in Equation 1 is typically not known for operational conditions (it depends on the spectral energy distribution of the illumination source on the scene and the spectral reflectivity of the various objects in the scene) the NVG-weighted transmission coefficient was calculated using $S(\lambda) = 1$ for all wavelengths. This simplifies the equation and typically does not significantly affect the results for the vast majority of broad-band reflectance distributions normally encountered. Figure 1 shows the spectral transmissivity curve for one of the gold-coated samples used in this study. The third-generation NVG sensitivity curve is plotted for reference.

$$T_{NVG} = \frac{\int_{450\,nm}^{950\,nm} P(\lambda)S(\lambda)G(\lambda)d\lambda}{\int_{450\,nm}^{950\,nm} S(\lambda)G(\lambda)d\lambda} \qquad (1)$$

where:

T_{NVG} = NVG-weighted transmissivity

$P(\lambda)$ = spectroradiometric scan through the transparent part

$S(\lambda)$ = spectral energy distribution of the light source (equal to 1 for our calculations)

$G(\lambda)$ = spectral sensitivity of the night vision goggle

Undocumented reports from some aircrew in different aircraft indicated that some transparencies, such as gold-coated F-16 canopies, may cause a reduction in NVG visual acuity compared to uncoated transparencies. Investigation into the NVG-weighted transmission level of currently fielded F-16 canopies revealed that there are at least three different gold coatings and two different indium-tin-oxide coatings in use. It was therefore the objective of this study to investigate the effect of coated transparent parts that included the full range of NVG-weighted transmission coefficients that might be found in the field. Since we could not obtain samples of all of the different types of coated windscreens it was decided to use what samples we did have in such a way as to provide a fairly wide range of transmissivities. Two gold-coated sections of transparencies were available: one with a fairly light coating and one with a relatively heavy coating. In order to expand the range even further, viewing through the heavily-coated sample was done at a tilted angle which made the transmission coefficient even smaller.

METHOD

Participants

The three participants in this study were not naive subjects in the traditional sense but highly trained psychophysical observers, two males and one female, ranging in ages from 35 to 46 years.

Apparatus and Stimuli

The tests utilized a new set of ITT Model F4949D (serial #3873) NVGs[4] that had P-43 phosphor image intensifier tubes and a measured gain[5] of about 6000. With the room lights off and the NVGs on, the observer first adjusted the interpupillary distance of the goggles. Then they adjusted the eyepiece lenses by looking at the dark ceiling with the goggles and focusing until the scintillation looked sharp. Objective lenses were focused by viewing a one-half moon illuminated, NVG resolution chart composed of square-wave gratings[6].

All observations were made in a light tight room. The observer sat in a chair behind a table with their eyes 9.14 m (30 ft) from the stimulus easel. On the table was a fixture that held an aircraft transparency sample and a foam board visual field mask which had a 15 cm high by 18 cm wide (6 by 7 in.) aperture. The observer held the NVGs but could rest his or her elbows on the table while looking through the hole and transparency at the stimulus. The goggles were powered using a regulated external power supply.

The stimuli were Landolt C's[7] printed using a high resolution photo-grade laser printer. All of the C's (in each set) were consecutively numbered 1 through n for ease of use with the computer program (see *Procedure* section) during the study. After the study, the observers' data were converted to Snellen equivalents. The high contrast (70% Michelson) set consisted of 69 C's ranging from 20/19.1 to 20/200.5 Snellen acuity for the 9.14 m viewing distance. C's 1 through 48 increased by about 2 minutes-of-arc (MOA) per step and C's 49 through 69 increased in about 2 to 4 MOA steps in order to insure a high upper range. The low contrast (20% Michelson) set consisted of 107 C's ranging from 20/19.1 to 20/236.8 Snellen acuity. For this set, C's 1 through 92 increased by about 2 MOA per step and C's 93 through 107 increased in about 2 to 4 MOA steps. The first stimulus presentation, as determined by the program, was always from the center of the set's range and all subsequent thresholds were found to be below this value.

The C's were mounted on 18 x 18 cm (7 x 7 in.) foam board. The letter and background were different gray levels, varied to achieve the two desired contrasts but maintain the same average reflectance. For presentation, the C was placed onto a larger surround board 61 x 61 cm (24 x 24 in.) that matched either the high or low contrast Landolt C background reflectance as appropriate. The background board was held on an easel and had a small ledge that held the letter C in the center. The ledge was invisible when viewed through NVGs. The C was then easily placed onto the ledge with the gap oriented either up or down.

The experimenter's station was to the side of the stimulus easel. The computer's electroluminescent, back-lighted liquid-crystal display was filtered and shrouded to eliminate any stray light from falling on the target pattern.

Three, pre-calibrated, 2856K incandescent lamps[8] were used to easily change to the different illumination levels. Apertures varied their intensity without affecting the color temperature. Illumination levels used were: 1x starlight = 3.4×10^{-4} lx (3.2×10^{-5} fc)[9]; 2x starlight = 6.7×10^{-4} lx (6.2×10^{-5} fc); 5x starlight = 1.8×10^{-3} lx (1.7×10^{-4} fc). A fourth lamp, set to about one-half moon illumination 1.3×10^{-1} lx (1.2×10^{-2} fc) was used to illuminate an NVG resolution target[6] during pretest goggle focusing.

Three transmission conditions were included in this study: a tilted heavily gold-coated sample, a non-tilted lightly coated sample, and no intervening transparency (100% transmission, hereafter termed baseline or high T_{NVG}). The T_{NVG} for the heavily gold-coated sample tilted to a 34 deg orientation was 58% (hereafter termed low T_{NVG}). The non-tilted (normal) lightly gold-coated sample had 76% transmissivity (hereafter termed medium T_{NVG}). This study used three different combinations of stimulus illumination, with three different levels of T_{NVG} coefficient to achieve nine total levels of equivalent illumination. Table 1 summarizes the nine equivalent illumination levels derived from the different illumination and T_{NVG} coefficient combinations.

Testing was conducted within randomized blocks of the lighting conditions because the observer had to adapt to that level before the test. First, an illumination source was randomly selected. Within that lighting level, the observer was tested with a randomized order of stimulus contrasts and transparency samples. Two levels of contrast (20 and 70%), three levels of illumination and three levels of T_{NVG} yielded nine experimental conditions for high contrast letters and nine experimental conditions for low contrast. The visual acuity through the NVGs for trained observers was measured as a function of these nine equivalent illumination levels.

Table 1. The nine different equivalent illumination levels produced by all combinations of the three levels of stimulus illumination and three levels of transparency T_{NVG} coefficients.

MULTIPLES OF STARLIGHT	LOW T_{NVG} coefficient T_{NVG} = 58%	MEDIUM T_{NVG} coefficient T_{NVG} = 76%	HIGH T_{NVG} coefficient T_{NVG} = 100 %
1x	0.58	0.76	1
2x	1.16	1.52	2
5x	2.9	3.8	5

Procedure

A portable computer executed a two-alternative, forced-choice Step Program adapted from Simpson[10]. The experimenter started the Step Program which asked for the initial setup parameters: Landolt C upper and lower stimulus identification numbers (1 through 69 for high contrast or 1 through 107 for low contrast), confidence level (95%), number to criterion (5), maximum total number of trials (50) and a data file name. Using a conservative 95% confidence level caused the program to require a few more trials before converging to threshold.

The proper stimulus surround was placed onto the easel, a 1x, 2x or 5x starlight lamp was energized and the transparency sample placed into the fixture. The observer then partially dark adapted to the goggle output luminance for about 10 minutes. The Step Program instructed the experimenter to place a given numbered (size) Landolt C in an up or down, randomized position. The stimulus was blocked from the observer's view by the experimenter during placement onto the easel. The experimenter asked the observer if he or she was ready, unblocked the stimulus for about 4 seconds, then blocked it again. The observer had to respond either "up" or "down". No feedback was ever given to the observer. The experimenter then removed the stimulus and entered the observer's response into the Step Program. Based on the response, the Step Program determined the next stimulus size and randomized its orientation. The procedure was repeated until criterion was reached or the maximum number of trials were met. All observers converged before reaching the maximum number of trials. This procedure averaged about 10 minutes per experimental condition with five minute rests after each condition and additional rest after completion of each lighting condition.

RESULTS

The study presented a total of 1015 stimuli to the three observers. Threshold criterion (5 correct responses at smallest, reliably seen gap size) was reached in 19 trials on the average, 10 being the fastest and 38 the slowest (see Fig. 2 for an example). Snellen acuity, which served as the dependent variable, was calculated from the viewing distance and the gap size of the Landolt C with the standard conversion that 20/20 Snellen acuity corresponds to a gap size of one minute of arc. Table 2 is a summary of the results for the high contrast Landolt C condition listing the Snellen acuity for each illumination/transparency combination for each trained observer and the average across observers. The equivalent illumination column is the fraction of starlight that was available to illuminate the target pattern after accounting for the transmission coefficient of the transparency. This value was calculated by multiplying the illumination level (1, 2, or 5 times starlight) by the transmission coefficient (0.58, 0.76, or 1.00) for each condition. Table 3 is a summary of the results for the low contrast condition.

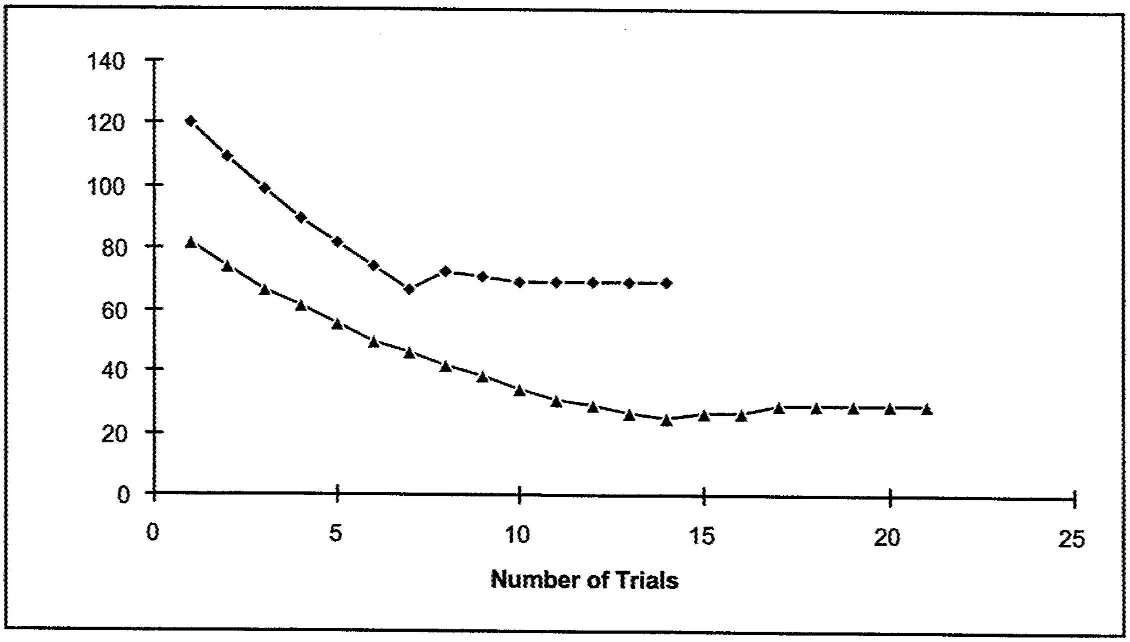

Figure 2. Typical Landolt C presentation sequences using the computer-based Step Program.

Table 2. Summary of high contrast (70%) stimuli data. All data are Snellen acuities (20/xx).

ILLUMINATION (X STARLIGHT)	T_{NVG} COEFFICIENT	EQUIV ILLUM	OBSERVER 1	OBSERVER 2	OBSERVER 3	MEAN
1x	LOW	0.58	66.8	63.0	61.1	63.6
1x	MEDIUM	0.76	61.1	59.2	49.7	56.7
1x	HIGH	1	53.5	51.6	47.7	50.9
2x	LOW	1.16	51.6	57.3	47.7	52.2
2x	MEDIUM	1.52	49.7	47.7	43.9	47.1
2x	HIGH	2	45.8	43.9	36.3	42.0
5x	LOW	2.9	36.3	40.1	36.3	37.6
5x	MEDIUM	3.8	36.3	32.5	34.4	34.4
5x	HIGH	5	36.3	32.5	34.4	34.4

Table 3. Summary of low contrast (20%) stimuli data. All data are Snellen acuities (20/xx).

ILLUMINATION (X STARLIGHT)	T_{NVG} COEFFICIENT	EQUIV ILLUM	OBSERVER 1	OBSERVER 2	OBSERVER 3	MEAN
1x	LOW	0.58	114.6	103.1	149.0	122.2
1x	MEDIUM	0.76	128.0	105.0	126.1	119.7
1x	HIGH	1	108.9	99.3	107.0	105.1
2x	LOW	1.16	114.6	84.0	122.2	106.9
2x	MEDIUM	1.52	112.7	108.9	82.1	101.2
2x	HIGH	2	105.0	99.3	70.7	91.7
5x	LOW	2.9	101.2	93.6	74.5	89.8
5x	MEDIUM	3.8	68.8	87.9	68.8	75.2
5x	HIGH	5	47.7	74.5	61.1	61.1

DISCUSSION

Although none of the combination of conditions (illumination and transmission coefficient) permitted a direct test of the equivalent illumination hypothesis, it was possible to graph the Snellen acuity results against the equivalent illumination to see if it would produce a reasonably smooth, monotonically decreasing curve. This is the type of curve that would be expected since, in general, visual acuity improves (Snellen acuity value is smaller) as light level to the eye increases[11]. Figures 3 and 4 show these graphs for the high contrast and low contrast conditions, respectively.

The graphs of Figures 3 and 4 include all of the individual observer data in addition to a dashed line that corresponds to the average for the three observers for each equivalent illumination condition. The high contrast graph of Figure 3 demonstrates a very clear pattern, although it is apparent that there is a certain amount of observer variability and differences between observers. Based on visual inspection of the graph in Figure 3, a curve fit was applied using a simple reciprocal model. The general form of the model equation was:

$$S = K + \frac{M}{E} \qquad (2)$$

where:

S = Snellen acuity (20/xx)
K = constant (empirically determined by least squares fit)
M = proportionality constant (empirically determined)
E = equivalent illumination

Table 4 is a summary of the model fit (Equation 2) for both the high contrast and low contrast Landolt C. The model is shown in Figures 3 and 4 as a solid line.

The model fits reasonably well for the high contrast condition (r = 0.981) and not too badly for the low contrast condition (r = 0.912) given that human observations are involved. It should be noted that this fit was done for a relatively small range of illuminations (0.58 to 5.0 times starlight) and

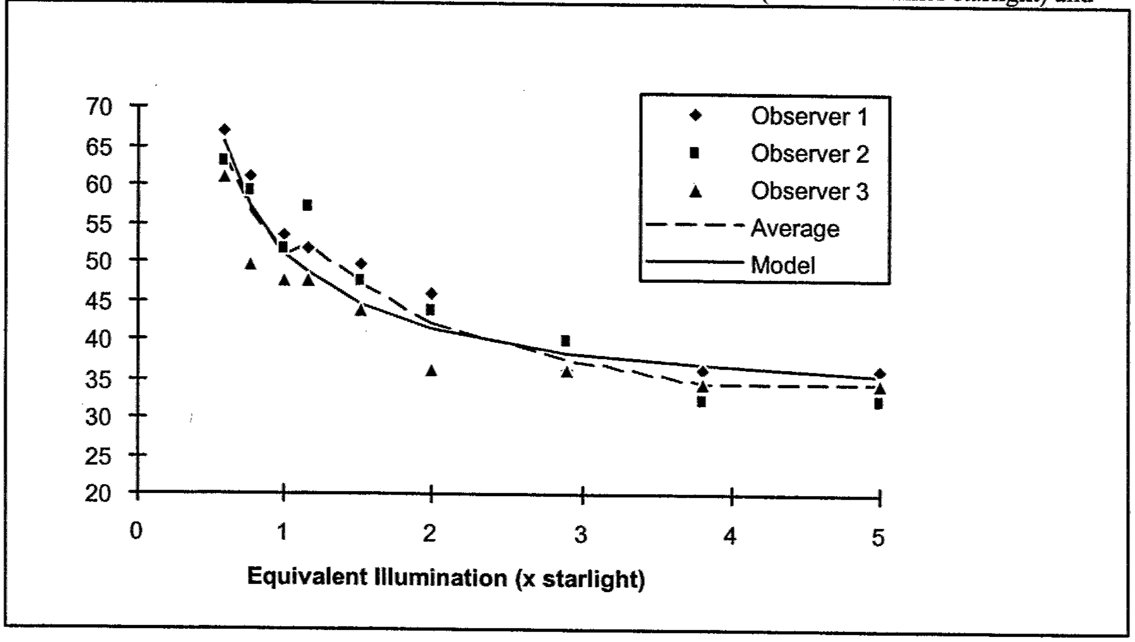

Figure 3. Plot of Snellen acuity as a function of starlight illumination for high contrast Landolt C stimuli (Table 2).

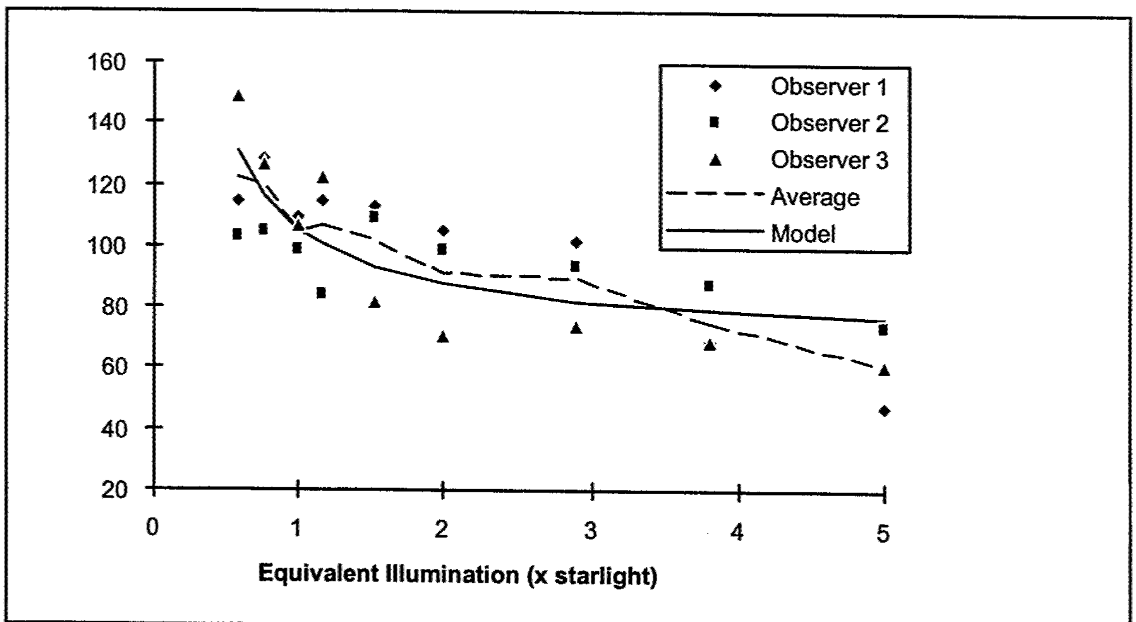

Figure 4. Plot of Snellen acuity as a function of starlight illumination for low contrast Landolt C stimuli (data from Table 3).

is therefore only valid for this range. It is possible the basic model (Equation 2) may still hold up for a greater range of illuminations but that has not yet been tested.

Table 4. Summary of model fit to data.

CONDITION	K	M	CORR (*r*)
70% CONTRAST	31.6	19.6	0.981
20% CONTRAST	70.0	35.3	0.912

The results shown in Figures 3 and 4 and the correlations in Table 4 support the validity of the hypothesis regarding using equivalent illumination and the T_{NVG} as a means of assessing the quality of aircraft transparencies with respect to NVGs. It is possible to use Equation 2 with the appropriate coefficients from Table 4 to reasonably predict the impact on visual acuity of a specific windscreen or canopy if its T_{NVG} value is known.

There is, however, an implicit assumption that must be addressed before applying the model presented herein. These results and the model presented assumes the transparency has a very low haze value[12]. Haze is a phenomenon caused by light scattering from materials within the transparency or from micro-scratches on the surface of the transparency (usually due to repeated cleaning). The effect of haze is to lower the contrast of objects viewed through the transparency which, in turn, would reduce visual performance (Snellen acuity). The implicit assumption was that the transparencies employed in this study had very little or no haze. The two transparencies used in this study were measured[13] and were found to have fairly low values of haze; 1.7% for the medium transmission and 2.4% for the low transmission transparency samples. If haze is present, then the model needs to be modified to include the loss in visual acuity due to contrast reduction. If haze is not present, then the contrast of objects viewed through a transparency remains the same no matter what the transmission coefficient is; only the apparent luminance of the object is affected. Future work in this area will address the haze issue.

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BIOGRAPHIES

ALAN PINKUS has been an Air Force psychologist since 1982. As a human factors engineer, he has worked on major systems including Royal Saudi Air Force KE-3 tanker, Gunship 2, LANTIRN, Air Force One and Joint-Stars. As a researcher, he has worked in the areas of image display metrics, night vision goggles, apparent motion, aircraft lighting, transparency analysis, vision from space, workload assessment and has lectured for NATO AGARD in Europe. Alan has a BS Degree (Wright State, 1974), an MA (University of Dayton, 1980) and a PhD (Miami University, 1992), all in Experimental Psychology. He holds seven patents (or pending) in the area of night vision goggle ancillary devices and has over 20 publications. He is a member of the Human Factors and Ergonomics Society (Southern Ohio Chapter), SAFE, Association of Aviation Psychologists and is active in the American Society for Testing and Materials Subcommittee F7.08 on Aerospace Transparencies.

H. LEE TASK has been employed as a research scientist for the US Air Force since 1971. He has served as chief scientist for the Armstrong Aerospace Medical Research Laboratory (prior to its reorganization and disestablishment in 1991) and is presently a senior scientist at the Visual Display Systems Branch of the Human Engineering Division, in the Armstrong Laboratory's Crew Systems Directorate, at Wright-Patterson AFB, Ohio. He is currently involved in research and development in the areas of helmet-mounted displays, vision through night vision goggles, optical characteristics of aircraft windscreens, vision, and display systems. He has a BS Degree in Physics (Ohio University), MS degrees in Solid State Physics (Purdue, 1971), Optical Sciences (University of Arizona, 1978), and Management of Technology (MIT, 1985) and a PhD in Optical Sciences from the University of Arizona Optical Sciences Center (1978). During his career he has earned 36 patents and has published more than 75 journal articles, proceedings papers, technical reports, and other technical publications. He is a member of the Human Factors and Ergonomics Society (HFES), the American Society for Testing and Materials (where he is chairman of Subcommittee F7.08 on Aerospace Transparencies and is a Fellow of the Society), the Association of Aviation Psychologists, SAFE association, the Society for Information Display (SID), and SPIE (the optical engineering society). He has served as reviewer for papers in SAFE, SID, and HFES.

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Effects of Laser Eye Protection and Aircraft Windscreens on Visual Acuity through Night Vision Goggles

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ABSTRACT

The combined use of hand-held laser pointers and night vision goggles (NVGs) is prevalent in nighttime tactical flight operations. Laser eye protection (LEP) is required during these missions to protect the eye from exposure to laser energy. The effects of the fielded FV-9 LEP visor and two prototype Wardove LEP spectacles on NVG-aided visual acuity (VA) were assessed. VA measurements were made through four types of aircraft transparencies using two different NVGs (4949C and 4949P) to determine if there were any interactions between the LEP, windscreens, and NVGs in their effects on VA. The results showed a correlation between the percent loss of NVG light due to the aircraft windscreens and the percent degradation in NVG VA (r=0.88). Also, the results revealed a small (8.5%), but statistically significant, degradation in NVG-aided VA with the FV-9 LEP for both NVG models. Neither Wardove spectacle had a statistically significant effect on NVG-aided VA compared to the no-LEP condition.

INTRODUCTION AND BACKGROUND

One of the primary performance characteristics associated with the use of NVGs is the level of visual acuity obtained when viewing through the NVGs. It has been shown that the VA obtained when viewing through NVGs depends on the light level of the scene being viewed (Pinkus and Task, 1998b). Previous studies have demonstrated NVG VA loss due to aircraft windscreens (Pinkus and Task, 1997) and due to LEPs (Riegler & Fiedler, 1998). The primary objective of this effort was to determine the amount of NVG VA loss that could be expected due to viewing through currently fielded aircraft windscreens and currently fielded LEPs and prototype LEPs under consideration for fielding.

METHOD

Participants.

Six NVG-experienced pilots, ranging in age from 32 to 46 years, participated in the evaluation. All participants had at least 20/20 unaided VA and demonstrated at least 20/35 NVG-aided VA at full moon equivalent illumination after NVG adjustment and focus.

Apparatus and Stimuli.

The evaluation was conducted at the Air National Guard Air Force Reserve Test Center (AATC) and Davis Monthan AFB, Tucson AZ using three F-16C and one A-10 aircraft on four consecutive nights. The aircraft were positioned in a suitably darkened hangar throughout the duration of each test. Each aircraft was equipped with a different canopy type. Two F-16 aircraft canopies had indium-tin oxide (ITO) coatings (Sierracin Type II and Texstar Type V). The third F-16 aircraft was equipped with a Texstar II gold-coat canopy.

The A-10 aircraft tested had uncoated acrylic "quarter panels" through which the observers viewed the visual acuity charts. The NVG-weighted transmission coefficient and haze was assessed for each canopy prior to NVG-aided VA data collection. Although the haze measurement technique was experimental, the transmission measurement was made using ASTM Standard Test Method F1863-98 for Measuring the Night Vision Goggle-Weighted Transmissivity of Transparent Parts. The device based on this test method that used to make these measurements is shown in Figure 1.

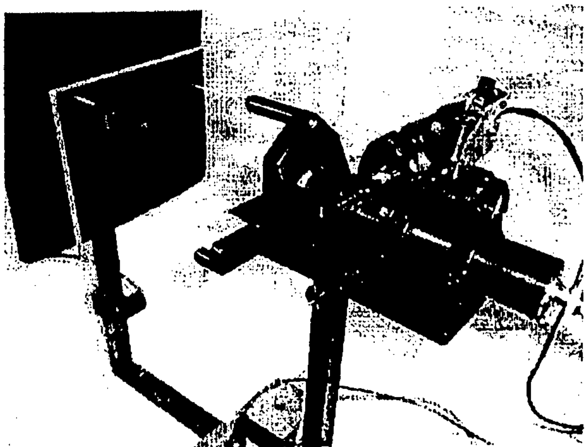

Figure 1. A close-up photograph of the infrared haze and transmission (IRH&T) measurement device used to measure the infrared (NVG spectrum) transmission coefficient of the aircraft windscreens used in this study.

The LEP devices tested consisted of one FV-9 (absorptive dye) and two WARDOVE (WD1 & WD2 reflective) spectacles (see Figure 2). Each LEP filter tested was mounted in a standard USAF aircrew spectacle frame. NVG luminous transmission was measured at 46% for the FV-9 filter, and 75% for the WD1 and WD2 filters.

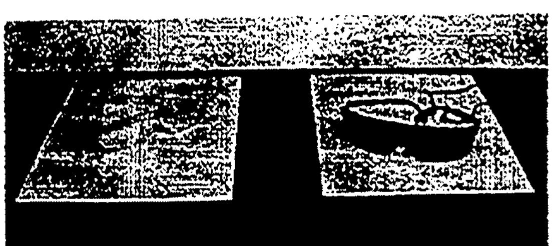

Figure 2. Wardove (left) and FV-9 (right) LEP Spectacles

NVG-aided VA was assessed using two NVG resolution charts composed of circular patches of square-wave gratings. Each chart contained six rows of six patterns (see Figure 3). All patterns on a given row were of the same spatial frequency. Successive rows increased in spatial frequency at relative intervals of approximately 12%. Spatial resolution values on chart "A" ranged (in Snellen notation) from 20/25 to 20/45, and chart "B" patterns ranged from 20/51 to 20/90. The modulation contrast of the patterns (as measured from the intensified NVG image of the pattern) was approximately 38%.

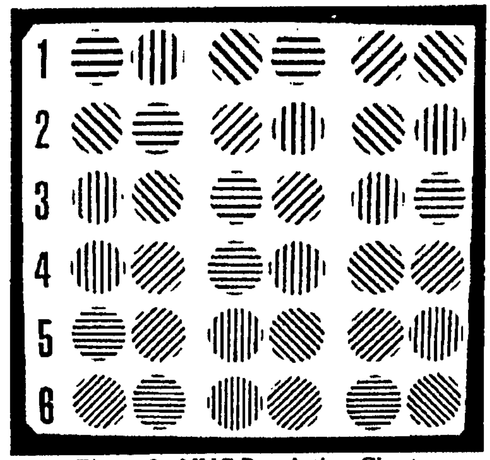

Figure 3. NVG Resolution Chart

Each pattern measured 4 inches in diameter and was positioned so that the bars were oriented either horizontal, vertical, 45° left, or 45° right. During data collection, the chart was mounted at eye-level on an aircraft maintenance stand, positioned 20 feet at a 45° viewing angle from the aircraft "straight-ahead" direction.

The NVG resolution chart was illuminated by a Hoffman LM-33-80 Night Sky Projector. The evaluation was conducted at clear starlight equivalent illumination (1.7 x 10^{-10} NR_B) Night Vision Imaging System (NVIS) radiance value as defined in ASC/ENFC 96-01, Lighting, Aircraft, Interior, NVIS Compatible. NVIS radiance was measured from the white portion of the resolution chart using a Photo Research 1530-AR spot photometer with a Class B filter, and verified with a Hoffman NVG-103 Inspection Scope.

Two models of the F4949 NVG (F4949C and F4949P) were used in this evaluation. These models are representative of current NVGs used by pilots employing laser pointers. The F4949P is a more recent model than the F4949C and has the same specification as the Omnibus IV F4949H and G models. Compared to the F4949C, the F4949P has better image quality due to increased gain, better resolution, and higher signal-to-noise ratio. The P-model also uses a P43 phosphor while the C-model uses a P22 phosphor.

Procedure

Aircraft Canopy Transmission Measurement

With the aircraft in a dark hangar, the NVG-weighted transmission coefficient of the canopy was measured in the general area of the canopy through which the observers would be viewing the visual acuity chart (see Figure 4). These measurements were made using the device described in the Apparatus section.

Figure 4. IRH&T measurement device being used to measure the percentage of NVG transmission of an F-16 canopy using ASTM Standard Test Method F1863-98.

Observer Visual Acuity Assessment
Each observer participated in one one-hour session per aircraft. Only one observer completed the evaluation for all four aircraft. The aircraft (i.e. canopy types) used for the six observers are listed in Table 1.

Table 1. Observer - aircraft combinations

Observer	Aircraft Used
A	A-10
B	Gold
C	ITO (II)
D	ITO(V)
E	Gold, ITO(II), ITO(V)
F	Gold, ITO(II), ITO(V), A-10

Prior to data collection, the hangar was darkened and the luminance ("brightness") of the F-16 cockpit displays was adjusted by an NVG-experienced pilot to a level judged to be operationally representative. The starlight projector was set to provide approximately full moon equivalent illumination of the chart area. The observer was seated in the pilot seat at a 20 foot viewing distance from the resolution chart. The observer then focused each NVG model to obtain maximum VA of a high contrast reference chart with the canopy up. The illumination level was decreased for the remainder of the session so the white area of the NVG resolution test chart had an NVIS radiance of 1.7 x 10^{-10} NR_B (clear starlight illumination).

On each trial, the observer "read" the line on the NVG resolution chart that could easily be resolved. The experimenter verified the accuracy of each response (horizontal, vertical, left, or right) and directed the observer to read successive lines increasing in spatial frequency. This was repeated until the observer reached a line that could not be resolved.

For each session, NVG-aided VA was first recorded with the canopy up using the first NVG model and no LEP. The canopy was then lowered and NVG-aided VA was assessed through the canopy. The canopy remained down for the three NVG + LEP viewing conditions, which were completed in a randomly determined order. After completion of the VA task for the first NVG model, the observer mounted the second NVG model and repeated the same procedure for this NVG. In sum, NVG-aided VA was assessed at five viewing conditions for each NVG model, two without LEP (canopy up and canopy down) and three with NVG + LEP (canopy down).

RESULTS

Aircraft Canopy NVG Visual Acuity Results
Table 2 is a summary of the NVG transmission coefficients measured for each of the aircraft canopies measured. In addition, Table 2 shows the percentage reduction in NVG-sensitive light due to the canopy and the corresponding average decrease in visual acuity caused by viewing through the transparency. The correlation coefficient between percent loss of NVG-light and percent loss of visual acuity was r=0.88. For this analysis, the visual acuity was taken as the smallest size grating for which the observer got at least 5 of the 6 orientations correct without missing more than 1 for any larger size grating row. No LEP was involved in any of these data.

Table 2. Summary of aircraft canopy NVG transmission coefficients and corresponding percentage light loss and visual acuity loss (UP=no canopy, DOWN=through canopy) averaged across the two NVGs used (no LEP).

		UP	DOWN	%	%
Canopy	NVG Trans Coefficient	Avg. VA	Avg. VA	VA decrease	Light Loss
Gold	0.56	39.0	51.9	33	44
ITO (II)	0.81	43.3	53.1	23	19
ITO (V)	0.74	42.5	53.0	25	26
A-10	0.88	40.9	42.9	5	12

An alternative analysis of the windscreen-only data was done to determine if the VA difference between windscreens was statistically significant. For this analysis the acuity value used was the smallest grating size that the subject could correctly identify at least 4 of the 6 target orientations correctly. One acuity value was then used for each combination of observer, aircraft (A-10, Gold, ITO(II), and ITO(V)), windscreen condition (Up, Down, WD-1, WD-2, and FV-9) and NVG (F4949C and F4949P). The windscreen conditions are referred to as LEP (laser eye protection) when the only levels used were

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WD-1, WD-2, and FV-9. Only 1 subject used all 4 aircraft. Table 3 contains the aircraft used by each observer (A through F) along with their mean acuity for the windscreen Up condition.

Table 3. Mean Snellen acuity (20/XX) when the windscreen was Up. There were 2 acuity values for each aircraft used (i.e. one for each NVG).

Observer	Aircraft Used	Mean Acuity for 'Up'	N
A	A-10	43	2
B	Gold	38	2
C	ITO	43	2
D	ITO(V)	51	2
E	Gold, ITO, ITO(V)	38	6
F	A-10, Gold, ITO, ITO(V)	38	8

When the observers were exposed to the windscreen Down condition (viewing through the windscreen), the percent increase in target size (decrease in visual acuity) from the windscreen Up condition (no windscreen) ranged from 0 to 41 with a median of 26 (N=22). There were 2 instances of 0 percent increase, both coming from the A-10 aircraft. The dependent variable used in the following analyses was the percent change in target size from the windscreen Down condition. A problem exists in that each subject did not use all aircraft.

Comparison of the aircraft is difficult. Observer E used 3 of the aircraft and observer F used all 4. With these 2 subjects the percent change in acuity was averaged across LEP and NVG for each aircraft. A 1-factor (aircraft) repeated measures analysis of variance using the Gold, ITO(II), and ITO(V) only, with error term observer*aircraft, did not find a significant difference among the 3 aircraft {$F(2,2)=0.01$, $p=0.9996$}. Means were: Gold=2.1, ITO(II)=2.1, and ITO(V)=2.3. Note that for Observer F the mean for A-10 was 2.0.

Laser Eye Protection NVG Visual Acuity Results

It was assumed that there was no interaction between aircraft and either LEP or NVG. For all observers the percent change from the windscreen Down condition was averaged across aircraft. The observers have different N for each mean. A 2-factor repeated measures analysis of variance was performed using this mean as the dependent variable with LEP (WD-2, WD-2, and FV-9) and NVG (F4949C and F4949P) as factors. Observer interactions were used as error terms. Results are shown in Table 4.

The main effect means for the NVGs were F4949C=3.8 and F4949P=4.4. Table 5 contains the mean and standard deviation of observers for the LEPs (after averaging across NVG). P-values are given from a t-test for Ho: mean=0.

Table 4. ANOVA results for NVG VA percent change from windscreen Down.

Source	SSQ	DF	Error SSQ	Error DF	F-Value	P-Value
LEP	379.1	2	142.4	10	13.31	0.0015
NVG	3.2	1	379.7	5	0.04	0.8448
LEP* NVG	49.0	2	264.6	10	0.93	0.4277

Table 5. Mean and std of subjects (N=6) for percent change from windscreen Down. P-value is for Ho: mean=0.

	Percent Change		
LEP	**Mean**	**Std**	**P-value**
WD-1	0.9	3.3	0.5244
WD-2	2.8	5.4	0.2596
FV-9	8.5	3.2	0.0013

Figure 5 contains the mean percent change from windscreen Down for each condition. Using the Bonferroni paired comparisons procedure with a .05 overall error level (per comparison error level=.05/3=0.0167) the minimum significant difference was 4.4 for comparing the means of the percent change from windscreen Down.

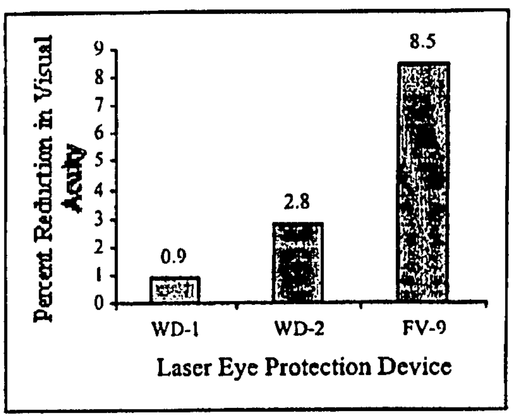

Figure 5. Mean percent change in NVG VA from Windscreen Down (No LEP).

DISCUSSION and CONCLUSIONS

One major problem of working with visual acuity as a dependent variable is the difficulty in determining what visual acuity should be assigned to a particular observer response to the Visual Acuity chart. The Visual Acuity chart used for this study was intended to make an objective assessment of VA by requiring the observer to identify the direction of the grating patches. Since there were 4 possible orientations for each patch and there were 6 patches for each acuity level this made it essentially impossible for observers to get all correct answers for a single row by guessing. However, the problem arises as to what to use as a cut-off value if the observer does not get all of the orientations right in a particular row. It is possible to calculate the probability of guessing correctly 3, 4, 5, or 6 of the patches in a row so that one may set an objective criteria for determining VA. But, in some cases observers produce strange results. For example, one observer in one of the conditions had the following sequence of responses: for the 20/45.1 row he got all 6 right, then got only 4 right in the 20/40.2 row but bounced back and got 5 in the 20/35.8 row. So what VA score should be assigned to this individual? It is apparent that he did significantly better than chance in all 3 rows but it is also apparent that he missed some indicating his NVG VA shouldn't be counted the same as someone who makes no errors and gets the 20/35.8 row correct. It is beyond the scope of this paper to solve this dilemma, however, this needed to be explicitly addresses as various analyses on the data used different criteria.

For the analysis comparing the effects of the aircraft transparency (by itself) on NVG visual acuity, an observer was given the VA score corresponding to the highest acuity level for which he got at least 5 of the 6 patches correct, but without missing more than 1 patch in any row of lower acuity. In the example above the individual was assigned a score of 20/45.1 since the 5 he got correct for 20/35.8 occurred after he missed 2 in the 20/40.2 row. However, for the LEP analyses a simple criteria of 4 correct was used. Both approaches are defensible and the only reason that there are two approaches here is because two different individuals did the analysis independently on the data and established their own criteria. This is an area that needs further research in that VA is quite often used to assess effects of different conditions but the "fuzziness" of exactly what should be used as a criteria for VA may sometimes make it difficult to assess or compare results.

With the preceding issue in mind, the major conclusions of this effort are that the NVG VA was indeed affected by the aircraft transparencies that were used and this effect was correlated to the transparencies transmission coefficients for NVG-sensitive light. In addition, the LEP effect was minimal (non-significant) for the two LEPs that had the highest luminous transmission (as measured for the NVGs used - about 75%) and statistically significant (although still small) for the LEP that had the lowest luminous transmission (the FV-9 at 46% transmission). These results are encouraging and are in line with past research into the effects of aircraft windscreens and laser eye protection on NVG visual acuity. It should be possible to develop a model based on NVG-weighted transmission coefficients (for the windscreens) and NVG phosphor emission weighted transmission coefficients (for the LEP) to accurately predict NVG VA effects. This is a topic for future work.

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Joe Riegler has been a human factors research scientist supporting Air Force R&D in the areas of visual performance assessment and crew-system interface evaluation since 1985. He is currently employed by The Boeing Company as a human factors engineer for the NVG Fly by Night Training Team, Warfighter Training Research Division, Air Force Research Laboratory, Mesa, AZ. In this position, he conducts human factors research examining various aspects of visual performance with night vision devices. He has a BA degree in Psychology (Thomas More College, KY 1981) and an MA degree in Human Factors (Wright State University, 1986). During his career, he has (co)authored over 25 technical reports, proceedings papers, and journal articles.

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AL-TR-1991-0011

ARMSTRONG LABORATORY

THE EFFECT OF SIGNAL-TO-NOISE RATIO ON VISUAL ACUITY THROUGH NIGHT VISION GOGGLES

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13. ABSTRACT *(Maximum 200 words)* Since 1971, night vision goggles (NVGs) have been used by the military to enable personnel to perform visual operations in a nighttime environment. The key component of these devices is the image intensifier tube. Currently, no studies were identified which relate the signal-to-noise ratio (SNR) of image intensifiers to human visual acuity. The purpose of the present research was to determine the effect of NVG intensifier tube SNR on visual acuity. Visual acuity, using PVS-7 third generation NVGs, was measured for twelve participants at quarter moon and starlight illumination levels for four intensifier tubes with different SNRs. The range of SNR examined was 11.37 to 17.92. Visual acuity was assessed using Landolt C charts with target contrasts of 20 to 95 percent. The distance at which the acuity targets were resolved was recorded for each of the four illumination and contrast conditions. The results showed that increases in image intensifier tube SNR, illumination level, and contrast affected visual acuity. Regression analyses were performed to obtain estimated equations relating SNR to visual acuity for each experimental condition. The results were used to develop predictive guideline tables to provide approximate percent degradation/improvement in visual acuity based upon intensifier tube signal-to-noise ratio.

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Summary

The purpose of the present research was to determine the effect of NVG image intensifier tube signal-to-noise ratio (SNR) on visual acuity. Visual acuity through PVS-7 NVGs was measured for twelve subjects at quarter moon and starlight illumination levels for four intensifier tubes with different SNRs. The range of SNRs examined was 11.37 to 17.92. Visual acuity was assessed using Landolt C charts with target contrasts of 20 and 95 percent. The results showed that image intensifier tube SNR, illumination level, and contrast had significant effects on visual acuity. Regression analyses were performed to obtain estimated equations relating SNR to visual acuity for each illumination and contrast condition.

The results showed a trend toward SNR having a greater impact on visual acuity at the two lowest illumination conditions than at the higher illumination condition. The results were used to produce guideline tables for estimating percent increases in visual acuity as a function of intensifier tube SNR. Due to the large differences between subjects in visual acuity performance with NVGs, it was concluded that further research should be conducted to examine the correlation between visual acuity obtained for unaided normal room light viewing and NVG viewing.

Preface

This evaluation was completed under work unit 7184-18-07 by members of the Crew Systems Effectiveness Branch, Human Engineering Division, Armstrong Aerospace Medical Research Laboratory, Wright-Patterson Air Force Base, Ohio and Logicon Technical Services, Inc., Dayton, Ohio. The authors thank Annette Zobel (LTSI) for her technical support throughout this study and Chuck Goodyear (LTSI) for his assistance with data analysis and interpretation.

Introduction

Night vision goggles (NVGs) have been developed by the US Army for use in night military operations. The key component of these devices is the image intensifier tube. The image intensifier tube is basically a light amplifier that is sensitive over the spectral region of about 600nm to 900nm (for the third generation intensifier). There are a number of parameters that are used to characterize the image intensifier such as gain, resolution, brightness, distortion, signal-to-noise ratio, etc (see Csorba [1]). Measurement procedures exist for determining the value of these parameters and others. However, there have been very few studies that relate these parameters to their impact on human visual performance with the NVGs. Specifically, no studies could be found that related the signal-to-noise ratio (SNR) with human visual acuity even though there exist specifications as to the SNR required for image intensifiers.

The purpose of the study described herein was to determine the effect of SNR on visual acuity. Four PVS-7, third generation image intensifier tubes were acquired that had four different SNRs. The PVS-7 tube was chosen because the PVS-7 NVGs use a single objective lens and a single image intensifier that is imaged to both eyes via beamsplitting optics and two eyepieces. This allowed the subject to observe the image through the NVGs with both eyes.

Visual acuity is normally measured by determining the minimum angular subtense of a specified test character (e.g. Landolt "C", tumbling "E", or Snellen letter) at which an observer can determine the orientation of the character (Landolt "C", tumbling "E") or be able to read the character (Snellen letters). A typical eye chart used for this type of measurement consists of lines of characters of different sizes. However, these charts are designed for use in vision screening and, due to the character size increments, are not very well suited for research.

Two other factors that affect visual acuity (both direct view and through night vision goggles) are contrast and illumination level. Visual acuity tends to be poorer for lower contrast levels and lower illumination levels.

Based on this information, it was decided to investigate visual acuity with the PVS-7 NVGs for two different illumination levels and two different contrasts. It was also necessary to develop a methodology by which the angular subtense of the visual acuity test character could be made continously variable to permit more accurate determination of acuity. Since angular subtense depends on the distance from the subject to the test target, a technique was used that continuously varied this distance in a controlled fashion. The subject was seated in a cart that moved at a uniform speed along a track toward the test target. This methodology provided an excellent means of getting a sensitive measure of visual acuity.

Method

2.1 Subjects

Twelve male volunteers participated in this study. The subjects ranged in age from 18 to 34 years (mean = 23.8, SD = 5.0). Each subject reported good ocular health and visual acuity of at least 20/20 corrected in each eye for distance vision.

2.2 Facilities and Equipment

The facility used for data collection was the zoom lane, see Figure 2.1, located in the Visual Dynamics Facility, Armstrong Aerospace Medical Research Laboratory, Human Engineering Division, Wright-Patterson AFB, Ohio. The equipment comprising the zoom lane was an electronically controlled cart powered by an electric motor and operated via a retractable cable system. The cart itself contained a height adjustable, high-backed seat, a side stick controller to input cart stop commands and an armrest to reduce arm fatigue during the experiment. A black plexiglass board was positioned on the front of the cart such that it could be raised to occlude vision between experimental runs. The subject was seated inside the cart, which traveled along a 12.2 meter (m) track. System control was provided by a Zenith 248 computer, which allowed the experimenter to input movement commands (e.g., starting, stopping, velocity and direction) and data collection functions from a remote control panel.

A moonlight simulator was used to approximate the spectral characteristics and luminance intensity levels of different phases of the moon. It was mounted on a tripod which was adjusted to provide calibrated illumination on the surface of the Landolt C charts used as visual stimuli for assessing visual acuity. A Photo Research PR-1980b Pritchard Photometer was used to measure the photometric luminance of the charts and background. This was performed several times during each session to verify that the luminance of the

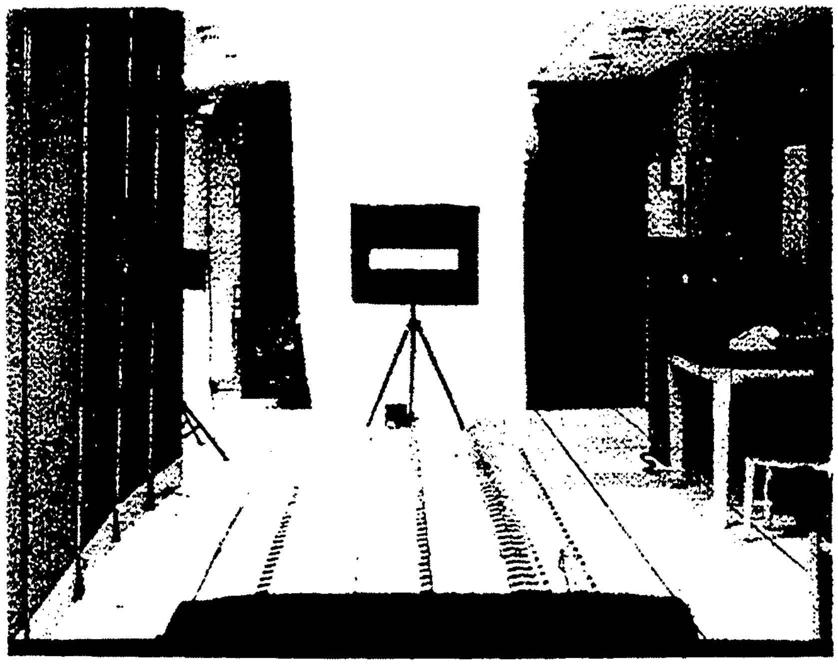

Figure 2.1: AAMRL Zoom Lane Laboratory

chart remained constant.

A pair of ITT AN/PVS-7B biocular night vision goggles (NVGs) were used as the optical test platform for this research. Four ITT third generation image intensifier tubes with similar characteristics, but different signal-to-noise ratios were used.

The AN/PVS-7B NVGs, like most NVGs, have a relatively fast (low F/number) objective lens to gather as much light as possible to enhance performance of the NVGs. However, this low F/number also reduces the depth of focus of the NVGs which, for the present experimental procedure, posed a problem. Since the dependent variable of this experiment was the angular subtense of the acuity target obtained by varying the distance from the observer to the chart, a large depth of focus was required. The depth of focus needed to be sufficiently large that the quality of the image would not be degraded over the zoom lane cart distance range (12.2 to 3.05 m; see Fig 2.2).

Depth of focus can easily be increased by reducing the objective lens aperture of the NVGs. However, this reduces the irradiance produced by the lens at the input side of the image intensifier tube. This effect can be corrected by increasing the radiance of the target to compensate for the light energy lost due to reducing the objective lens aperture. Since the irradiance at the image plane of a lens (the input side of the NVGs in this case) is proportional to the square of the clear aperture of the lens (usually the lens diameter), then the revised radiance necessary can be calculated from the square of the ratio of the original lens diameter to the modified lens system diameter (the aperture placed over the lens). The PVS-7 lens has an effective diameter of 20.8 mm. and the aperture used to increase depth of focus was 4 mm. Thus the target radiance was increased by a factor of $(\frac{20.8}{4})^2$ or 27. Table 2.1 lists some converted values used for this study.

2.3 Stimuli

Visual Acuity Charts

The Landolt C chart format was chosen as the visual stimulus for measuring acuity in this study. Visual acuity was assessed for two levels of positive letter-to-background contrast, 20 and 95 percent. Modulation contrast (C) was calculated using the following equation:

$$C = \frac{Backgrnd_{Lum} - Target_{Lum}}{Backgrnd_{Lum} + Target_{Lum}}$$

A visual acuity of 20/20 represents detection of a gap width (open end of C) subtending 1 minute of arc, using the Landolt C procedure. The Landolt C letter size is five times its gap width. Two letter sizes were used to ensure that both the high and low contrast letters would remain in focus and could be resolved within the zoomlane range (12.2 m to 3.05 m). Letters having gap widths of 4.7 mm and 7.6 mm were used for the high and low contrast conditions, respectively. These represented Snellen fraction sizes of 20/36 and 20/57 at a distance of 9.1 m (30 ft.). The Landolt Cs were displayed on acuity charts which measured 0.15 m by 0.61 m and contained high contrast or low contrast letters on a white background. The letters were separated by a distance of 70 mm.

Each trial was initiated at a distance of 12.2 m from the acuity chart. The trial ended when the subject was able to determine the orientation of each C on the chart. The change in angular subtense of the Landolt C gap as a function of distance from the acuity chart is plotted in Figure 2.2 for both high and low contrast letters.

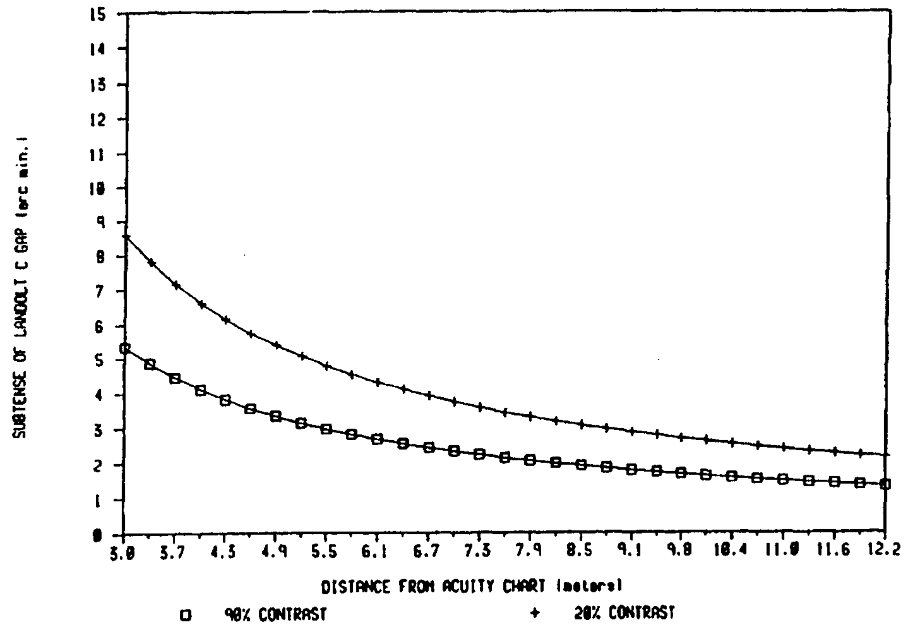

Figure 2.2: Change in Landolt C gap angular subtense as a function of zoomlane distance for 20% and 95% letters

Luminance Levels

The Landolt C target stimuli were presented on white foam core boards having a reflectance of approximately 100 percent. Since there is a convention in the night vision goggle community to relate illumination levels to fraction of moon illumination, it was necessary to make some assumptions in order to arrive at an appropriate reflected luminance level from the target test chart.

The first concern was determining what level of illumination was considered to be "full moon". From the RCA Electro-Optics Handbook [2] , a value of 0.0235 foot-Candles (ft.-C) illumination is listed as maximum full moon illumination. It should be noted that actual moon illumination depends heavily on weather conditions (light haze can reduce illumination considerably), moon elevation level above the horizon, and orientation of the surface illuminated. Further, the vast majority of naturally occurring objects have a reflectance factor considerably less than unity, thus reducing the apparent luminance of the object. For purposes of this study, it was decided to have the white areas of the stimulus target simulate a 50% reflective Lambertian (fully scattering) surface. Due to the way English units of luminance and illuminance are defined, one foot-candle of illumination gives rise to one foot-Lambert of luminance for illumination falling on a perfect Lambertian reflector with unity reflectance.

Table 2.1: Moon illumination and acuity chart luminance values used in present experiment

MOON ILLUM. LEVEL	DESIRED ILLUM. (Ft.-C)	ASSUMED REFLECT. (percent)	DESIRED LUM. (Ft.-L)	ADJUST. FACTOR	REQ. CHART LUMINANCE (Ft.-L)
Full	0.0235	50	0.0118	27	0.3186
0.25	0.00588	50	0.00294	27	0.0794
0.01	0.000235	50	0.000118	27	0.0032

Based on these assumptions: 1) full moon illumination is 0.0235 ft.-C, 2) the stimulus target is Lambertian (perfectly diffusing); and 3) a 50% reflective surface is desired, the simulated moon illumination source should, for full moon illumination, be adjusted to provide an illumination of 0.0235/2 or 0.0118 ft.-C, which gives rise to 0.0118 ft.-L luminance, at the white areas of the target. This value is for the NVGs with no aperture over the lens. If the aperture is in place, this value needs to be increased by a factor of 27 as discussed earlier. Table 2.1 lists the fractional moon illumination levels, the corresponding target luminance that would result from a 50% reflective surface, and the luminance that was required to compensate for the 4mm aperture over the objective lens of the NVGs.

2.4 Procedure

Training Trials

Prior to data collection each subject participated in one block of eight trials; two at each illumination and contrast condition. These trials served to familiarize subjects with the task while allowing for dark adaptation. Each subject was individually tested following the same procedure outlined for the data collection trials. On each training trial, subjects were presented a chart containing four Landolt Cs of diminishing size. Subjects stopped the cart and called out the orientation of each C in succession, starting with the largest. The cart was advanced forward until each C orientation was correctly identified.

Data Collection Trials

Each subject performed the experiment seated in the cart which moved at a constant velocity of 0.25 meters per second toward the acuity chart. At the beginning of each trial, the cart was positioned so that the subject's eyes were at a distance of 12.2 m from the acuity chart. During data collection, all the Landolt Cs on a given chart were the same size. After verifying that the subject was ready and the NVGs were properly focussed, the experimenter initiated cart movement from the computer workstation. Upon cart movement, the subject lowered the vision occluder and viewed the acuity chart. The subject stopped the cart by depressing the trigger switch on the side stick controller when he was "virtually certain" he could determine the orientation of all of the Cs. After stopping the cart, the subject read aloud the orientation of each C. If the subject's responses were correct, the distance was recorded and the cart returned to the starting position. If an incorrect response was made or the experimenter was uncertain of the subject's response, the subject was asked to read the entire chart again. If the response was incorrect, the cart was advanced forward until the subject could correctly determine the orientation of each letter or until the end of the track was reached. After each trial, the subject raised the vision occluder and rested while the cart was returned to the starting position.

2.5 Experimental Design

This study incorporated a 2x2x4 repeated measures experimental design. The independent variables were the illumination level (0.01 and 0.25 moon), the contrast of the acuity charts (20 and 95 percent) and the signal to noise ratio (SNR) of the four image intensifying tubes (17.92, 15.28, 13.71 and 11.37). The dependent variable was visual acuity (measured as the minimum angle of resolution computed from the distance from the acuity targets when the subject correctly identified the orientation of all Cs. Each subject participated in 32 data collection trials, two at each experimental condition. The trials were grouped across the four image intensifier tubes and presented in blocks of eight. The order of presentation of the four blocks was counterbalanced across the twelve subjects.

Results

The distance from the NVG objective lens to the acuity chart was recorded on each trial and used to compute the mean resolution angle in minutes of arc for each condition. The data was then transformed to 1/min. of arc as a measure of visual acuity. For ease of interpretation, visual acuity will be used instead of resolution angle when describing the results and conclusions.

3.1 ANOVA Results

An analysis of variance (ANOVA) was conducted on the visual acuity data (1/min. of arc). The independent variables in the ANOVA were SNR of the image intensifier tube (4), illumination level (2), and contrast (2). SNR was considered a categorical independent variable in the ANOVA, since the signal-to-noise ratio may not be the only factor differentiating the four tubes tested. F tests involving effects with more than one degree of freedom in the numerator had a Geisser-Greenhouse correction performed [3]. All pairwise mean comparisons were done using paired t-tests from reduced models.

The mean visual acuity obtained for each intensifer tube as a function of contrast and illumination is in Figure 3.1. The results of the ANOVA showed significant main effects of SNR (P=0.0021), illumination (P=0.0001), and contrast (P=0.0001) on visual acuity, with increases in each variable resulting in increased visual acuity. The ANOVA revealed significant interactions for SNR by illumination (P=0.0061) and illumination by contrast (P=0.0183). A summary table of the ANOVA results is provided in Appendix A.

Tests for simple interactions were performed within the SNR by illumination interaction (displayed in Figure 3.2) to isolate the source of the interaction. The tests showed significant interaction (P=0.0131) only when tube SNR = 15.28 was used with each of the other levels of SNR, indicating that the effect of illumination was consistent across the three remaining tubes tested.

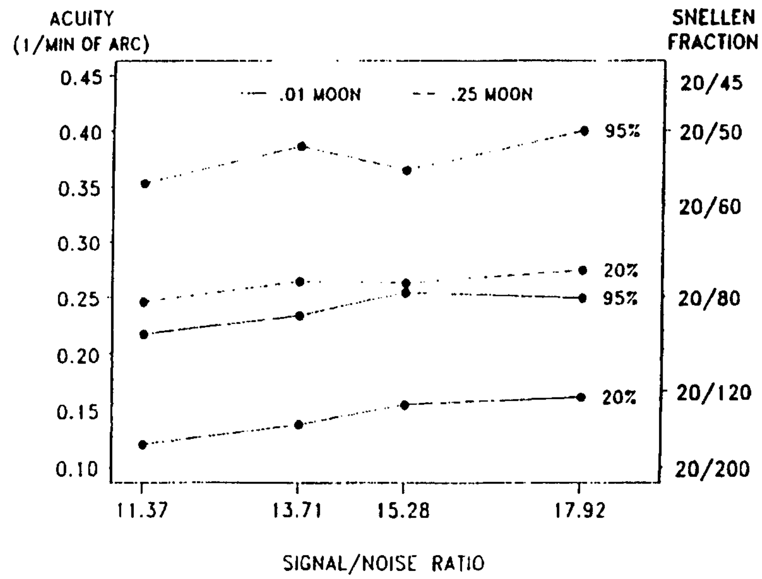

Figure 3.1: Mean visual acuity as a function of SNR, illumination, and contrast

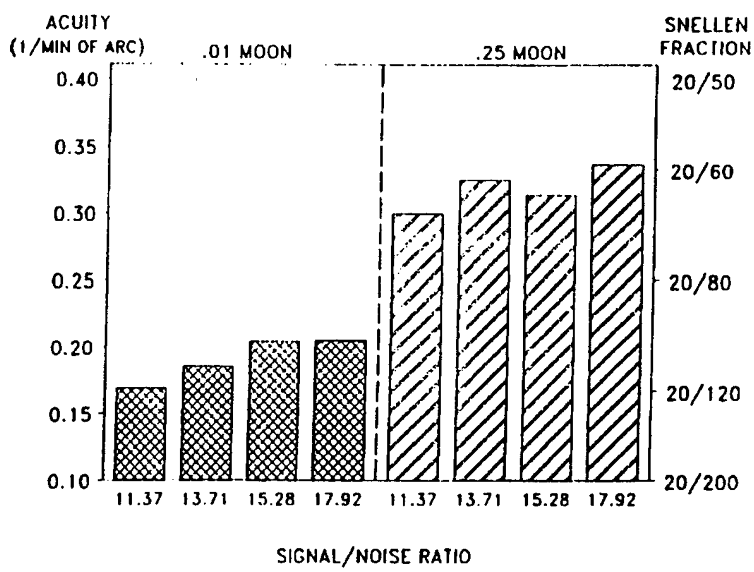

Figure 3.2: Mean visual acuity as a function of tube SNR and illumination averaged across contrast

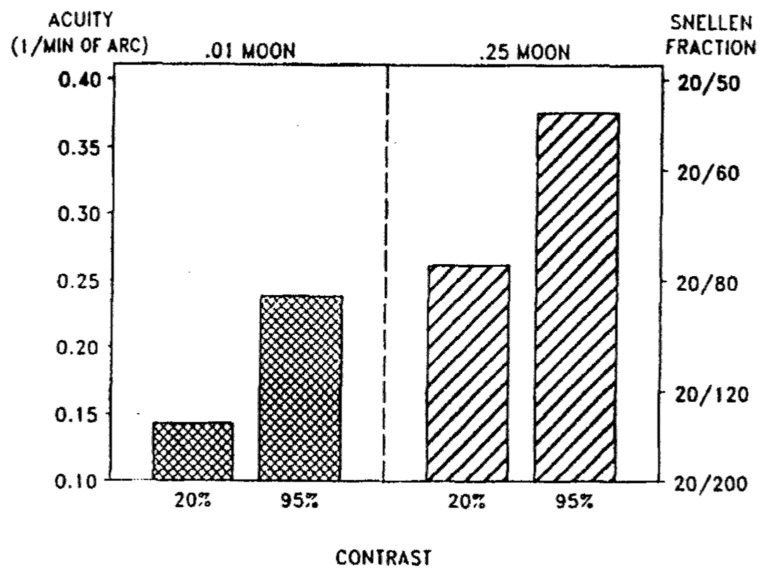

Figure 3.3: Mean visual acuity as a function of illumination and contrast averaged across SNR

Inspection of the significant illumination by contrast interaction (Figure 3.3) indicates that the mean difference in visual acuity between the two contrast conditions was significantly greater at the 0.01 moon illumination than at the 0.25 moon level. T-tests also revealed that for each level of SNR and contrast, visual acuity was significantly greater at the 0.25 moon illumination level at the 0.001 significance level.

3.2 Regression Analysis

Regression analyses were performed on the visual acuity data to obtain an estimated equation relating intensifier tube SNR to visual acuity. Separate regressions were performed for each of the four illumination and contrast conditions. In each regression, the independent variable was 1/SNR and the dependent variable was acuity in 1/min. of arc. The reciprocals were used since the relationship between SNR and acuity is asymptotic, and they provided a better fitting curve to the data than a linear model. The estimated equations are listed in Table 3.1 for each illumination and contrast condition. Plots of each estimate are displayed in Figure 3.4. Analysis of covariance indicated that the estimates describing the relationship between SNR and visual acuity did not differ significantly across the four illumination and contrast conditions, $(P = 0.016)$.

The equations listed in Table 3.1 were used to produce tables of guidelines for predicting percent increases in acuity for a range of SNRs from 10 to 20, (Tables 4.1 through 4.4). Relative percent increases in visual acuity predicted for the SNRs tested in this study are listed in Table 3.2 for each condition. The values in this table represent the percent increase in acuity predicted when increasing from a specific SNR value (left column) to a higher SNR value (top row). Due to the significant interaction involving tube SNR 15.28, the regression analysis was performed again without this tube included. The estimated equations for this regression are listed in Table 3.3.

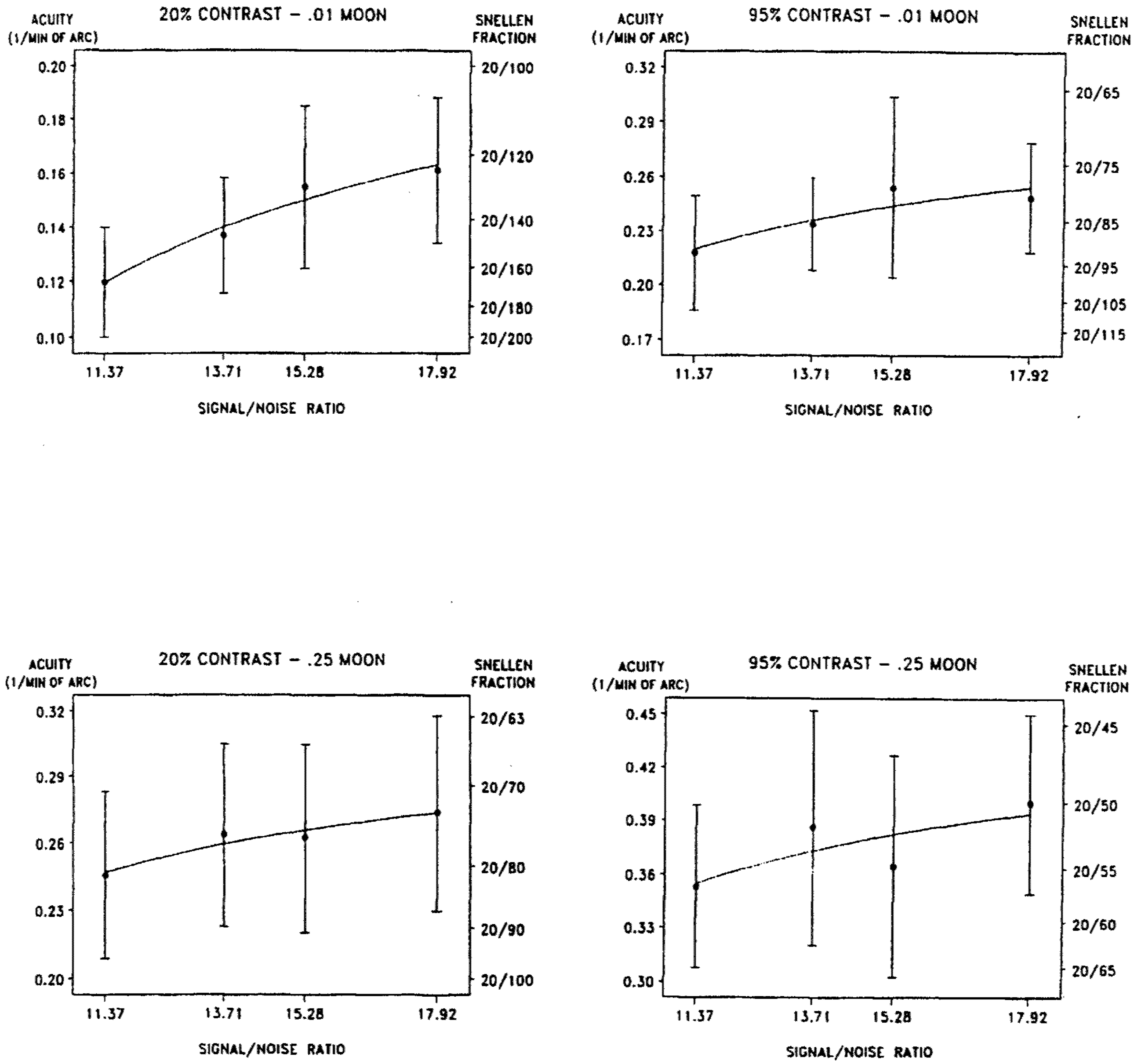

Figure 3.4: Estimated equations depicting relationship between SNR and visual acuity for each illumination and contrast condition

Table 3.1: Estimated Equations for each illumination and contrast condition

ILLUM. LEVEL	CONTRAST	ESTIMATED EQUATION	CORR	P
0.01 MOON	20%	0.2390 - 1.3596/SNR	0.98	0.0172
0.01 MOON	95%	0.3151 - 1.0875/SNR	0.91	0.0935
0.25 MOON	20%	0.3193 - 0.8217/SNR	0.96	0.0378
0.25 MOON	95%	0.4614 - 1.2107/SNR	0.78	0.2185

Table 3.2: Percent increase in visual acuity from a lower SNR (left column) to a greater SNR (top row) between the SNRs used in this study

		SNR		
CONDITION	SNR	13.71	15.28	17.92
Illum. = 0.01	11.37	15%	20	27
Contrast = 20%	13.71		7	14
	15.28			8
		13.71	15.28	17.92
Illum. = 0.01	11.37	7%	10	14
Contrast = 95%	13.71		3	7
	15.28			4
		13.71	15.28	17.92
Illum. = 0.25	11.37	5%	7	10
Contrast = 20%	13.71		2	5
	15.28			3
		13.71	15.28	17.92
Illum. = 0.25	11.37	5%	7	10
Contrast = 95%	13.71		2	5
	15.28			3

Table 3.3: Estimated equations with tube SNR 15.28 excluded from analysis

ILLUM. LEVEL	CONTRAST	ESTIMATED EQUATION	CORR	P
0.01 MOON	20%	RES = 0.2328 - 1.2966/SNR	0.99	0.0396
0.01 MOON	95%	RES = 0.3024 - 0.9572/SNR	0.99	0.0332
0.25 MOON	20%	RES = 0.3234 - 0.8630/SNR	0.98	0.1269
0.25 MOON	95%	RES = 0.4836 - 1.4387/SNR	0.96	0.1753

Discussion

The purpose of this study was to quantify the relationship between NVG image intensifier tube signal-to-noise ratio and human visual acuity. The results showed that increases in intensifer tube SNR resulted in better visual acuity at both quarter moon and starlight illumination for both high and low contrast targets. The functions describing the relationship between SNR and acuity did not statistically differ across the four conditions tested, although there was a trend toward SNR having a greater impact on acuity under lower visibility conditions. This trend failed to reach significance due to the large amount of variability between subjects and the small number of intensifier tube SNRs tested. A study using more subjects and a greater number of SNR levels may be expected to result in a significant effect of SNR on acuity under low illumination and contrast conditions. The effects of target contrast and illumination on acuity were as expected, with higher contrast and illumination levels resulting in better visual acuity.

The results of the regression analyses were used to generate tables of guidelines for predicting percent increases in acuity as a function of SNR. These guidelines, contained in Tables 4.1 through 4.4, allow the user to estimate percent increases in visual acuity performance over an SNR range of 10 to 20. The values in the tables are estimated percent increases in visual acuity as SNR is increased from a lower value (left column) to a greater value (top row).

Inspection of these tables reveals that improvements in visual acuity with increases in SNR vary depending upon the illumination and contrast. For example, Table 4.1 shows that doubling SNR (from 10 to 20) results in a 40% improvement in visual acuity for low illumination and low contrast. However, the same increase in SNR results in only a 15% increase in acuity for both the 20% and 90% contrast targets at quarter moon illumination (Tables 4.3 and 4.4). Therefore, increases in SNR have their greatest impact on visual performance under conditions of lower illumination. This is better illustrated by the following example.

It might be expected that an individual's visual acuity performance with intensifier tubes having an SNR of 20 would be significantly better than the acuity achieved with an SNR of 15 (a 33% difference in SNR). However, the present results show that such an increase results in only an estimated 13% improvement in acuity for 20% contrast targets and a 7% improvement for the 95% contrast targets at .01 moon illumination (Tables 4.1 and 4.2). Likewise, the same increase in SNR fo quarter moon illumination improves acuity by only 5% for both levels of contrast (Tables 4.3 and 4.4). This may be a negligible improvement for some NVG scenarios.

It should be noted that the values in the tables are estimated increases predicted from "best case" laboratory viewing conditions. These values also represent average increases derived from the mean acuity of the individuals tested in this study. Operational scenarios, employing other measures of acuity for different individuals, may yield different results.

Subject variability also proved to be a significant factor affecting visual acuity through NVGs in the present study. Although all subjects reported 20/20 visual acuity prior to testing, acuity for NVG viewing ranged from 20/108 to 20/175 in the most degraded visibility condition (low illumination, low contrast) and from 20/42 to 20/65 in the highest illumination and contrast condition. Inspection of the data showed only slight differences in the subjects' rank order acuity performance across the four conditions, indicating that certain subjects were consistently better in their acuity performance than others. This may have been due to differences between subjects in the criterion adopted when responding to the acuity charts. Subjects showing poorer acuity may have been more conservative in responding, causing them to come in closer to the acuity chart before making a decision; whereas, subjects with better acuity may have been less conservative in making their responses and stopped the cart at greater distances from the acuity chart. This subject variability also suggests that an individual's acuity through NVGs may not be correlated with acuity measured for unaided normal room light viewing. This could have implications for NVG selection and training criteria, where a reliable pre-flight method of determining expected acuity levels during NVG flight missions is necessary. Further research should be done to determine if a correlation exists between acuity measured for unaided viewing and NVG viewing.

Table 4.1: Prediction Matrix for SNR-Visual Acuity .01 Moon 20% Contrast

	PERCENT INCREASE IN ACUITY													
SNR	11	11.37	12	13	13.71	14	15	15.28	16	17	17.92	18	19	20
10	11	14	18	23	26	27	31	31	33	35	37	37	38	40
11	-	3	8	14	17	19	22	23	25	27	29	29	31	33
11.37	-	-	5	11	15	16	20	20	22	25	27	27	29	30
12	-	-	-	6	10	11	15	15	17	20	22	22	24	25
13	-	-	-	-	4	5	9	10	13	15	18	18	20	21
13.71	-	-	-	-	-	1	6	7	9	12	14	14	16	18
14	-	-	-	-	-	-	4	5	8	11	13	13	15	17
15	-	-	-	-	-	-	-	1	4	7	9	9	11	13
15.28	-	-	-	-	-	-	-	-	3	6	8	8	10	12
16	-	-	-	-	-	-	-	-	-	3	6	6	8	10
17	-	-	-	-	-	-	-	-	-	-	3	3	5	7
17.92	-	-	-	-	-	-	-	-	-	-	-	0	3	5
18	-	-	-	-	-	-	-	-	-	-	-	-	2	4
19	-	-	-	-	-	-	-	-	-	-	-	-	-	2

Table 4.2: Prediction Matrix for SNR-Visual Acuity .01 Moon 95% Contrast

	PERCENT INCREASE IN ACUITY													
SNR	11	11.37	12	13	13.71	14	15	15.28	16	17	17.92	18	19	20
10	5	6	8	11	12	13	15	15	17	18	19	19	20	21
11	-	1	4	7	8	9	11	11	13	14	15	15	16	17
11.37	-	-	2	5	7	8	10	10	11	13	14	14	15	16
12	-	-	-	3	5	5	7	8	9	11	12	12	13	14
13	-	-	-	-	2	3	5	5	6	8	9	9	10	11
13.71	-	-	-	-	-	1	3	3	5	6	7	7	9	10
14	-	-	-	-	-	-	2	3	4	5	7	7	8	9
15	-	-	-	-	-	-	-	1	2	3	5	5	6	7
15.28	-	-	-	-	-	-	-	-	1	3	4	4	5	6
16	-	-	-	-	-	-	-	-	-	2	3	3	4	5
17	-	-	-	-	-	-	-	-	-	-	1	1	3	4
17.92	-	-	-	-	-	-	-	-	-	-	-	0	1	2
18	-	-	-	-	-	-	-	-	-	-	-	-	1	2
19	-	-	-	-	-	-	-	-	-	-	-	-	-	1

Table 4.3: Prediction Matrix for SNR-Visual Acuity .25 Moon 20% Contrast

	PERCENT INCREASE IN ACUITY													
SNR	11	11.37	12	13	13.71	14	15	15.28	16	17	17.92	18	19	20
10	3	4	5	7	9	9	10	11	12	12	13	13	14	15
11	-	1	2	4	6	6	8	8	9	10	11	11	11	12
11.37	-	-	2	4	5	5	7	7	8	9	10	10	11	11
12	-	-	-	2	3	4	5	6	6	7	8	8	9	10
13	-	-	-	-	1	2	3	4	4	5	6	6	7	8
13.71	-	-	-	-	-	0	2	2	3	4	5	5	6	7
14	-	-	-	-	-	-	1	2	3	4	5	5	6	6
15	-	-	-	-	-	-	-	0	1	2	3	3	4	5
15.28	-	-	-	-	-	-	-	-	1	2	3	3	4	5
16	-	-	-	-	-	-	-	-	-	1	2	2	3	4
17	-	-	-	-	-	-	-	-	-	-	1	1	2	3
17.92	-	-	-	-	-	-	-	-	-	-	-	0	1	2
18	-	-	-	-	-	-	-	-	-	-	-	-	1	2
19	-	-	-	-	-	-	-	-	-	-	-	-	-	1

Table 4.4: Prediction Matrix for SNR-Visual Acuity .25 Moon 95% Contrast

	PERCENT INCREASE IN ACUITY													
SNR	11	11.37	12	13	13.71	14	15	15.28	16	17	17.92	18	19	20
10	3	4	6	8	9	9	11	11	12	13	14	14	14	15
11	-	1	3	5	6	6	8	8	9	10	11	11	12	12
11.37	-	-	2	4	5	5	7	7	8	9	10	10	11	11
12	-	-	-	2	3	4	5	6	7	8	8	9	9	10
13	-	-	-	-	1	2	3	4	5	6	6	7	7	8
13.71	-	-	-	-	-	0	2	2	3	4	5	5	6	7
14	-	-	-	-	-	-	2	2	3	4	5	5	6	6
15	-	-	-	-	-	-	-	0	1	2	3	3	4	5
15.28	-	-	-	-	-	-	-	-	1	2	3	3	4	5
16	-	-	-	-	-	-	-	-	-	1	2	2	3	4
17	-	-	-	-	-	-	-	-	-	-	1	1	2	3
17.92	-	-	-	-	-	-	-	-	-	-	-	0	1	2
18	-	-	-	-	-	-	-	-	-	-	-	-	1	2
19	-	-	-	-	-	-	-	-	-	-	-	-	-	1

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Appendix

The results of the ANOVA conducted on the visual acuity data are summarized in Table 5.1 below.

Table 5.1: Analysis of Variance (ANOVA) Summary Table

SOURCE	SUM OF SQ.	NUM DF	DEN DF	F	P	P (G.-G.)	EPSILON
SNR	0.06769	3	33	8.55	0.0002	0.0021	0.639
ILLUM	1.57146	1	11	295.03	0.0001	NA	NA
CON	1.05767	1	11	423.98	0.0001	NA	NA
SNR*ILL	0.01235	3	33	6.00	0.0022	0.0061	0.7431
SNR*CON	0.00116	3	33	0.90	0.4501	0.4287	0.7481
ILL*CON	0.00890	1	11	7.66	0.0183	NA	NA
SNR*ILL*CON	0.00468	3	33	1.67	0.1926	0.2117	0.6609

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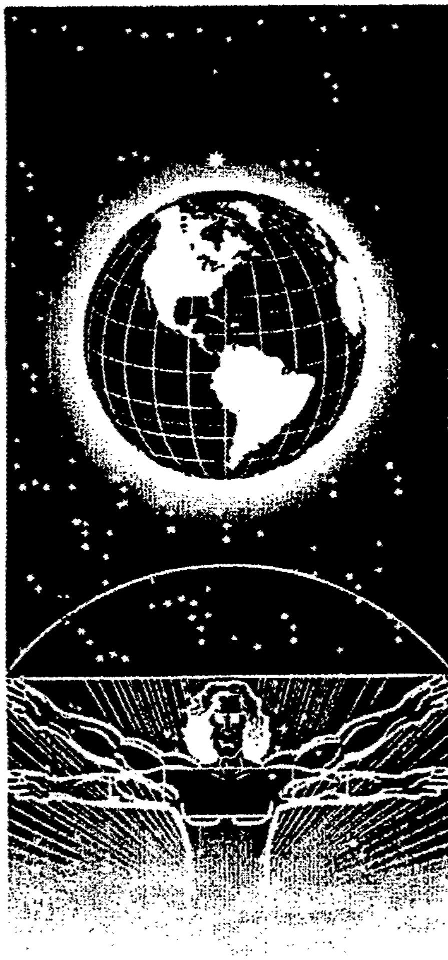

UNITED STATES AIR FORCE RESEARCH LABORATORY

THE EFFECT OF EYEPIECE FOCUS ON VISUAL ACUITY THROUGH ANVIS NIGHT VISION GOGGLES DURING SHORT- AND LONG-TERM WEAR

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January 2001

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Human Effectiveness Directorate
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2255 H Street
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13. ABSTRACT *(Maximum 200 words)*

The eyepiece lenses of ANVIS night vision goggle are ostensibly adjusted for optimum visual acuity (VA). Many users however do not adjust the eyepieces competently. This paper examines whether a single-focus eyepiece is capable of producing satisfactory VA while maintaining comfortable vision over extended periods. In a short-term ANVIS wear study, a range of eyepiece focus produced comparable VA independent of luminance and contrast. The single best-overall eyepiece focus produced vision equal to, or better than, that of subject-adjusted eyepieces, producing VA within 2% of optimal. However, zero diopter eyepieces reduced VA by 10%. In a long-term ANVIS wear study, -1.5 diopter eyepieces caused half of the subjects to complain of blurred or uncomfortable vision. These studies indicate -0.75 diopter eyepieces provide optically-corrected ANVIS users with near optimal binocular VA and satisfactory visual comfort during extended ANVIS use.

14. SUBJECT TERMS

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THE EFFECT OF EYEPIECE FOCUS ON VISUAL ACUITY THROUGH ANVIS NIGHT VISION GOGGLES DURING SHORT- AND LONG-TERM WEAR

INTRODUCTION

The AN/AVS-6 Aviator Night Vision Imaging System (ANVIS) is a helmet-mounted binocular night vision goggle used by military aviators. ANVIS is similar to unity magnification binoculars in that it has two parallel eye tubes to view through (Figure 1). Each eye tube has three rudimentary parts: objective lens, image intensifier tube, and eyepiece lens. The objective lens collects and focuses light on the image intensifier tube. The image intensifier tube amplifies and transduces near-infrared light into visible light. The eyepiece acts as a simple magnifier to view the image produced by the image intensifier tube.

The objective and eyepiece lenses are focused monocularly. These lenses are independent of each other in that one cannot compensate for blur caused by the other. The objective lens focuses ANVIS to different distances, changing image clarity without changing the stimulus to visual accommodation. The eyepiece lens determines the optical distance of the image seen by the eye, and thereby regulates the accommodative stimulus. During eyepiece focusing, the eyepiece is moved closer to, or further from, the image intensifier tube, thereby, changing the optical distance of the eyepiece image. Eyepiece focus (EF) is equal to the reciprocal of the image distance and is expressed in terms of diopters (or reciprocal meters). Negative EFs produce optical images that are closer than optical infinity. For example, an eyepiece with a –2 diopter EF (i.e., -2 diopter eyepiece) produces an optical image that is (2^{-1} =) 0.5 meters away. A zero diopter eyepiece produces an image at optical infinity. Inceptive night vision goggles required adjustable eyepieces to compensate for refractive error because their short eye relief precluded concurrent spectacle wear. Modern night vision goggles have adequate eye relief; yet, adjustable eyepieces remain in the designs of future night vision goggles.

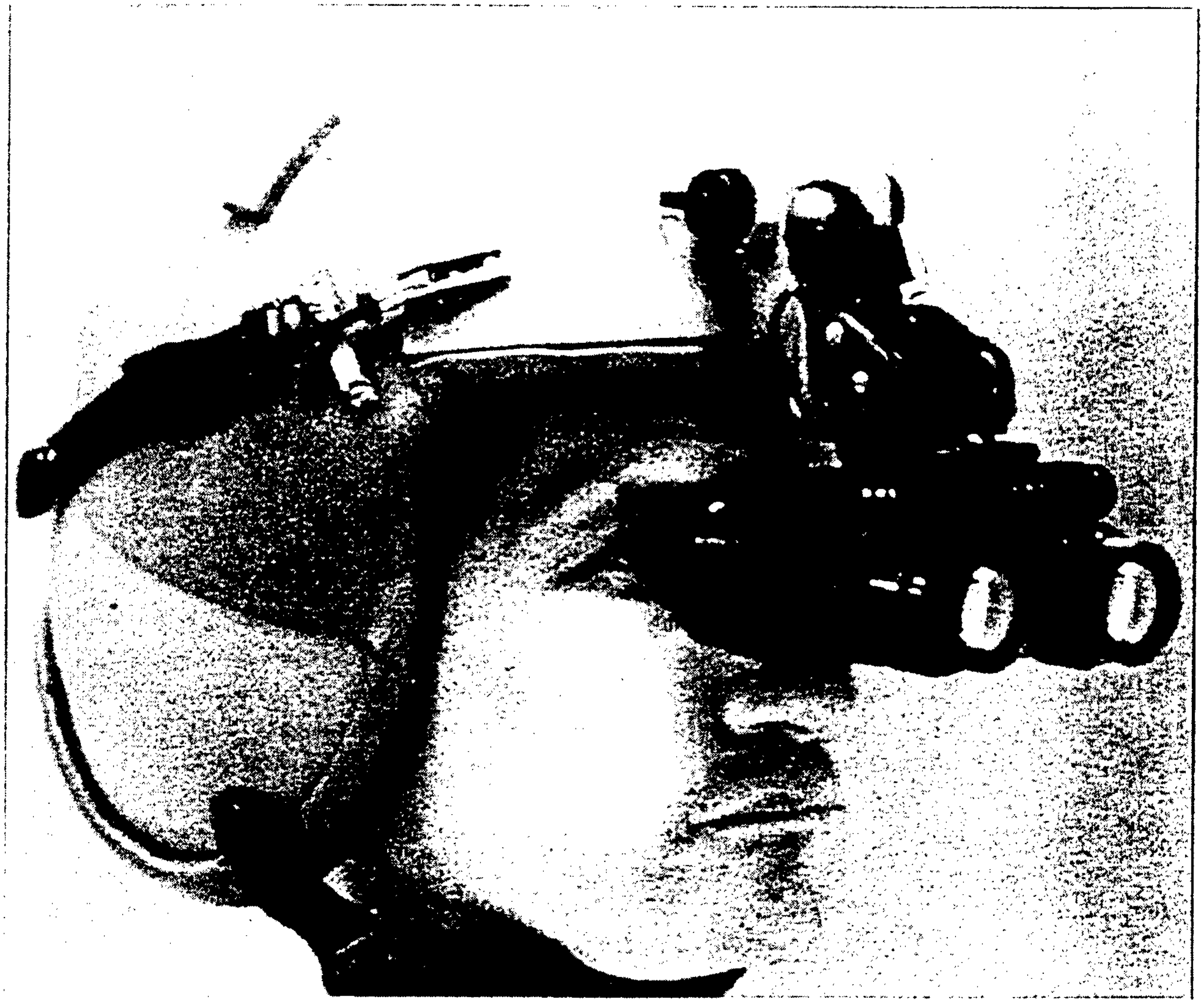


Figure 1. The Aviator's Night Vision Imaging System.

Adjustable eyepieces seem necessary for ANVIS users to "optimize" vision, and to re-focus for changing visual requirements. There is much scientific evidence (Leibowitz and Owens, 1975a,b, 1978; Hennessy, 1975; Johnson, 1976; Smith, 1983; Owens 1984) suggesting that visual accommodation is biased towards intermediate distances (0.5 to 2 meters), blurring distant objects particularly under a variety of conditions relevant to ANVIS. These conditions include instrument-viewing, low luminance, and featureless environments (Smith, 1983; Owens, 1984); the respective resulting over-accommodations are called instrument myopia, night myopia, and empty-field myopia. This accommodative bias is thought to fully manifest in the dark and is therefore often called (the eye's) "dark focus." Johnson (1976) reported that monocular vision is best for objects located near dark focus. Since dark focus is idiosyncratic (Leibowitz and Owens, 1975a, 1978), adjustable eyepieces seem necessary to satisfy all ANVIS users. Indeed, Kotulak and Morse (1994a, c) reported visual acuity (VA) through ANVIS improved 23% when the eyepieces were subject-adjusted than when set to zero diopters.

Kotulak and Morse (1994a,b) also measured eye focus while subjects viewed a distant chart unaided, and then through ANVIS with zero diopter eyepieces. Eye focus averaged 0.35 diopters for both conditions, indicating no instrument myopia occurred. However, their subjects over-focused the eyepieces (-1.13 diopters) despite the absence of instrument myopia. And, the eyepieces were not adjusted for dark focus (+0.45 diopters) either. (Note, negative EF corresponds with positive eye focus similar to how negative spectacle lenses compensate for myopic eye focus, or nearsightedness.) So, eyepiece adjustment did not depend on dark focus nor instrument myopia. This raises the possibilities that the eyepieces were not adjusted for optimum VA and consequently that single-focus eyepieces may perform as well.

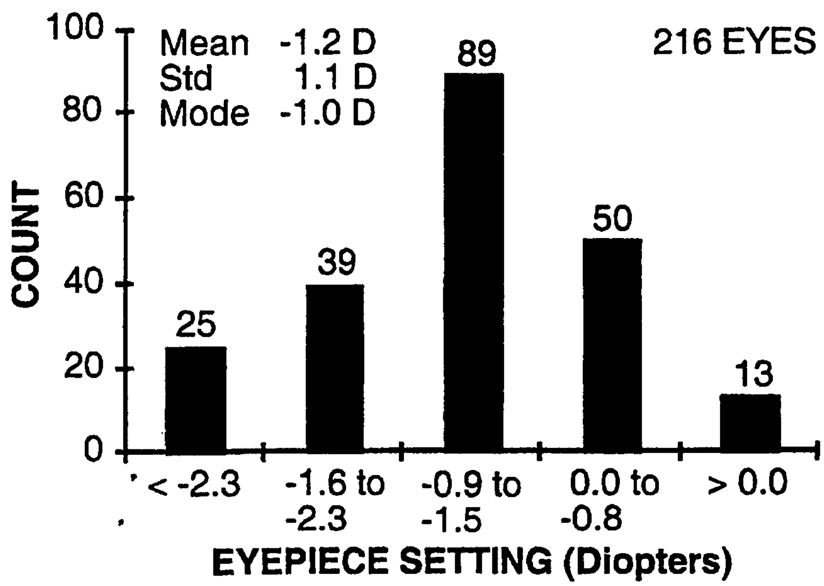
Single-focus eyepieces have distinct advantages over adjustable eyepieces. Single-focus eyepieces are simpler, lighter, and cheaper because focus mechanisms are not needed. Shorter single-focus eyepieces would reduce ANVIS's overall length, bringing the center-of-gravity closer to the head while maintaining eye relief. Adjustable eyepieces require a telecentric optical design to minimize changes in image size and brightness as the eyepiece is adjusted (Keating, 1988). Single-focus eyepieces lack this requirement and therefore can be better optimized for optical aberrations such as curvature-of-field and astigmatism. Finally, single-focus eyepieces would eliminate a precarious adjustment along with its requisite training.

An unpublished 1993 in-house survey reported that most Air Force users considered focusing to be the most frequent and difficult of all ANVIS adjustments. This result is not surprising for at least two reasons. First, ANVIS's compact fast optics makes focusing a sensitive task. The objective and eyepiece lenses (focal length = 27 mm) produce a 1.4 diopter change in EF for each millimeter of lens translation, making smooth precise changes in optical power difficult to accomplish. Also, the objective lenses (f-number = 1.2) produce tiny depths-of-field. Assuming ANVIS's resolution is limited by the image intensifier tube (i.e., 17.5 cycles per degree, or about 20/35 Snellen), ANVIS's depth-of-field is calculated to be ±0.022 diopters. So, a 35 micron translation of the objective lens can traverse ANVIS's entire depth-of-field. Such a small tolerance makes it unlikely that the objective lenses are precisely focused, making the best image seen during eyepiece adjustment less than optimum. How eyepiece adjustment interacts with objective lens-induced blur is unknown. Second, there is no anchor for accommodation during eyepiece adjustment. Eyepiece adjustment manipulates the accommodative stimulus; however, accommodation is free to respond to the changing stimulus. Covariance of the accommodative stimulus and response during eyepiece adjustment, and its impact on the final eyepiece setting, has not been studied. But, it likely results in a wide range of eyepiece settings yielding "best VA", leading to an uncertain endpoint. The focus endpoint is influenced by the starting EF and the focusing strategy employed (Schober, 1970; Wesner and Miller, 1986); this variability in endpoint suggests accommodation is active during eyepiece adjustment.

Normally, accommodative and vergence stimuli are synchronous. (Vergence eye movements shift binocular fixation to different distances by moving the eyes horizontally in opposite directions.) Our eyes must increase accommodation and converge binocular fixation for near targets, and lessen accommodation and diverge binocular fixation for distant targets. Accommodation and vergence eye movements are neurologically linked (Fincham and Walton, 1957; Hung and Semmlow, 1980; Schor and Kotulak, 1986); stimulating one stimulates the other. This synkinetic relationship increases the responsiveness of both ocular motor systems (Schor and Kotulak, 1986; Leibowitz et al., 1988; Jiang et al, 1991).

With ANVIS, accommodative and vergence stimuli are dissociated. Eyepiece adjustment changes the accommodative stimulus without changing the vergence stimulus. ANVIS eyepieces are typically adjusted when viewing monocularly; so, vergence is not stimulated. Monocular eyepiece adjustment results in a more minus endpoint than binocular adjustment (Schober, 1970; Wesner and Miller; 1986), presumably, because vergence helps control accommodation during binocular viewing. Therefore, EFs resulting from monocular eyepiece adjustment may not be appropriate for extended binocular viewing because accommodation and vergence eye movements have limited ability to respond differentially (Borish, 1975a). During the aforementioned Air Force survey, 133 users focused an ANVIS (with a laboratory-calibrated eyepiece scale) in their usual way while wearing habitual optical corrections. Twenty-four users merely set the eyepieces to zero diopters by using the eyepiece scale; this was an occasionally taught strategy at the time of the survey. Of the remaining 108 subjects, 30% adjusted the eyepieces to exceed -1.5 diopters (Figure 2a). These high minus eyepieces are likely to cause blur and/or discomfort because it creates a significant mismatch between accommodative and vergence stimuli. To see distant objects, these users must accommodate to an image located closer than 59 cm to see clearly, yet must maintain parallel visual axes to see singly.

The two eyepieces may also be adjusted unequally since they are adjusted at different times. Half of the surveyed adjusted the two eyepieces unequally by more than 0.9 diopters (Figure 2b). Accommodation does not respond adequately to differential stimuli greater than 0.5 diopters (Stoddard and Morgan, 1942; Ball, 1950; Spencer and Wilson, 1954; Campbell, 1960). And, since the eye's depth of field is about ±0.43 diopters (Campbell, 1957), only one eye sees clearly at a time.



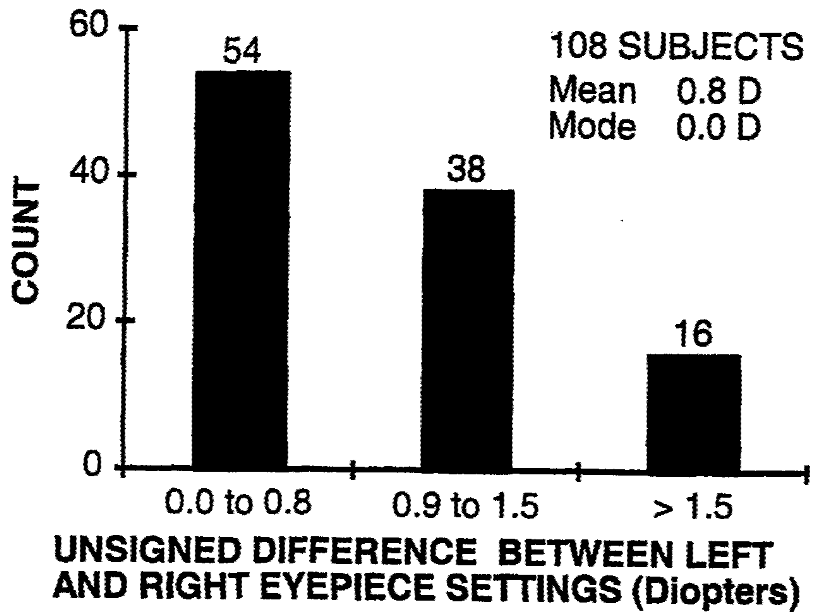


Figure 2b.

Figure 2. Frequency count of eyepiece settings by 108 Air Force ANVIS users as a function of **a)** eyepiece setting and **b)** unsigned difference between left and right eyepiece settings.

To be a viable solution to the problems of adjustable eyepieces, single-focus eyepieces must provide satisfactory vision and visual comfort over a range of appropriate luminances and contrasts for extended periods of time. To this end, this two-part study measures binocular VA through ANVIS 1) as a function of EF, luminance, and contrast in a short-term ANVIS wear study, and 2) as a function of the EF used during a four-hour ANVIS wear period.

Note, the accommodative stimulus depends not only on object distance (which is determined by the ANVIS eyepiece), but also uncorrected refractive error (Miller, 1990). Individuals with unaided 20/20 vision may vary in refractive error from slightly myopic (near-sighted) to greater than two diopters hyperopic (far-sighted) (Borish, 1975b). Hyperopes must accommodate to see distant objects clearly, and even more so to see close objects. Myopes cannot focus on far objects, and accommodate less than normal to see close objects. For example, a young 1.5 diopter hyperope and a 0.5 diopter myope are both capable of 20/20 unaided distant vision, but when looking into a -0.5 diopter eyepiece, the respective accommodative stimuli are two and zero diopters. So, each must accommodate a different amount to see clearly. In our studies, all subjects were optically-corrected to equate the accommodative stimulus across subjects.

SHORT-TERM WEAR STUDY

Method

Subjects

Twelve subjects (24 years ± 6) participated; each demonstrated 20/20 VA in each eye and 40 arc-seconds of stereopsis. Only one subject wore habitual optical correction (-2 diopters); however, with that correction in place, this subject was considered the same as the others. Subjects were optically refracted to a "most plus lens power for best binocular VA" endpoint using standard clinical techniques (Borish, 1975c; Michaels, 1975). Due to the eye's depth-of-field and accommodation, there is a range of lens powers producing best VA during clinical refraction. The clinical endpoint is the most plus (or least minus) lens power producing best VA. In this way, at least conceptually, the visual near point is maximized while maintaining best distant VA. All subjects had less than 0.5 diopters of anisometropia and astigmatism; any astigmatic correction was subsequently ignored.

Visual Acuity Task

The visual stimulus was a square "E" randomly presented in one of four orientations (Figure 3) for one-second exposures on a super VGA monitor located twenty feet away. The version of ANVIS used by the Air Force is not sensitive to visible light because visible light is filtered out by the objective lens to make ANVIS more compatible with aircraft cockpit lighting. Only the monitor's blue phosphor was used so that the monitor would not be too bright for ANVIS. The subject's task was to push a four-way thumb switch in the direction that the presented "E" pointed. Eight presentations were made at each "E" size level. A one-second delay separated responses from ensuing presentations. If six responses were correct then the "E" would shrink by 0.1 log units and another series of eight presentations was made. When the "E" was sufficiently small that less than six responses were correct, then the "E" would grow by 0.05 log units and a final series of eight presentations was made. VA was interpolated from the last three levels of tested "E" sizes by the following method. The base VA was defined as 0.05 log units greater than the largest of the three final levels. For each level, the number of correct responses was tallied. Then, three was subtracted from each tally to compensate for random guesses; the result was truncated to zero if it was less zero. Next, the three results were summed and multiplied by 0.01. VA was calculated by subtracting this number from the base value and expressed as the log of the minimum angle of resolution (log MAR) in arc-minutes. MAR pertains to the angular size of the "E" stroke width.

Figure 3. The target was a square E in one of four orientations.

Design

The statistical design was a four-way total within ANOVA with Greenhouse-Geisser (1959) correction. VA was the dependent variable. Data met the statistical assumption of equal variance. EF, luminance, contrast, and repetition were the independent variables. Five EF (0.0, -0.5, -1.0, -1.5 diopters, and subject-adjusted), three luminance (0.045, 0.319, and 2.24 fL), and three contrast (30%, 47%, and 64%) levels were used. Luminance and contrast were measured from the left ANVIS eyepiece. Each experimental condition was tested three times.

Procedures

On a training day, subjects were familiarized with experimental methods, and carefully trained to focus ANVIS eyepieces to a "most plus lens power for best VA" endpoint. During the focusing procedure, subjects viewed a high contrast square-wave chart located 20 feet away. The chart, known as the 3x3 NVG Resolution Chart , has nine four-inch-square grating patches varying in bar width from 1.75 to 5.0 arc-minutes. The chart's background luminance was approximately 2.2 fL as measured through the left ANVIS eyepiece. Left and right eyepieces were focused independently as subjects monocularly viewed the chart.

On the first of three experimental days, each subject adjusted the ANVIS eyepieces. Resultant EFs were measured with a dioptometer (Coleman, Coleman, and Fridge, 1951), and became the "subject-adjusted" EFs for the entire experiment. A set of ANVIS goggles was rigidly mounted to a heavy table. A 20° uniformly illuminated screen was placed behind the monitor; the background screen's brightness was matched to the monitor's brightness as seen through the left ANVIS eyepiece.

Before each experimental session, the experimenter focused the objective and eyepiece lenses while looking through ANVIS with an afocal 8x telescope at the "3 by 3" chart. Each experimental session featured a single luminance level. EF was varied by placing thin lenses immediately behind the ANVIS eyepieces. Luminance was controlled with neutral density filters placed in front of the ANVIS objective lenses. Contrast ($\Delta L/L$) was controlled through software. Subjects began each session with 15 minutes of dark adaptation. Subjects adapted to the display luminance for one minute before each trial. Luminance was counterbalanced across subjects. Contrast and EF were randomized over each set of fifteen trials. Three sets of fifteen trials were performed each day. After each session, the experimenter again looked through ANVIS with the afocal 8x telescope to ensure that neither the objective nor the eyepiece lenses had changed focus. Head movements were minimized with a chin cup and headrest. Experimental sessions were typically eighty minutes long.

Results

Table 1 summarizes refractive error and eyepiece adjustment measurements. Although the average refractive error (n = 24 eyes) was slightly hyperopic (+0.23 diopters ± 0.38), the eyepieces were adjusted myopically (-1.05 diopters ± 0.34), resulting in an average accommodative stimulus of 1.28 diopters (± 0.55) with a range of +0.5 to +2.5 diopters. The average unsigned EF difference between the two eyes was +0.40 diopters (±0.29) with a maximum difference of +0.75 diopters. Table 2 lists the average subject-adjusted EF and unsigned interocular difference in subject-adjusted EF for the aforementioned Air Force Survey, Kotulak and Morse study (1994a), and this study. Values from the two laboratory studies agree well. The most striking difference is that the survey reported twice the inter-subject variability as the two laboratory studies. The survey also reported a greater disparity between right and left eyepiece settings. Differences from the survey likely reflect the recent detailed training of subjects in the two laboratory studies.

	Average	Std Dev	Range
Refractive Error	+0.23	0.38	-0.25, +1.00
Eyepiece Focus	-1.05	0.34	-1.75, -0.25
Accommodative Stimulus	+1.28	0.55	+0.50, +2.50
|Δ| Refractive Error	0.08	0.12	0.00, +0.25
|Δ| Eyepiece Focus	0.40	0.29	0.00, +0.75
|Δ| Accommodative Stimulus	0.48	0.25	0.00, +0.75

Table 1. Summary of subject refractive error, user-adjusted ANVIS eyepiece focus, and resulting accommodative stimulus. |Δ| represents unsigned differences between right and left eyes (or eyepieces). Units are diopters

	Average EF (Std Dev)	|Δ| EF (Std Dev)
Air Force Survey	-1.17 (1.13)	0.83 (0.99)
Kotulak and Morse	-1.13 (0.63)	0.57 (0.47)
Current Study	-1.05 (0.34)	0.40 (0.29)

Table 2. Average user-adjusted ANVIS eyepiece focuses are listed with standard deviations for an unpublished Air Force survey, Kotulak and Morse (1994a), and the current study. |Δ| represents unsigned differences between right and left eyepieces. Units are diopters.

Figure 4 plots VA as a function of luminance, contrast and EF. The effects of luminance and contrast on VA are well known (van Meeteren and Vos, 1972; Richards, 1977). VA improves with increasing luminance ($F_{2,22} = 326$, $p < 0.0001$) and contrast ($F_{2,22} = 913$, $p < 0.0001$). Contrast influences VA more when luminance is low ($F_{4,44} = 25$, $p < 0.0001$). More interestingly, EF ($F_{4,44} = 8.4$, $p < 0.01$) affects VA without interacting with luminance or contrast. Specific comparisons between EFs (Table 3) were made using a pooled two-tailed t-test where the error term was calculated by pooling the variance of the three repetitions across luminance, contrast, and EF. Zero diopter eyepieces reduced VA by nearly 10%; other specific comparisons were not significant. Other main effects and interactions were not significant.

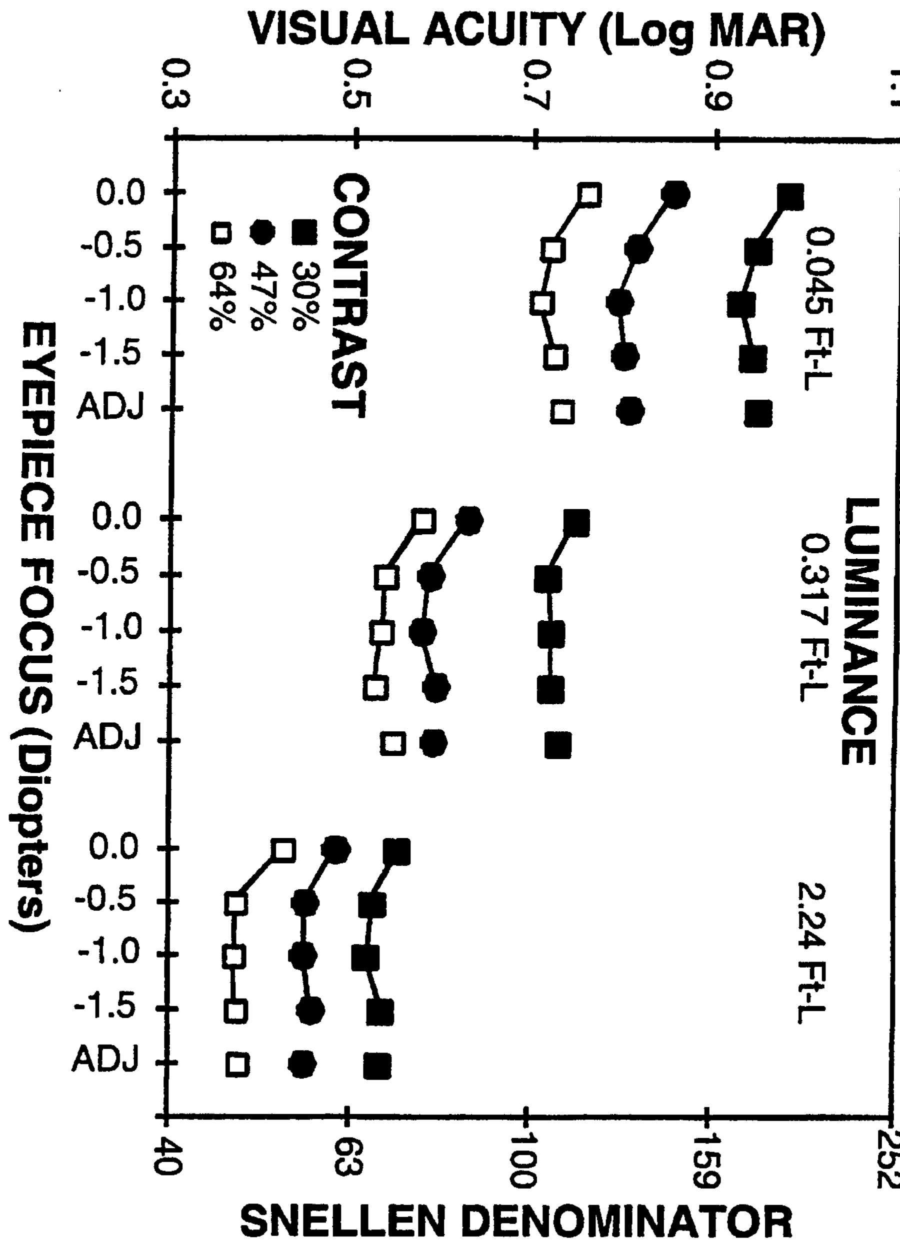


Figure 4. Group-averaged visual acuity through ANVIS is plotted as a function of luminance, contrast (ΔL/L) and eyepiece focus. Note, since subjects were optically corrected, the accommodative stimulus equals eyepiece focus.

Specific Comparisons	Change in Log MAR	Visual Acuity Improvement	Pooled t-Test df = 44
0.0D to -0.5D	-0.038	9.1%	p < 0.0001 *
0.0D to -1.0D	-0.045	10.9%	p < 0.0001 *
0.0D to -1.5D	-0.038	9.1%	p < 0.0001 *
0.0D to Adjusted	-0.033	7.9%	p < 0.0005 *
-0.5D to -1.0D	-0.007	1.6%	p > 0.4
-0.5D to -1.5D	0.001	-0.2%	p > 0.9
-0.5D to Adjusted	0.005	-1.2%	p > 0.5
-1.0D to -1.5D	0.007	-1.6%	p > 0.4
-1.0D to Adjusted	0.012	-2.8%	p > 0.2
-1.5D to Adjusted	0.005	-1.2%	p > 0.6

Table 3. Specific comparisons of eyepiece focus in short-term ANVIS wear study. Asterisks indicate statistical significance (p = 0.05).

Subsequent analyses were conducted separately for each subject to determine whether EF requirements for best VA were idiosyncratic. For each subject, specific comparisons were made between the subject-adjusted, best-overall, and optimum EFs using two-tailed t-tests where the error terms were calculated by pooling the variance of the three repetitions across luminance, contrast, and EF. The best-overall EF was -1.0 diopters, producing the best average VA across all conditions and subjects. Each subject's optimum EF produced the best average VA across all conditions. EFs of -0.5 and -1.0 diopters were each optimum for five subjects. Zero diopter eyepieces were not optimum for any subjects. Table 4 lists each subject's optimum EF, and VA for subject-adjusted, best-overall, and optimum EFs.

		Eyepiece Focus		
Subject	Optimum EF	Optimum	Best-Overall	Subject-Adjusted
1	0.5	0.560	0.561	0.558
2	0.5	0.629	0.643	0.633
3	0.5	0.602	0.614	0.607
4	0.5	0.587	0.601 *	0.610 *
5	0.5	0.654	0.670 *	0.706 *†
6	1.0	0.602	0.602	0.621
7	1.0	0.654	0.654	0.678
8	1.0	0.616	0.616	0.640 *†
9	1.0	0.622	0.622	0.647 *†
10	1.0	0.620	0.620	0.645 *†
11	1.5	0.597	0.604	0.608
12	1.5	0.616	0.655 *	0.654 *
AVERAGES				
Log MAR		0.613	0.622	0.634
Snellen Acuity (20/)		82.1	83.7	86.1
Visual Acuity Loss			2.0%	4.9%

Table 4. Average visual acuities (VA) through optimum, best-overall, and subject-adjusted ANVIS eyepiece focus (EF) are listed by subject. Asterisks and obelisks indicate a statistical difference (df = 36, p = 0.05) from optimum and best-overall EFs, respectively. Group-averaged VA are listed below as log MAR and Snellen equivalent along with per cent VA loss from optimum.

Subject-adjusted and optimum EFs were compared to determine whether subjects indeed optimized VA through eyepiece adjustment. At a 0.05 per-comparison probability level, subject-adjusted eyepieces produced optimal VA for half of the subjects. VA was reduced by 7.5% for the remaining subjects. Overall, subject-adjusted eyepieces reduced VA by 5%. Only one comparison was significant at a 0.05 procedure-wise error level.

Similarly, best-overall and optimum EFs were compared except that a statistically more powerful 1-tailed t-test was used because, by definition, the best-overall EF could not surpass the optimum EF. At a 0.05 per-comparison probability level, the best-overall EF produced optimal VA for 75% of the subjects. VA was reduced by 5.5% for the remaining subjects. Overall, the best-overall EF reduced VA by 2%. No comparisons were significant at a 0.05 procedure-wise error level.

Subject-adjusted and best-overall EFs were compared to determine whether single-focus eyepieces could produce VA comparable to subject-adjusted eyepieces. At a 0.05 per-comparison probability level, the best-overall EF produced (up to 5%) better vision for 25% of the subjects. Only one comparison was significant at a 0.05 procedure-wise error level. No subject saw better with subject-adjusted eyepieces.

LONG-TERM WEAR STUDY

Method

Subjects

Twelve subjects (23 years ± 4) participated; each demonstrated 20/20 VA in each eye and 40 arc-seconds of stereopsis; six participated in the above short-term wear study. None wore habitual optical correction. Subjects were optically refracted to a "most plus lens power for best binocular VA" endpoint. All subjects had less than 0.5 diopters of anisometropia and astigmatism; any astigmatic correction was subsequently ignored. Refractive errors ranged from -0.25 to +1.00 diopters with an average of +0.33 diopters (±0.4).

Design

The statistical design was a four-way total within ANOVA with Greenhouse-Geisser (1959) correction. VA was the dependent variable, and was measured as log MAR. The method for measuring VA is described above. The independent variables were EF (0.0, -0.75, -1.5 diopters), luminance (0.32 and 0.05 fL), time (pre- and post-extended wear), and EF worn during the extended-wear period (0.0, -0.75, -1.5 diopters). Each experimental condition was tested twice, and these results were averaged.

Procedures

On a training day, subjects were familiarized with experimental procedures. Equipment and general methods are described above. Three experimental sessions were performed on separate days; each featuring a single EF level worn during a four-hour ANVIS wear period. VA was measured through a table-mounted ANVIS as a function of EF and luminance. Target contrast ($\Delta L/L$) was 46%. The order of luminance and EF was randomized within each of two sets of six trials.

After initial VA measurements, the subject wore a second head-mounted ANVIS for four hours with the EFs set to one of three levels. The order of EFs worn during the extended-wear period was counterbalanced across subjects. ANVIS was held to the subject's head with a Litton hair net harness. Peripheral vision was blocked to restrict vision to ANVIS's 40° field-of-view. Small apertures and neutral density filters were placed before ANVIS's objective lenses to increase the depth-of-field and to make the ANVIS display luminance approximately two foot-lamberts. Subjects were free to wander around the room, but they mostly played video games or watched video-taped movies on a large projection screen. An experimenter stayed with the subject to ensure the subject's safety, and that the subject remained alert and attentive to the video game or movie.

After the extended wear period, VA was re-measured with the table-mounted ANVIS. Subjects were not allowed to look away from the table-mounted ANVIS during VA tasks. Care was taken to prevent subjects from looking around the room when switching from the head-mounted ANVIS to the table-mounted ANVIS. Pre- and post-extended wear VA measurements required twenty minutes each. Experimental sessions were five hours long.

In addition to measuring ANVIS VA, each experimental session began and ended with two sets of unaided VA measurements. Unaided VA was measured using the monitor's green phosphor. Each experimental condition was tested twice, and the results were averaged. Target luminance was 2.7 fL and contrast was 46%. A separate two-way total within ANOVA was performed. Independent variables were time (pre- and post-extended wear) and extended-wear EF (0.0, -0.75, -1.5 diopters).

Results

Unaided VA was not affected by time ($F_{1,11} = 0.42$, $p > 0.6$) or by EF used during the extended wear period ($F_{2,22} = 0.22$, $p > 0.6$). There were no significant interactions.

Figure 5 depicts all main effects for ANVIS VA. As in the short-term study, VA was significantly affected by luminance ($F_{1,11} = 4602$, $p < 0.0001$) and EF ($F_{2,22} = 18.3$, $p < 0.001$). Specific comparisons (Table 5) were made for EF using a two-tailed t-test where the error term was calculated by pooling the variance of the two trials across extended-wear EF, time, and luminance. Subjects saw 13% better with -0.75 diopter eyepieces than with zero diopter eyepieces. VA was not affected by extended-wear EF ($F_{2,22} = 0.13$, $p > 0.8$) or time ($F_{1,11} = 2.97$, $p > 0.1$). There were no significant interactions. Notably, the best EF for VA before the extended ANVIS wear remained the best afterwards, regardless of the EF used during the extended-wear period. So, eyepiece adjustment seems unnecessary for retaining good VA during extended ANVIS use.

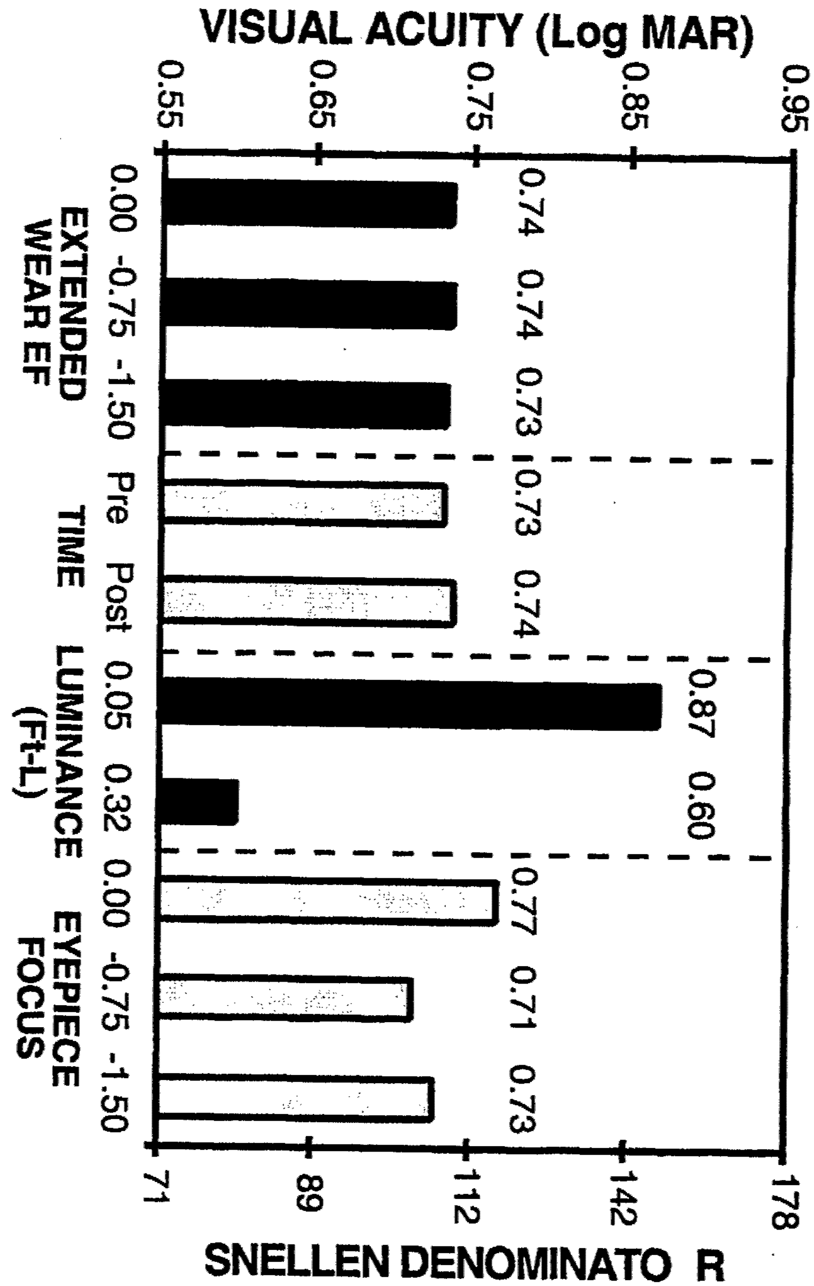


Figure 5. Group-averaged visual acuity through ANVIS is plotted for eyepiece focus (EF) used during the extended-wear period, time (pre- and post-extended wear), ANVIS display luminance, and EF. Note, since subjects were optically corrected, the accommodative stimulus equals EF.

Specific Comparisons	Change in Log MAR	Visual Acuity Improvement	Pooled t-Test df = 22
0.00D to -0.75D	-0.054	13.2%	p < 0.001 *
0.00D to -1.50D	-0.041	9.9%	p < 0.005 *
-0.75D to -1.50D	0.013	-3.0%	p > 0.1

Table 5. Specific Comparisons between eyepiece focus in long-term ANVIS wear study. Asterisks indicate statistical significance ($p = 0.05$).

Without solicitation, six subjects complained of uncomfortable and less than clear vision during the extended-wear period with -1.5 diopter eyepieces. Four of these subjects thought they saw poorly during post-extended wear VA tests; however, no change in VA was measured. Another subject, an ambitious ROTC cadet aspiring to be a fighter pilot, insisted on discontinuing after two hours of extended-wear due to very uncomfortable vision. Fortunately, this subject completed the entire -1.5 diopter EF extended-wear condition on another day. Diplopia was not reported by any subject. No complaints were reported for the extended-wear periods featuring zero and -0.75 diopter eyepieces.

Discussion

We confirm Kotulak and Morse (1994a) in that vision through ANVIS night vision goggles is better when the eyepieces are adjusted by the user than when set to zero diopters. But, we found less improvement with subject-adjusted eyepieces (8% versus 23%). This difference may be explained by uncorrected refractive error. Subjects were optically-corrected in this study. Subjects were uncorrected and slightly myopic (-0.1 diopters ± 0.4) in Kotulak and Morse's study. Images at optical infinity are beyond the accommodative range of myopes, and therefore cannot be seen clearly. Nonetheless, merely setting the ANVIS eyepieces to zero diopters is not an auspicious strategy.

Binocular VA improved with -0.5 diopter eyepieces, and then was insensitive to EF over a range of -0.5 to -1.5 diopters even as VA varied greatly with luminance and contrast. This suggests that accommodation was as accurate as it needed to be to achieve near optimum VA. Only half of the subjects adjusted the eyepieces for optimum VA. Therefore, the superiority of subject-adjusted over zero diopter eyepieces is likely due to the mere addition of minus EF rather than actual optimization of VA by the user. A -1.5 diopter eyepiece caused half of the subjects to complain of blur and discomfort during extended use. Presumably, these symptoms were caused by ocular motor responses to dissonant accommodative and vergence stimuli. The average accommodative stimulus after eyepiece adjustment was only slightly less (1.3 diopters); therefore, some subjects may have become symptomatic with their subject-adjusted EFs during extended use. On the other hand, -0.75 diopter eyepieces caused no symptoms. Varying luminance and contrast does not necessitate a change in EF, nor does extended ANVIS use.

Our principal finding is that, for users who are optically corrected to a "most plus lens power for best binocular VA" endpoint, -0.75 diopter eyepieces provide satisfactory comfort and near optimal binocular VA for extended ANVIS viewing. However, the accommodative stimulus is the relevant factor, and it is determined by EF and uncorrected refractive error. So, more broadly, the accommodative stimulus should be approximately 0.75 diopters for extended ANVIS use. This result may extend to other binocular visual displays.

The major impediment to implementing this knowledge is that ANVIS users without habitual optical corrections may range from slightly myopic to moderately hyperopic. This dictates a range of EFs to achieve the desired 0.75 diopter accommodative stimulus. We suggest three possible eyepiece designs for future generations of ANVIS:

1. Single-focus -0.75 diopter eyepieces. This is the simplest design. However, it will make uncorrected hyperopes effectively more hyperopic, increasing the chance of uncomfortable and less clear vision. Single-focus -0.5 diopter eyepieces may be an appropriate compromise since it provided the largest incremental improvement in VA from zero diopter eyepieces.

2. Single-focus zero diopter eyepieces with modified spectacle correction. Emmetropes, myopes, and the optically-corrected would wear spectacles (or contact lenses) with a -0.75 diopter over-correction. Uncorrected hyperopes do not need this over-correction since it is built in to themselves.

3. Single-focus zero diopter eyepieces with thin lens inserts. ANVIS would contain a holder for a thin -0.75 diopter lens to be placed immediately behind the eyepiece. Emmetropes, myopes, and the optically-corrected would use the lens; uncorrected hyperopes would not.

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ARMSTRONG LABORATORY

VISUAL ACUITY VS. FIELD-OF-VIEW AND LIGHT LEVEL FOR NIGHT VISION GOGGLES (NVG)(U)

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13. ABSTRACT *(Maximum 200 words)*

Parameters typically used to characterize night vision goggles (NVG) are visual acuity (resolution) and field-of-view (FOV). An increase in FOV is accomplished by providing higher magnification of the image intensifier tube. However, increased magnification means that the pixels will subtend a larger angle, thus leading to lower NVG visual acuity. An inverse relationship between visual acuity and field-of-view is expected based upon this optical/geometrical relationship. This relationship should be examined as production of NVG resolution quality increases. A trade-off study examining FOV and resolution was conducted with three observers having 20/20 corrected Snellen acuity. The NVGs had fields-of-view of 40, 47, and 52 degrees, respectively. Five levels of ambient scene illumination (corresponding to output luminance levels of 0.01, 0.03, 0.08, 0.26, and 1.4 ft-L) were provided by a 2856K light source. The targets used in the study were 95+% contrast square wave targets ranging in size from 45 cycles/degree to 5 cycles per degree. A walk-back method of adjustment was employed. The results indicate that the geometric relationship between field-of-view and visual acuity is valid.

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PREFACE

The work described in this technical report was funded under Program Element 62202F Project 7184-18-07 entitled "Night Vision Devices" and Program Element 63231F Project 3257 entitled "Helmet-Mounted Systems Technology" (HMST). This report documents an initial effort by this laboratory to conduct a series of night vision goggle parameter trade-off studies which will impact future design of night vision devices by the 6.3 and 6.4 program offices. The authors wish to thank our volunteer subjects, Ms. Maryann Howes-Barbato, Mrs. Martha Hausmann, and Mr. David Sivert who graciously donated their time to participate in the study. We would also like to thank ITT Corporation of Roanoke, Virginia for their generous loan of the NVGs used in this study.

INTRODUCTION AND BACKGROUND

Two key parameters used to characterize night vision goggles (NVGs) are visual acuity (resolution) and field-of-view. An increase in field-of-view is accomplished by providing higher magnification of the image intensifier tube. However, since the image intensifier tube has a fixed linear resolution at its output screen, increased magnification means that the "picture elements" (pixels) will subtend a larger angle with respect to the eye, thus leading to lower visual acuity when viewing through the NVGs. An inverse relationship between visual acuity and field of view of NVGs is expected based solely upon this optical/geometrical relationship (see equation 1 and Figure 1).

$$\mathbf{R} = \frac{\mathbf{N}}{2\phi} \qquad (1)$$

where: **N** = number of pixels across the display (no units)
R = acuity (resolution) in cycles per degree
ϕ = field of view in degrees

An underlying assumption of this relationship is that the observer's visual system is much better than the resolution seen through the NVGs. As NVGs are produced with increased resolution, this simple geometric relationship between field of view and visual acuity may no longer be valid; especially for lower light levels where the human observer baseline visual acuity is considerably poorer.

Many different methods have been used to determine visual acuity through NVGs for different contrast and light levels. These have included the use of Landolt "Cs," tumbling "Es," square-wave and sine-wave gratings, and lettered charts [1-4]. For purposes of this study we have selected the square-wave grating approach as the one that most closely parallels the theoretical basis for this study. Using this target pattern, the limiting resolution (acuity) for the NVGs corresponds to the highest spatial frequency square-wave grating (with 100% contrast) that can just barely be resolved when viewing through the NVGs. This limiting resolution can theoretically be thought of as the spatial frequency at which the modulation threshold function (MTF) of the NVG intersects the contrast threshold function (CTF) of the human observer as depicted in Figure 2. Therefore, the limiting resolution is due to both display limitations (MTF) and visual limitations (CTF). Since the visual contrast threshold function is a monotonically increasing function (for spatial frequencies higher than about 5 cycles per degree), this means the cross-over between the MTF and the CTF will take place at higher contrast levels for NVG MTFs that are higher. In the hypothetical case of Figure 2, the two MTFs shown are produced by using two different optical systems in conjunction with the same image intensifier tube. The wide field of view (FOV) MTF is exactly half of the narrow FOV MTF since the wide FOV is exactly twice as large as the narrow FOV. The implicit assumption in this example is that the optical system MTF in each case is considerably better than the image intensifier MTF. If the model of limiting resolution presented in Figure 2 is correct, then calculating limiting resolution from only geometric considerations is perhaps an oversimplification.[5-6]

If it is true that the limiting resolution can be calculated only from geometric considerations then the contrast threshold criteria would have to be constant across spatial frequency as shown in Figure 3. In this case the wide FOV NVG would have exactly one half the limiting resolution as the narrow FOV (i.e. $\mathbf{R_w = 1/2\, R_n}$).

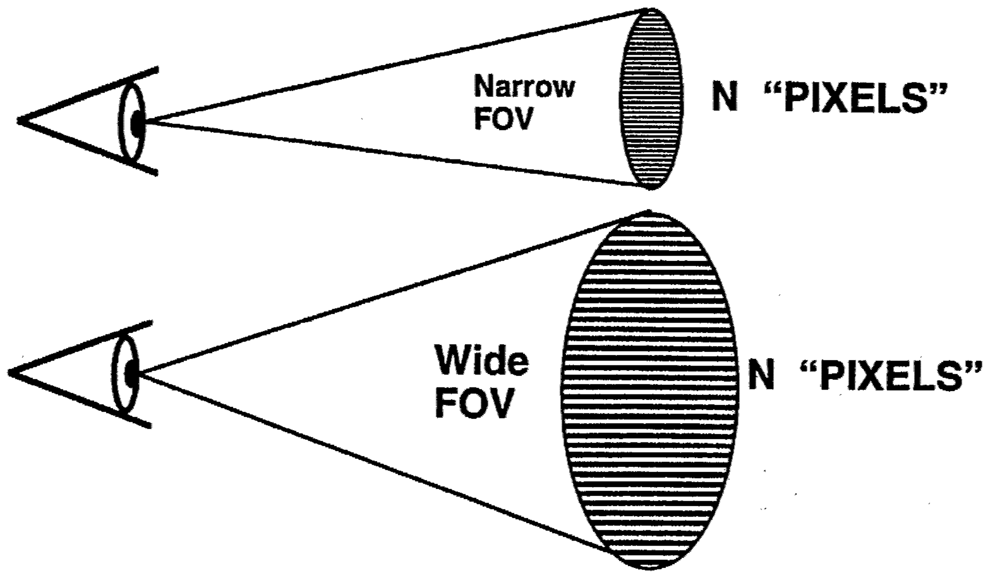

Figure 1. Geometric trade-off between field of view and resolution. Since there are a fixed number of picture elements (pixels) in the image intensifier output the angular subtense of each picture element will be larger (and therefore poorer resolution) with a wider field of view.

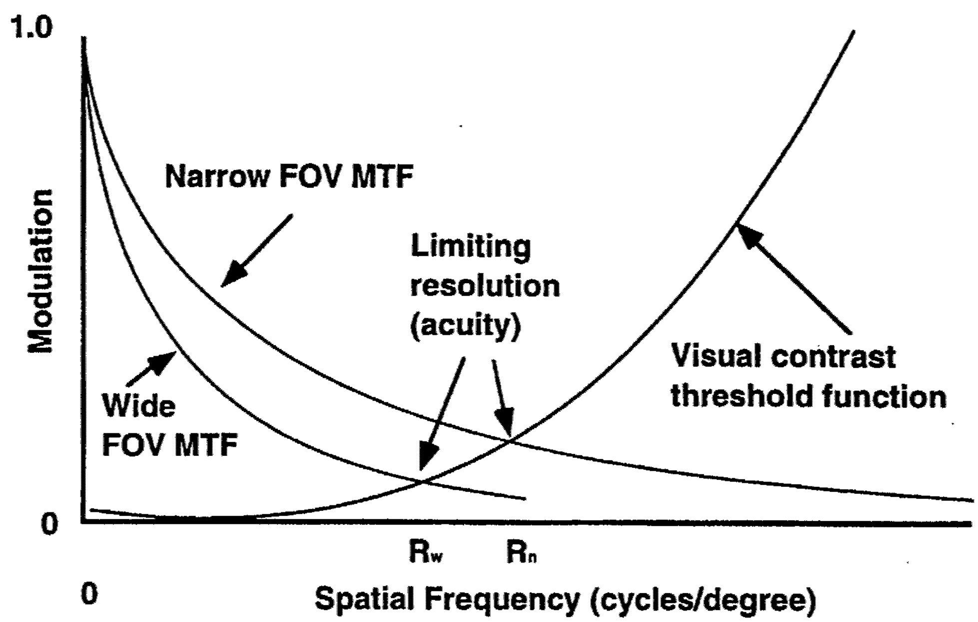

Figure 2. Determination of limiting resolution from the intersection of the NVG modulation transfer function (MTF) and the human visual system contrast threshold function (CTF). Note that even though the narrow field of view (FOV) is exactly one half of the wide FOV, the wide FOV limiting resolution is greater than one half of the narrow FOV limiting resolution due to the slope of the visual CTF.

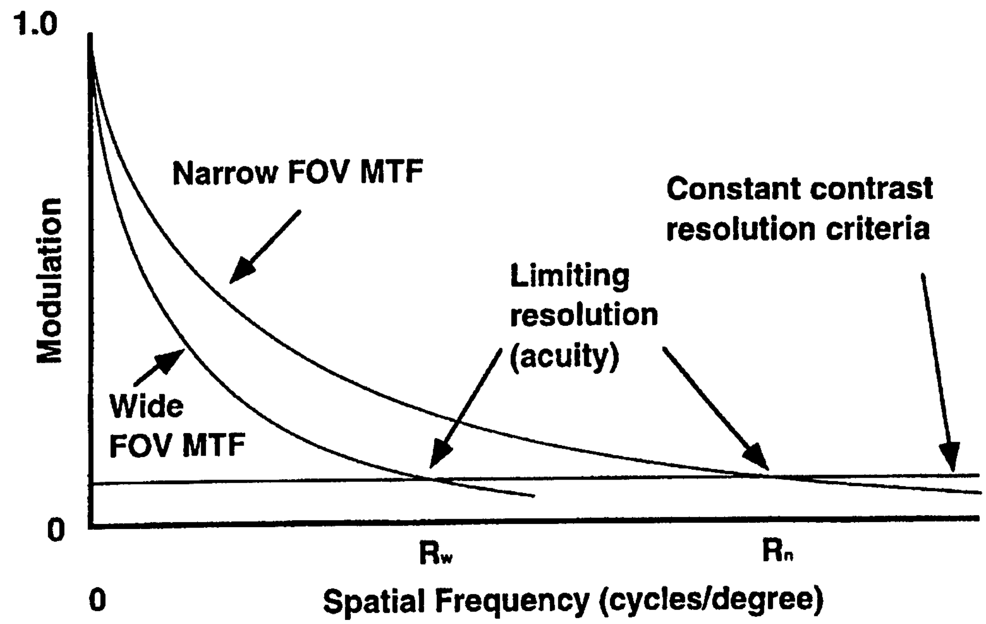

Figure 3. Modulation transfer function (MTF) of a hypothetical image intensifier tube as viewed through two optical systems (wide and narrow) with the wide field of view (FOV) set at twice the size of the narrow FOV.

To test this hypothesis, a small study was conducted using a 40 degree FOV NVG and a 47 degree FOV NVG borrowed from ITT Corp. of Roanoke, VA. The visual acuity of nine subjects was tested viewing through both NVGs for five different illumination conditions. The visual acuity was recorded in terms of Snellen acuity with the assumption that 20/20 Snellen acuity corresponds to 30 cycles per degree. Figure 4 is a graph of the results of this study. The graph of Figure 4 shows the actual average acuity obtained for the 40 degree FOV and 47 degree FOV NVGs compared with the acuity that would be predicted for the 47 degree FOV NVG based on the results of the 40 degree NVG and simple geometry. The 47 degree FOV predicted curve was obtained by multiplying the 40 degree data by (47/40) thus making acuity worse (higher Snellen fraction) by a factor equal to the ratio of the increase in FOV. As is apparent from the graph, the predicted curve was quite close to the actual curve with the exception of the very lowest luminance level. At the lowest luminance level the actual Snellen acuity was slightly better but still not significantly different ($p>.05$) than the predicted acuity that would be expected if limiting resolution can be based on the model presented in Figure 2. With this encouraging result we were ready to do a more extended study when NVGs with three FOVs became available for a relatively short time (40 deg, 47 deg, and 52 deg FOV). However, a multiplicity of problems too involved and embarrassing to expound upon here resulted in inconclusive results. With only a short time remaining on the availability of these NVGs we decided to do a brief study involving only three highly trained observers to compare the effects of luminance on the question of field of view versus visual acuity trade-off. To eliminate some of the problems that caused our inconclusive results of the ill-fated "main" study we used only one ocular of each of the NVG's and we selected a single image intensifier tube (which was moved from NVG to NVG) to be used for all conditions. The pathways of scientific investigation never run smoothly!

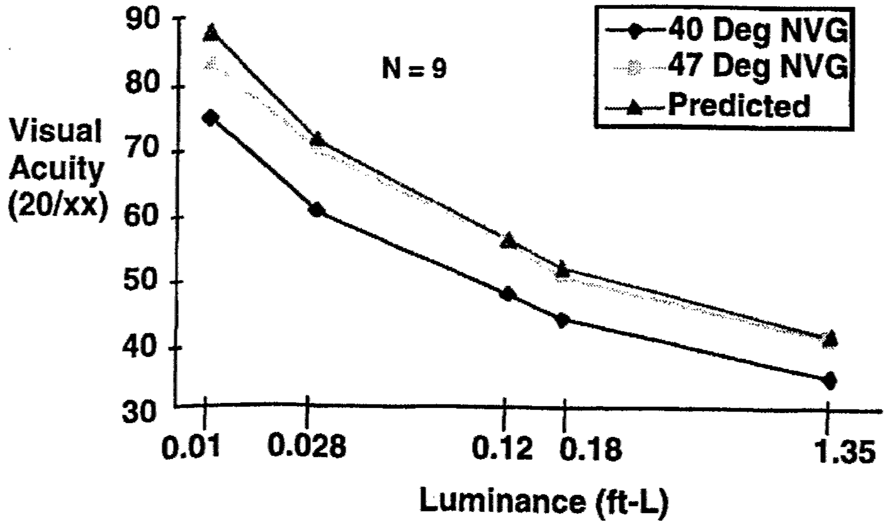

Figure 4. Average visual acuity of nine subjects for two different NVGs having 40 degree and 47 degree fields of view. Visual acuity for the 47 degree FOV NVG is compared with predicted visual acuity for this NVG based on the subjects visual acuity obtained for the 40 degree NVG.

METHOD

Observers

Three well trained observers, two females and one male, ranging in age from 33 to 42 years participated in the study. All of the subjects had 20/20 or corrected to normal binocular acuity as measured by a standard Snellen eye chart. The three observers who participated were laboratory personnel that were selected for their superior visual capability and their familiarity with focusing techniques and operation of NVGs. These were the same observers that routinely assess the resolution of NVGs acquired for evaluation.

Apparatus

The three NVGs used in the study were prototype NVGs having serial numbers of #004, 008, and 009 manufactured by ITT Corporation of Roanoke, VA. The NVGs were manufactured such that they presented intensified fields of view of 40, 47, and 52 degrees. ITT fitted the left tube of each pair of NVGs with an image intensifier which had a high signal to noise ratio. Image intensifier #80270 was chosen by laboratory personnel to be swapped among the three pairs of NVGs. This swapping method was chosen because previous pilot studies with "matched" tubes indicated variations in visual performance most likely due to individual tube differences. Prior to each experimental session, a telescope with 8x magnification was used to ensure that the left tube diopter lens focus was at about 30 feet (about 0.1 diopters). The right tube of each pair of NVGs was covered with a black cap during the experimental session. The non-dominant eye of the observer was covered with an eye patch.

NVG output luminance was provided by a 2856K light source which was filtered by aluminum aperture plates. The four aperture plates were chosen such that they would give rise to NVG output luminances of 0.01, 0.03, 0.08, 0.28, and 1.9 fL. These output luminance levels correspond roughly to what would be seen if ambient conditions were between overcast starlight and full moon. Uniformity of test target luminance was checked before and after each experimental session using a Pritchard 1980B photometer.

The test targets used in the study were linear square-wave targets similar in format to those employed by the AF 3X3A NVG Resolution Chart [7] which is widely used by aircrews to check their NVGs prior to a mission. Four test charts were employed which had alternating horizontal and vertical square-wave patterns ranging in Snellen size from 20/15 to 20/120, corresponding to 45 cycles/degree to 5 cycles/degree. Modulation contrast for the targets was approximately 95%. A typical example of one of the four test charts used in the study is shown in Figure 5.

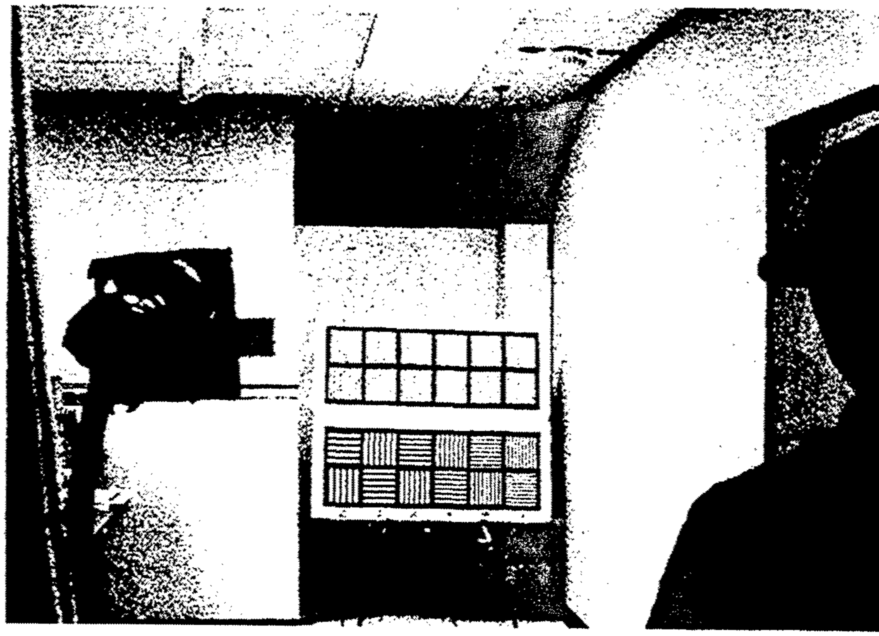

Figure 5. Test Chart Used in Study

Procedure

Prior to viewing the test charts, the subject dark adapted for 20 minutes. After dark adaptation was complete, the subject was positioned at a distance of 30 feet from the test chart, and an eye patch was placed on the non-dominant eye. The right tube of the NVGs was covered with a black cap, and the subject looked at the test chart through the left tube using the dominant eye. (The left tube of the NVGs was set at 0.1 diopters using a dioptometer). The subject looked at the test chart and identified the smallest resolvable vertical square wave target, and then walked backwards until that same pattern was no longer resolvable. The observer then moved forward until the vertical pattern again became resolvable. The final distance from the acuity chart was recorded, and the resulting acuity was calculated using the following formula:

$$SA = \frac{30}{D} xx \qquad (2)$$

where **SA** = Snellen acuity (denominator) at threshold
xx = Snellen denominator of vertical grid chosen by observer
D = subject's distance from chart at threshold (in feet)

This walk back procedure was repeated four times for each of the five NVG output luminance levels for a total of 20 trials per session. Order of output luminance level was randomized within each testing session. Only one NVG was tested during each experimental session, with order of NVG presentation randomized. The sessions were conducted on three consecutive days for each subject.

RESULTS

The average visual acuity as a function of light level for each of the NVG systems (40, 47, and 52 deg) for the three observers is depicted in Figure 6. Qualitatively, the results are somewhat similar to the previous study in that visual acuity does get worse as light level is reduced and as field of view is increased. However, since the visual capability of the three trained observers is not uniform the grouped results of Figure 6 hides these individual effects. Table 1 is a summary of the results for each observer.

Table 1. Summary of results: average Snellen acuity for the three subjects, three NVG fields of view and five output light levels

	SUB 1			SUB 2			SUB 3		
OUTPUT LUM	40	47	52	40	47	52	40	47	52
0.01 ft-L	81	88	117	70	80	96	55	67	73
0.03 ft-L	57	64	77	55	67	70	44	53	55
0.08 ft-L	50	53	61	46	56	60	37	46	48
0.28 ft-L	36	46	50	39	47	49	30	40	41
1.91 ft-L	33	39	43	34	39	41	25	34	34

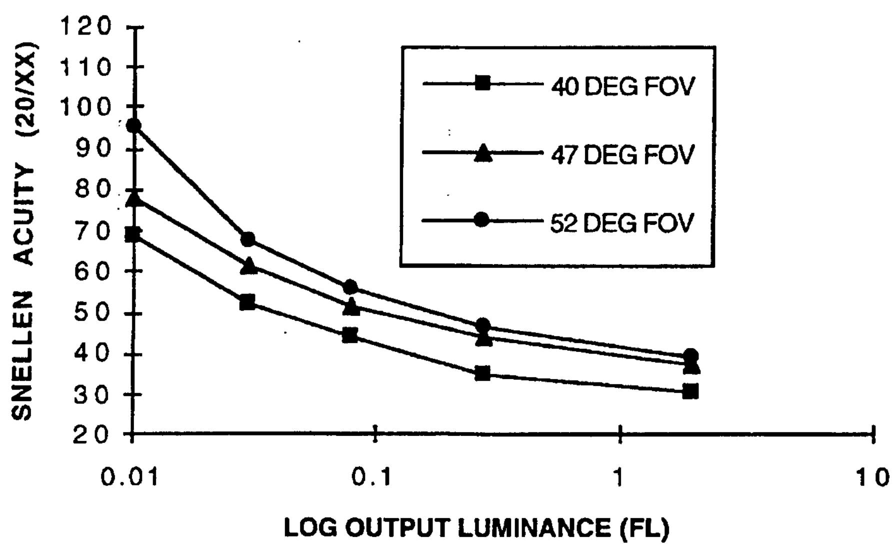

Figure 6. Visual acuity as a function of NVG output luminance for a single image intensifier tube viewed through three different NVG optical systems for the three trained observers.

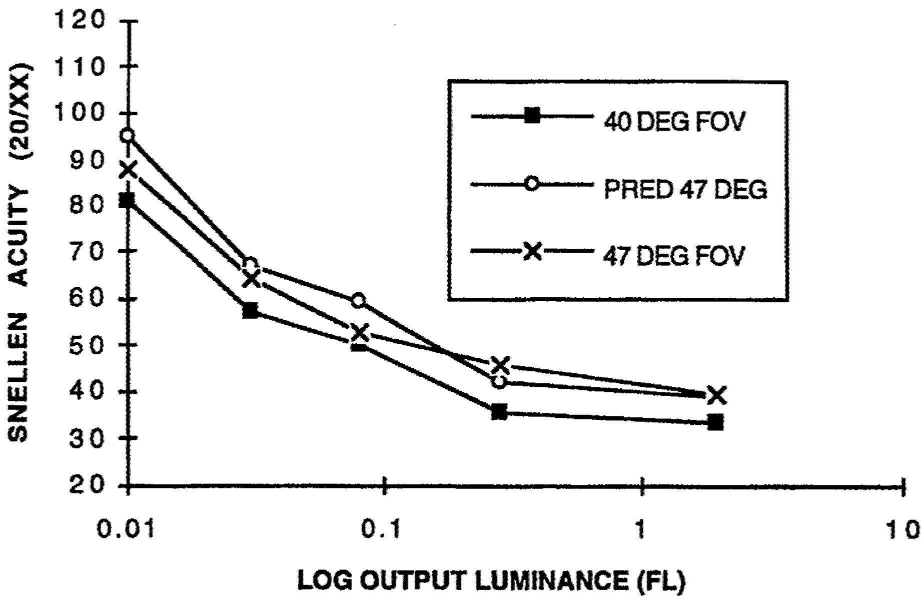

Figure 7. Predicted and actual acuity of subject one for 47 degree FOV.

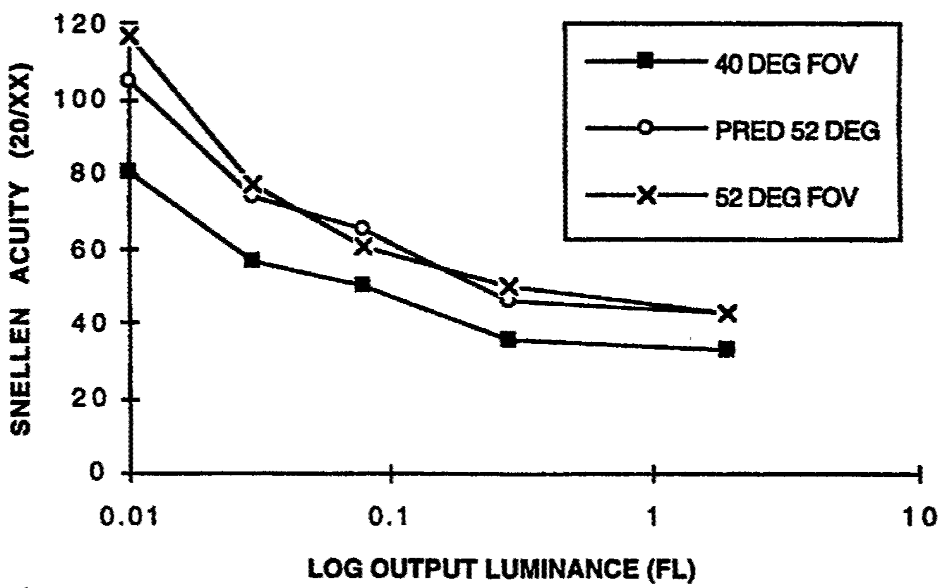

Figure 8. Predicted and actual acuity of subject one for 52 degree FOV.

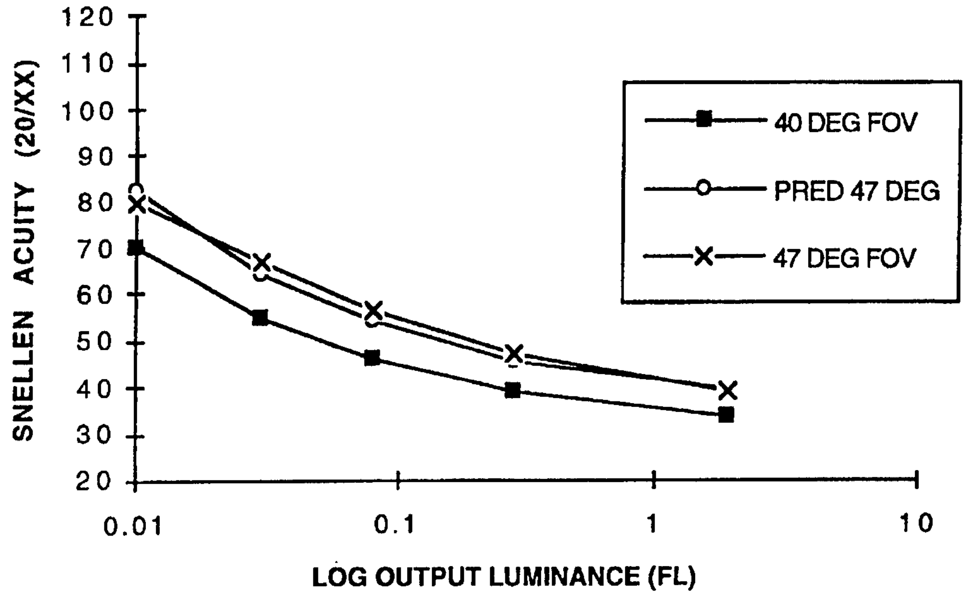

Figure 9. Predicted and actual acuity of subject two for 47 degree FOV.

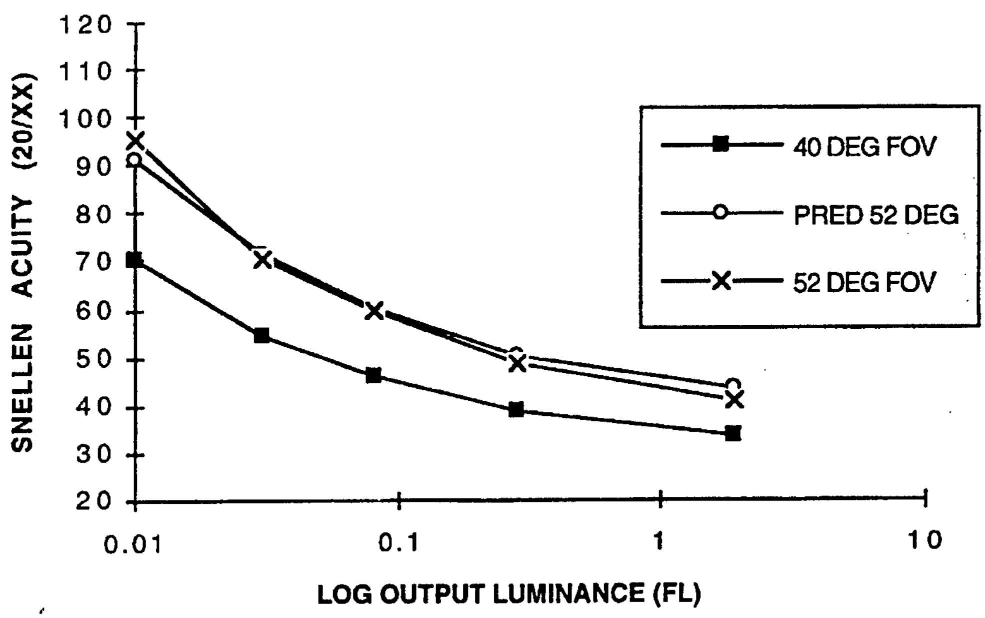

Figure 10. Predicted and actual acuity of subject two for 52 degree FOV.

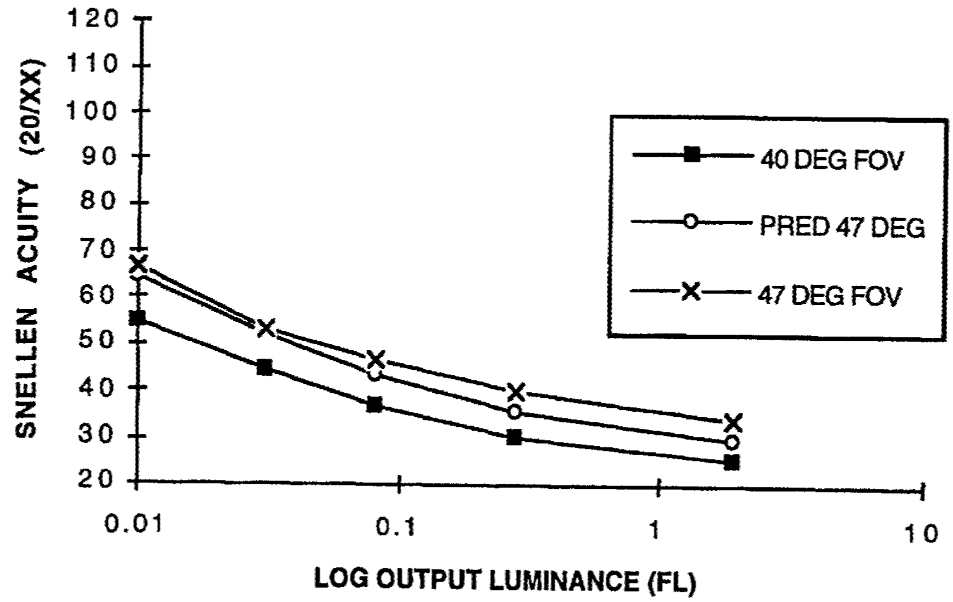

Figure 11. Predicted and actual acuity of subject three for 47 degree FOV.

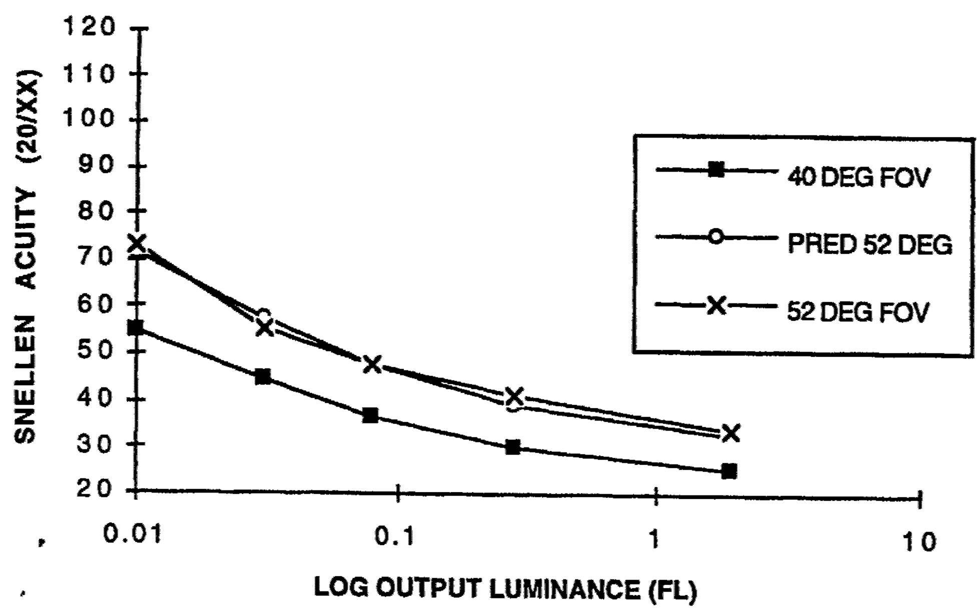

Figure 12. Predicted and actual acuity of subject three for 52 degree FOV.

DISCUSSION

For the 52 degree FOV data (Figures 8, 10 and 12) the predicted visual acuity (using geometric considerations only) came very close to the actual visual acuity for all luminances and all subjects with the exception of the lowest luminance level for observer 1. For this one point, the predicted visual acuity was notably better (lower number) than the actual acuity recorded although this difference was not statistically significant. This difference was also in the wrong direction for supporting the non uniform contrast criteria model depicted in Figure 2. For the 47 degree FOV data (Figures 7, 9 and 11), observer 2 provided results that support the geometric model very well but observers 1 and 3 results were less clean. Observer 1 was somewhat erratic as a function of luminance (we found out later that observer 1 had recently had a change of glasses prescription but used the old, undercorrected prescription during this study). Observer 3 seemed to be consistently worse than predicted (higher Snellen number) for the higher luminance levels which again is in the opposite direction from what one would expect using the visual contrast threshold function criteria model of Figure 2. The bottom line conclusion is that it appears that the simple geometric model of the inverse relationship between resolution and field of view is adequate for characterizing this particular design trade-off for current tube qualities.

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2. NIGHT VISION IMAGING SYSTEM (NVIS) COMPATIBILITY: LIGHTING AND DISPLAYS

The compatibility or incompatibility of aircraft cockpit lighting and displays with NVGs is a major issue in aviation. In general, the aircraft interior lighting and displays are considered compatible if they do not interfere with the exterior scene-viewing capability of the NVGs. Since observers look under the goggles to directly see the cockpit instruments and displays (except for viewing the head-up display), a compatible cockpit must also provide sufficient light of appropriate color content equivalent to that of a non-compatible cockpit. A related issue is that the NVG-compatible lighting and displays must also be useable under daylight conditions. When NVGs were first used in aircraft cockpits, they were called second-generation devices because they used second-generation image intensifier tubes. These tubes were sensitive to light across the entire visual spectrum (400 nm blue through 700 nm red) as well as through the near-infrared (NIR; 700 nm through 950 nm). Since cockpit instrumentation emits large amounts of NIR, it is extremely difficult to make it fully compatible (as defined above) with NVGs. Techniques to improve NVG compatibility by using complementary color filters also resulted in lowered second-generation NVG performance (Task & Griffin, 1982a; 1982b).

Compliant lighting refers to cockpit lighting systems that meet the specific luminance and night vision imaging system (NVIS) radiance requirements of Mil-L-85762A (26 August 1988, Military Specification, Lighting, Aircraft, Night Vision Imaging System (NVIS) Compatible.) and Mil-Std-3009 (2 February 2001, Department of Defense Interface Standard for Lighting, Aircraft, Night Vision Imaging System (NVIS) Compatible). It is possible for an aircraft cockpit lighting and display system to be NVG compatible, as previously defined, but not be NVG compliant, as per Mil-L-85762A. Recent, as yet unpublished, studies show that the reverse may also be true if the lighting or displays produce direct reflections in the aircraft windscreen that the NVGs must view through.

Another issue associated with NVG-lighting compatibility involves external lighting (navigation lights, anti-collision strobes, position lights, etc.). None of the articles in the present section address this issue, but it is normally highly desirable to make sure the external aircraft lighting can be used in conjunction with the NVGs without causing degradation in NVG performance.

The first article, Blouin (1997), provides basic information about human vision and dark adaptation. This is an important issue because visual acuity through NVGs tends to be improved by increasing the output luminance of the NVGs. This increase changes the individual's light adaptation state, making it necessary for the cockpit lighting to be correspondingly higher, so that crewmembers can properly see their instruments and displays. Task & Griffin (1982a; 1982b) describe various techniques developed to make helicopter cockpit lighting NVG compatible. Slusher (1985) provides an excellent reference for the determination of what luminance level should be attained in the aircraft cockpit for aircrew use. Pinkus (1988) describes a broad view of techniques used to make a cockpit NVG compatible. Donohue-Perry (1984) demonstrates that electroluminescent lighting obeys the laws of photometry and can be used for NVG compatible lighting. Craig, Bartell, Hettinger & Riegler (1993) describes NVG compatible lighting for fixed-wing aircraft. Marasco, Bowyer & Boulter (2001) and Marasco (2001) examine the issue of "super" luminance levels for cockpit displays in order to achieve higher aircrew member visual acuity capability with respect to the display and the displayed information. The last article, Task (1998), describes the pros and cons of using chemical light sticks as an interim method of achieving NVG compatible lighting.

These articles are reprinted to provide the reader with a reference and background to better understand NVIS compatibility of lighting and displays.

Blouin, G. K. (1982). ***Dark adaptation of rated Air Force officers using electroluminescent versus incandescent light sources.*** (Report No. AFAMRL-TR-82-2). Wright-Patterson AFB, OH: Air Force Aerospace Medical Research Laboratory.

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AFAMRL-TR-82-2

DARK ADAPTATION OF RATED AIR FORCE OFFICERS USING ELECTROLUMINESCENT VERSUS INCANDESCENT LIGHT SOURCES

GEORGE K. BLOUIN, CAPTAIN, USAF

SCHOOL OF SYSTEMS AND LOGISTICS
AIR FORCE INSTITUTE OF TECHNOLOGY

JANUARY 1982

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19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Night Vision	Adaptation
Electroluminescence	Vision
Electroluminescent Lighting	Lighting
Dark Vision	Night Lighting
Dark Adaptation	Cockpit Lighting

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

An experimental study was conducted to determine the effects of electroluminescent versus incadescent light sources on the dark adaptation of rated Air Force officers. The parameters of dark adaptation that were tested are (1) absolute luminance threshold of vision; (2) resolution of visual detail as provided by square wave spatial frequency gratings; and (3) comfort level of

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20. ABSTRACT (Cont'd)

cockpit lighting as determined by rated Air Force personnel. Results show that (1) electroluminescent and incandescent light sources have the same effect on the absolute luminance threshold and the resolution of visual detail; and (2) significant differences exist between the two light sources in the comfort level of cockpit lighting as chosen by the subjects.

PREFACE

This work was accomplished at the Crew Systems Effectiveness Branch of the Human Engineering Division, Air Force Aerospace Medical Research Laboratory under Project 7184, Man-Machine Integration Technology, Work-units 71841144, Image Display Mensuration/Enhancement, and 71841215, Lighting and Light Control. Research was monitored by Dr. Harry L. Task and partially funded by the PRAM (Producibility, Reliability, Availability and Maintainability) Program Office.

another type of light source whose effect on dark adaptation has not been determined. Electroluminescent lighting differs from an incandescent light in that it is a solid state device which absorbs electrical energy and converts it to a steady uniform glow.

Typically, an EL lamp is a polycrystalline copper doped, zinc sulfide powder phosphor that, when excited by an alternating current, causes an electron shift within the phosphor atom, thereby releasing photons, or light. The EL lamp emits light in a relatively narrow bandwidth, has no infrared component, is capacitive in nature, and differs from the conventional incandescent light source in the same sense that transistors differ from vacuum tubes (6). It is not a new light source; but due to recent improvements in color stability, more efficient power supplies, and micro-encapsulation techniques, it shows great promise for a wide range of applications. The EL lamp is currently being used in buses, trucks, automobiles, and in aircraft for instrument and cargo area lighting (6). It could also be used for home security, emergency exit signs, and appliances.

Currently, the PRAM (Producibility, Reliability, Availability, Maintainability) Program Office of the Aeronautical Systems Division at Wright-Patterson AFB, Ohio, in response to Military Airlift Command Statement of Need

(MAC SON) 02-79, is conducting field experiments to determine if EL lighting is suitable for austere airfield lighting. In addition, the capabilities of EL lights on C-130 cargo and cockpit areas are being pursued by PRAM. During the tests of electroluminescent lighting on C-130 aircraft, it was stated that EL lamps "could be viewed at very close ranges without affecting night vision [5]."

Night Vision

Night vision, the ability of an individual to see at night, depends on the individual's level of dark adaptation. Dark adaptation and night vision involve increased visual sensitivity resulting from exposure to decreasing quantities of visible light. The most frequently tested aspect of dark adaptation is the absolute light level or the threshold of seeing (3:9).

> The absolute light sense is the most fundamental and most frequently measured parameter of dark adaptation. Historically, the absolute, minimal, contrast, or relative brightness thresholds have been used as the criteria of individual night vision ability [3:36].

Visual acuity is another factor which has an effect on night vision. Visual acuity is not only concerned with the ability of an individual to recognize a target, but also involves the capacity to discriminate fine details in an object or scene that is viewed (3:26). The discrimination of fine details or resolution involves the individual responding to a separation between elements of a pattern. The most common pattern used is a grating pattern, similar to Figure 1, in which the widths of the dark and bright lines are made equal (4:325). Normally, a series of gratings from coarse to fine is presented and visual acuity is specified in terms of the angular width of one line for the finest grating that can be resolved (4:325).

> Visual acuity, in the sense of resolution, is the reciprocal of the angular separation between two elements of the test pattern when the two images are barely resolved [4:325].

Therefore, fine lines indicate a high degree of acuity and wide lines, a low degree.

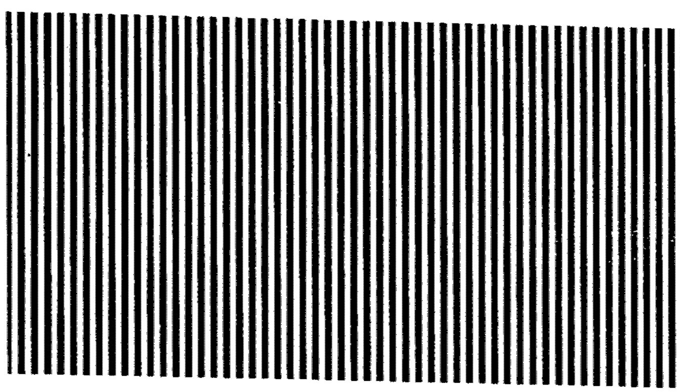

Figure 1. Acuity Grating

Dark adaptation and visual acuity may be quantified to determine an individual's night vision and the type of light source to be used, i.e., electroluminescent or incandescent may be chosen based on that quantitative data. However, once the type of light is fixed, the aircraft crewmember only has one variable which he may control and that is the qualitative variable of light comfort level.

Therefore, to test the effects of electroluminescent versus incandescent light sources on dark adaptation, this paper will focus on the quantitative aspects of absolute luminance and visual acuity as well as the qualitative aspect of light comfort level.

Problem Statement

A requirement exists for an evaluation of electroluminescent lamps to provide quantitative data of their effect on dark adaptation of the human eye. This evaluation focuses on the following:

1. Absolute Luminance Threshold of Vision
2. Resolution of Visual Detail as Provided by Square Wave Spatial Frequency Gratings (see Appendix A)
3. Comfort Level of Cockpit Lighting as Determined by Rated Air Force Personnel

Justification

By initiating a field study into the use of EL lamps in response to MAC SON 02-79, PRAM established the correlative need to evaluate EL lighting to determine:

1. The Effect of EL Lights on Human Visual Parameters
2. The Desirability of Expanding the Use of EL lighting for Cockpit and Runway Light Uses

Specifically, prior to committing additional funds and physical resources to the procurement of EL lamps for cockpit and airfield lighting, Air Force decision makers must be provided with quantitative as well as qualitative data on electroluminescent lighting.

Objectives

To determine the effects of an EL light source on the dark adaptation threshold of the human eye.

To determine the effects of an EL light source on visual acuity using square wave spatial frequency gratings.

To determine the cockpit lighting comfort range using EL and incandescent (INC) light sources.

Hypotheses

An EL light source affects the dark adaptation threshold of the human eye in the same manner as an incandescent light source.

An EL light source affects the grating resolution, at a predetermined spatial frequency, in the same manner as an incandescent light source.

Rated Air Force personnel select the same or greater cockpit luminance levels when using an EL light source than when using an incandescent light source.

Literature Review

A large number of scientists and medical personnel have examined the endogenous factors (those factors which have an individual physiological and anatomical basis) which influence dark adaptation. Many scientists have also examined the numerous exogenous factors (those factors which are in the environment and subject to experimental control) which influence dark adaptation. But, there is currently no research being conducted into the exogenous factor of the effect of electroluminescent lighting on the parameters of dark adaptation and visual acuity.

A literature search was conducted into the area of dark adaptation and visual acuity using electroluminescent lighting. The search included the resources of the Defense Technical Information Center (DTIC), of the Defense Logistics Agency at Alexandria, Virginia, the Integrated Visual Image Technology Section (IVITS) of the Air Force Aerospace Medical Research Laboratory (AFAMRL) at Wright-Patterson Air Force Base (WPAFB), and the Air Force Wright Aeronautical Laboratories (AFWAL) Technical Library at WPAFB.

The IVITS library is a working library specifically geared toward vision and display technology. The AFWAL library search included an index of all conference papers for the years 1973 through 1980 as provided by the Dialog Information Retrieval Service. In addition, the AFWAL search included all research in progress or completed in the past two years as listed with the Smithsonian Science Information Exchange (SSIE).

CHAPTER II

METHODOLOGY

The purpose of this chapter is to describe the apparatus used in the experiment, the scope of the experiment, and the procedures followed during the experiment.

Apparatus

Figure 2 is a schematic representation of the night vision tester (NVT) used during the experiment to provide the dark adaptation curves and the spatial threshold curves. Figure 3 is a picture of the night vision tester and the Pritchard photometer. The NVT allows for an 8 degree field of view, and the slide wheel contained five slides of varying square wave gratings. The five spatial frequencies tested with the slides were 1, 1.6, 6.25, 10, and 12.5 cycles per degree (cpd). The light source was an electroluminescent panel approximately 2 inches x 8 inches. The EL panel was filtered with the use of an ND2 filter to reduce the light output to threshold levels. The Variac controlled the voltage level to the EL panel, thereby controlling the light output. A Pritchard photometer was used to generate a calibration curve of the NVT which related the Variac voltage to a luminance level.

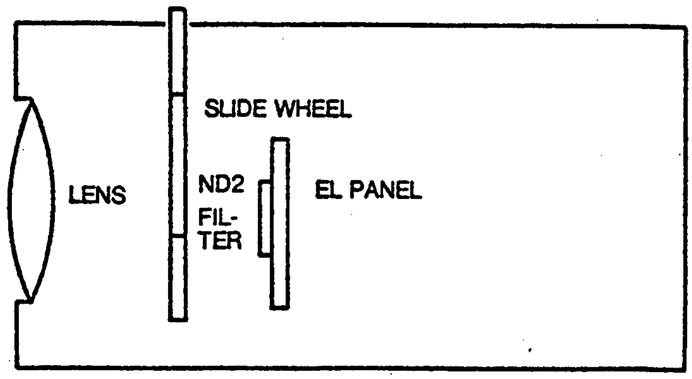

Figure 2. Schematic of the Night Vision Tester

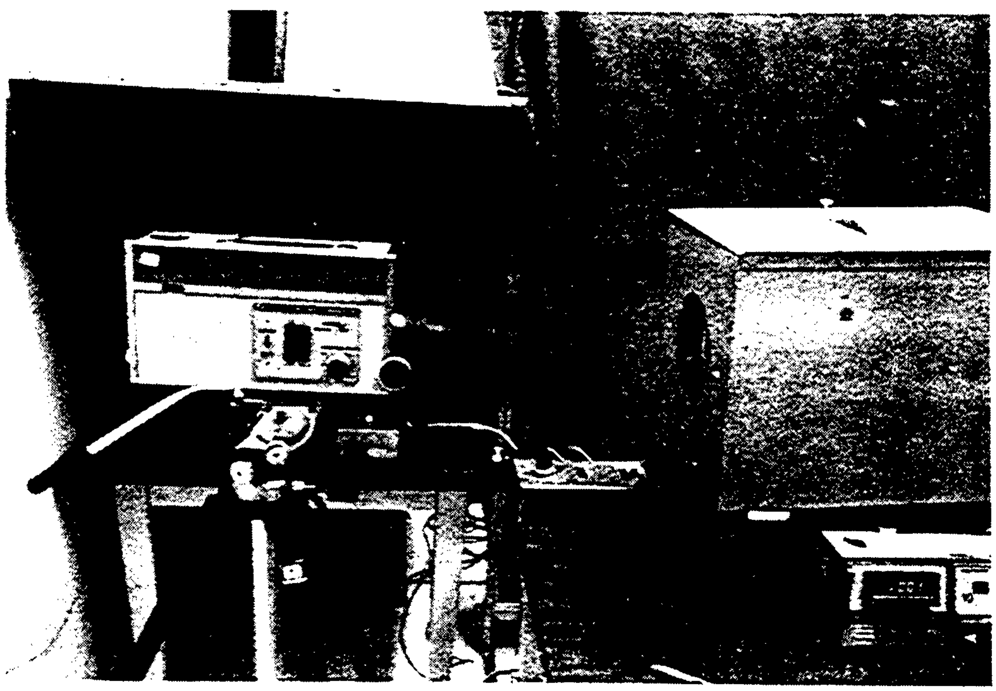

Figure 3. Night Vision Tester

The pseudo-cockpit environment, as shown in Figure 4, had four control panels or dials taken from a variety of aircraft. The panels were illuminated by either EL or incandescent lamps which were filtered to remove any color differences. Figure 5 is a graph of the relative output versus wavelength of the EL and INC light sources. Figure 6 shows where each light source falls on the Uniform Chromaticity Scale (UCS). A Variac, identical to the one on the NVT, was used to vary the voltage and subsequently the illumination of the control panels. Again, a Pritchard photometer was used for calibration curves for each light source.

The raw data was recorded by a Texas Instruments Silent 700 ASR Electronic Data Terminal, shown in Figure 7. The terminal and its associated software recorded the subject's response time as well as the voltage level for both the NVT and pseudo-cockpit area. In addition, a control box with switches to turn each Variac on or off and a switch for light source selection was provided.

Scope

The experiment was conducted using ten active duty Air Force officers. Each subject had 20/20 visual acuity with or without corrective lenses as measured with a standard eye chart. The sample was not entirely random, as the subjects were volunteers attending the Air Force Institute

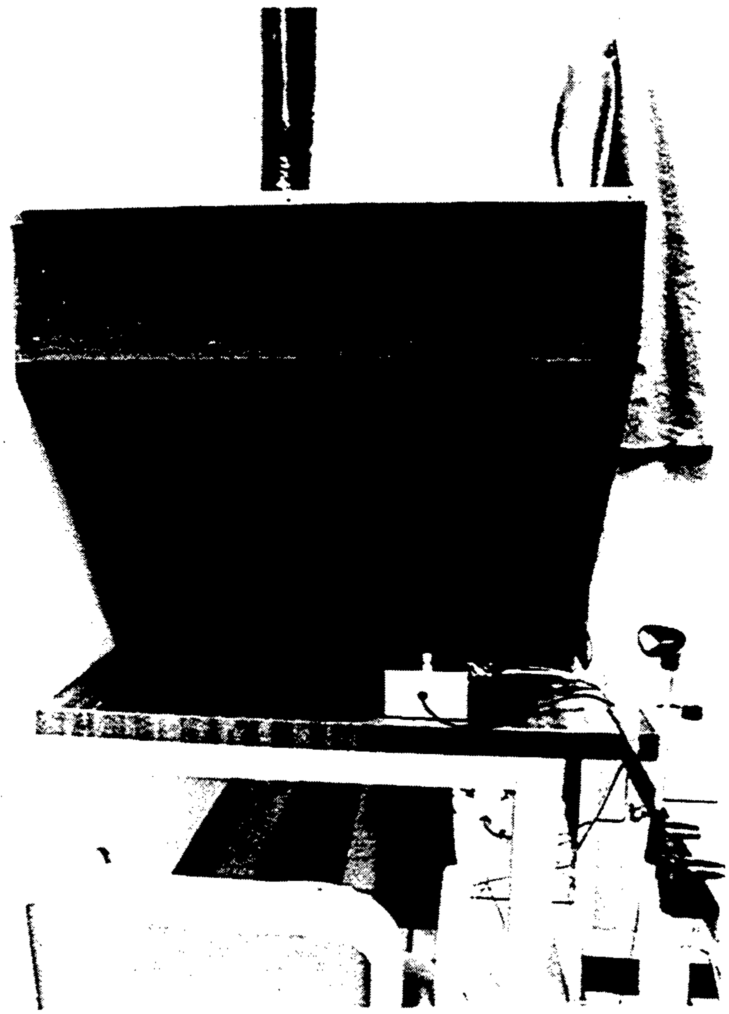

Figure 4. Pseudo-Cockpit Environment

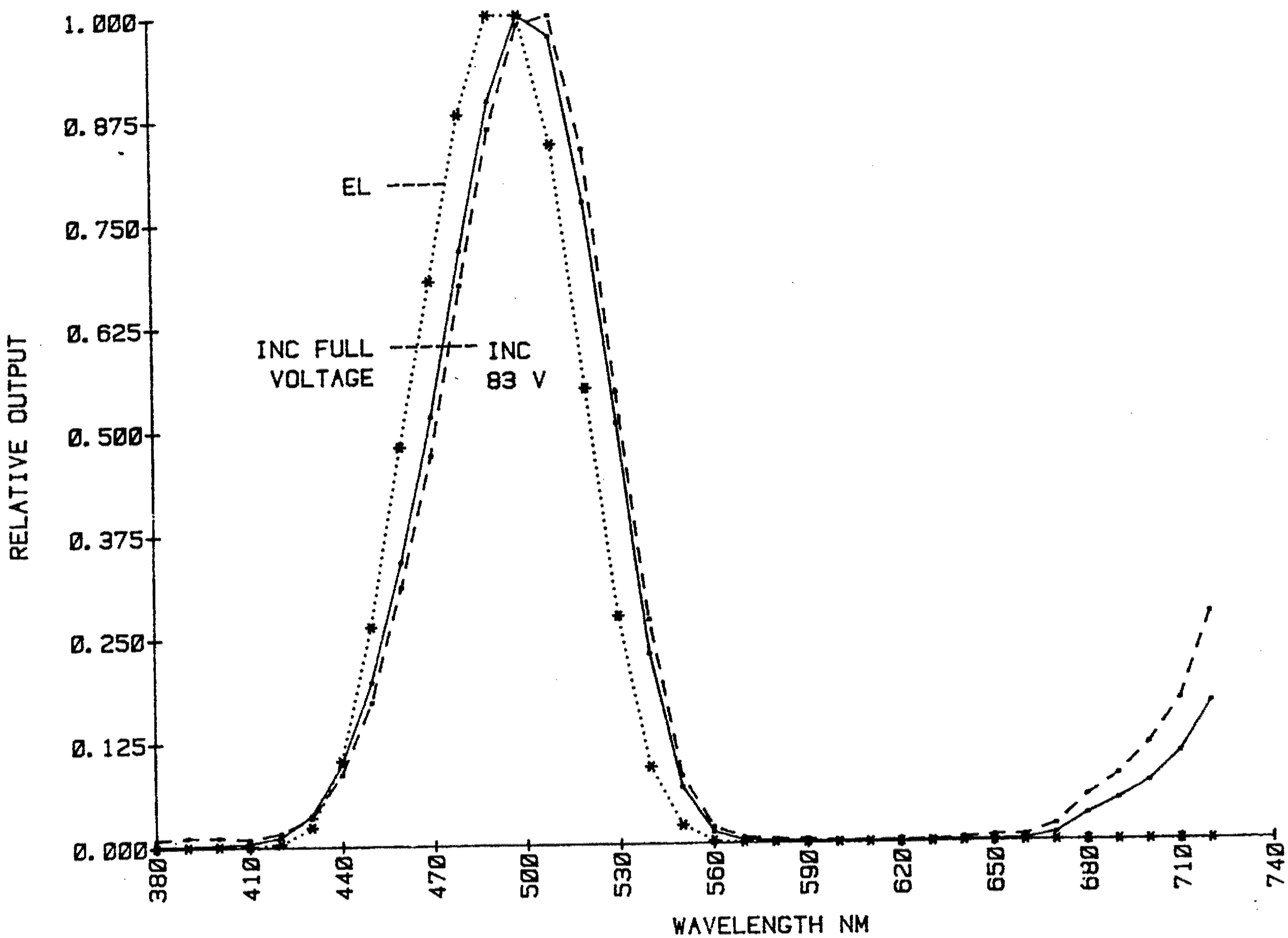

Figure 5. Relative Output versus Wavelength

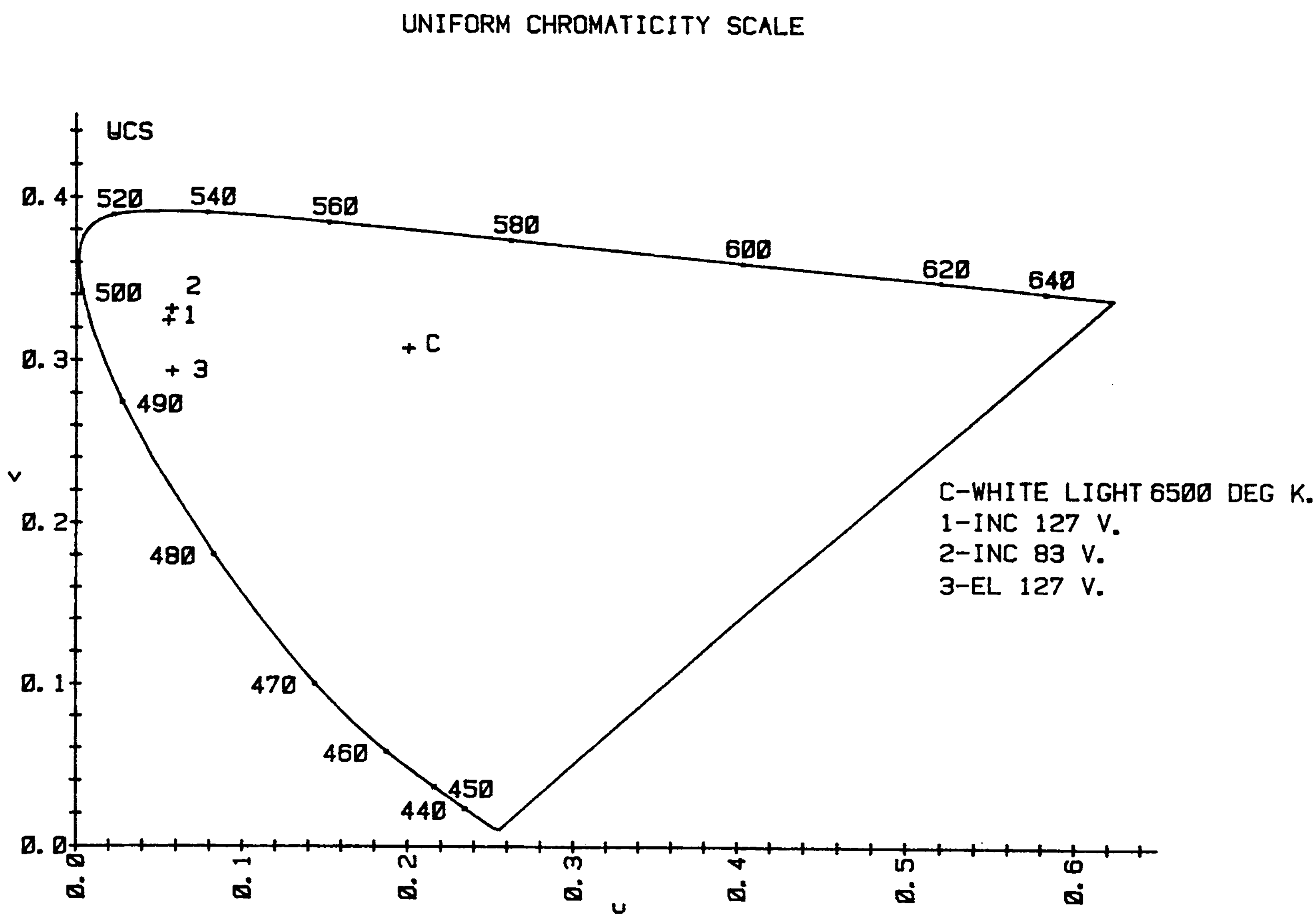

Figure 6. Uniform Chromaticity Scale

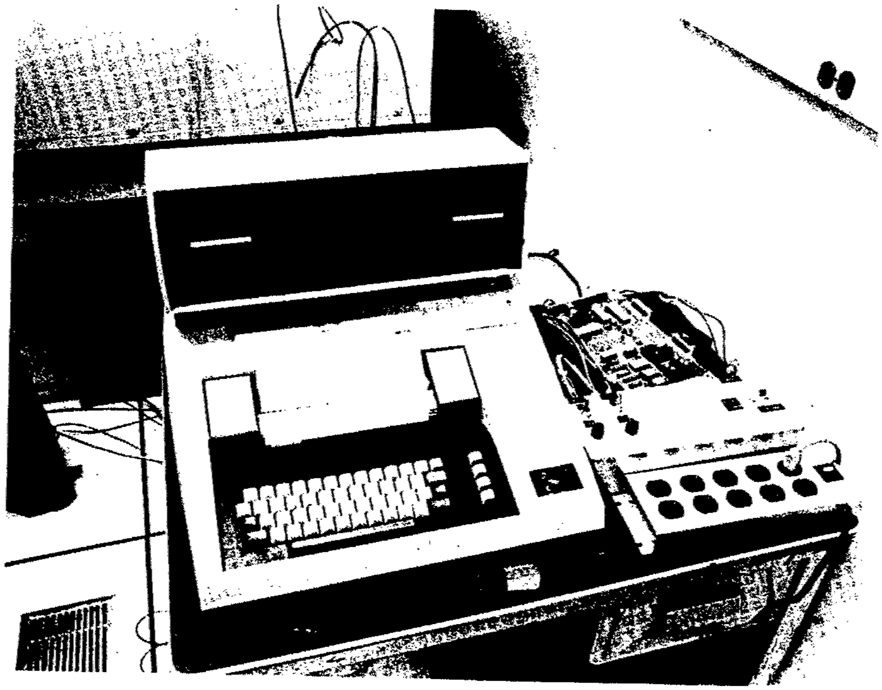

Figure 7. Texas Instrument Silent 700 Terminal

of Technology, but there was no reason to suspect that the night vision capacity of the group would differ from a random sample's capacity. All subjects were male, between the ages of 28 and 35. The experiment was conducted between the hours of 1030 and 1730 over a six-day period and took approximately 2.5 hours per subject to complete.

Procedure

The experiment can be broken down into four tasks:

1. Adaptation
2. Threshold/Frequency
3. Response
4. Comfort

The first two tasks were accomplished using the NVT only and provided baseline data of the absolute threshold and spatial frequency response of each subject. Task 3 used both the NVT and the pseudo-cockpit environment and provided data on the effect of the different light sources on the subject's absolute dark adaptation threshold and grating resolution. Task 4 relied solely on the pseudo-cockpit environment and provided data on the subject's luminance level preference for each of the two light sources (EL and INC).

Prior to the start of Task 1, the subject was shown the equipment, given a written explanation of the procedure (Appendix B), and signed a consent form (Appendix C).

Table 1 shows in outline form the procedure followed during the experiment. Each subject was instructed to press the response button when he could just distinguish the light for Task 1. Tasks 2 and 3 required the subject to press the response when he could just distinguish the light and press again when he could just distinguish the gratings. For Task 4, the subject was instructed to adjust the light level to where he would perform a normal flying mission.

TABLE 1

EXPERIMENTAL PROCEDURE

TASK 1: ADAPTATION

Sequence:

1. Lights turned out in room.
2. Timer starts.
3. Subject sets Variac to threshold and presses response button.
4. Time and Variac voltage recorded.
5. Subject returns Variac to zero setting and waits 30 seconds before repeating Step 3.
6. Subject continues for approximately 30 minutes.

TASK 2: THRESHOLD/FREQUENCY

Sequence:

1. Experimenter positions grating 1 into NVT.
2. Subject sets Variac to threshold and presses response button to record voltage.
3. Subject sets Variac to resolve gratings and presses response to record voltage.
4. Repeat Steps 2 and 3 eight times.
5. Repeat for each of five gratings.

TABLE 1--continued

TASK 3: RESPONSE

Sequence:

1. Experimenter randomly selects light source (EL or INC) at predetermined luminance level (~0.02 ftL).
2. Subject views pseudo-cockpit light area for 90 seconds.
3. Experimenter turns off light which starts timer.
4. Subject turns to NVT and adjusts Variac 2 to absolute threshold and presses response.
5. Elapsed time and voltage are recorded.
6. Subject adjusts Variac to resolve grating number 4 (10 cpd) and presses response.
7. Time and voltage are recorded--timer reset.
8. Repeat 1 through 7 eight times for each light source.

TASK 4: COMFORT

Sequence:

1. Experimenter randomly selects light source (EL or INC).
2. Subject adjusts cockpit Variac to comfort level and presses response.
3. Variac voltage and light source (EL or INC) are recorded.
4. Repeat 1 through 3 eight times for each light source.

CHAPTER III

ANALYSIS AND INTERPRETATION

Introduction

The purpose of this chapter is to provide the statistical techniques used to analyze the experimental data, explain the results of each portion of the experiment, and discuss those results.

Statistical Techniques

A single factor repeated measures design analysis of variance (ANOVA) was performed to determine the effects of different light sources (incandescent and electroluminescent) on the subject's absolute dark adaptation threshold and grating resolution threshold before and after light exposure. A one-way ANOVA with repeated measures was performed on the comfort portion of the experiment. The subject means for each condition were used as inputs to each cell. All results were tested at an alpha level of .05. A summary of the one-way ANOVAs with repeated measures is provided in Appendix H.

Results

The data for Task 1 dark adaptation and Task 2 resolution of each spatial frequency is graphed and shown in Appendix D and E, respectively. The data for Task 3 response and Task 4 comfort portions of the experiment are tabulated in Appendices F and G.

The graphs of the dark adaptation curves approximate the classical work of Hecht and McFarland, but a direct comparison cannot be made due to the differences in apparatus and technique. The amount of noise in the system did not allow for acceptable curve fitting of the data. The graphs show considerable variability between subjects, e.g., Subject 1 attained his threshold level of approximately 1×10^{-6} ftL within 12 minutes, whereas Subject 7 only required 5 minutes to attain the same threshold level. The threshold levels varied between subjects from 3×10^{-7} ftL to 8×10^{-6} ftL.

The subjects mean values of luminance threshold for resolution of spatial frequencies varied considerably. Resolution of the 10 cycles per degree grating required an average luminance level of 0.004 ftL for Subject 7, but 0.019 for Subject 2. The respective standard deviations are 0.009 and 0.004.

The results of the absolute threshold portion of Task 2 and Task 3 in the experiment relate to research Question 1 found in Chapter I. The computerized results of the ANOVA are provided as Appendix I and the F- ratios and their probabilities are listed in Table 2. The results indicate that the null hypothesis cannot be rejected, and led to the conclusion that an EL light source affects the dark adaptation threshold of the human eye in the same manner as an incandescent light source at the .05 alpha level.

TABLE 2

ABSOLUTE THRESHOLD RESULTS

ANOVA	F- Ratio	Probability
Before vs INC vs EL	1.192	0.3585
Before vs INC	1.107	0.3277
Before vs EL	1.629	0.2426
INC vs EL	0.036	0.8549

The results of the grating resolution portion of Task 2 and Task 3 in the experiment relate to research Question 2 found in Chapter I. The computerized results of the ANOVA are provided in Appendix J and the F- ratios and their probabilities are listed in Table 3.

The results do not allow for the rejection of the null hypothesis, and led to the conclusion that the two light, sources affect grating resolution threshold in the same manner. The F- probability of the incandescent versus electroluminescent ANOVA of 0.0203 seems to contradict all

TABLE 3

GRATING RESOLUTION F- RATIOS
AND PROBABILITIES

ANOVA	F- Ratio	Probability
Before vs INC vs EL	2.131	0.1812
Before vs INC	2.834	0.1308
Before vs EL	1.435	0.2652
INC vs EL	8.331	0.0203

previous results. Therefore, a Siegel-Tukey Test was performed on that particular data. The assumption of normality was relaxed, and the test was conducted with the hypothesis as follows:

$$H_o: \quad VAR(INC) = VAR(EL)$$

$$H_a: \quad VAR(INC) \neq VAR(EL)$$

The test was conducted at the .05 alpha level and the results do not allow for the rejection of the null hypothesis. The calculations are provided in Appendix K.

The results of Task 4, the comfort portion of the experiment, relate to the third hypothesis found in Chapter I. The computerized results of the one-way ANOVA are provided in Appendix L. The F- ratio of 11.531 and P(F) 11.531 = .0094 led to the rejection of the null hypothesis, and the conclusion that individuals selected lower luminance levels with the EL light source than with the incandescent light source. The ratio of incandescent to electroluminescent averaged 1.4. This indicates that the subjects selected 40 percent more light for their comfort when using the incandescent light source.

Discussion

A cursory look at the data provided in Appendix D indicates the wide variability of both absolute threshold and grating resolution between individual subjects. Subject 7 was not included in the analysis of the entire experiment. It was learned the subject had been diagnosed as having Aides Pupils. Aides Pupils is a condition where the pupils of the eye are fixed and do not respond to changes in light levels. Though Subject 7 met the initial criteria of 20/20 vision and a rated Air Force officer, it was felt the abnormality of Aides Pupils was sufficient to disqualify his results.

Subject 6 was not included in the analysis of the absolute threshold portion of the experiment. His data indicates he was two orders of magnitude different than any other subject in the posttreatment portion of the experiment. Apparently, exposure to the EL and INC light sources completely destroyed his rod vision, and he was operating with the use of his cones to detect light. It is also interesting to note Subject 6's dark adaptation curve

(Appendix D) is one of the higher curves encountered in this experiment.

The lack of evidence to reject the null hypothesis for the first two research questions is not surprising. The eye reacts to a photon of light of a particular wavelength, regardless of the source of light. The rejection of the null hypothesis for research Question 3 was unexpected. A recheck of the experimental apparatus revealed that the photometer was measuring an infrared component with the incandescent light source. This explains about 8 percent of the difference, but still leaves over 30 percent to be explained. The dynamics of the equipment as it relates to the curves of the EL and INC light sources may be another source of the differences found in this experiment.

The dynamics of the equipment refers to the fact that the Variacs used were linear in nature and controlled the voltage for each light source. As can be seen by Figure 8, the electroluminescent light source was somewhat linear with respect to voltage, but the incandescent source was not linear. This may explain the remaining differences found in this experiment.

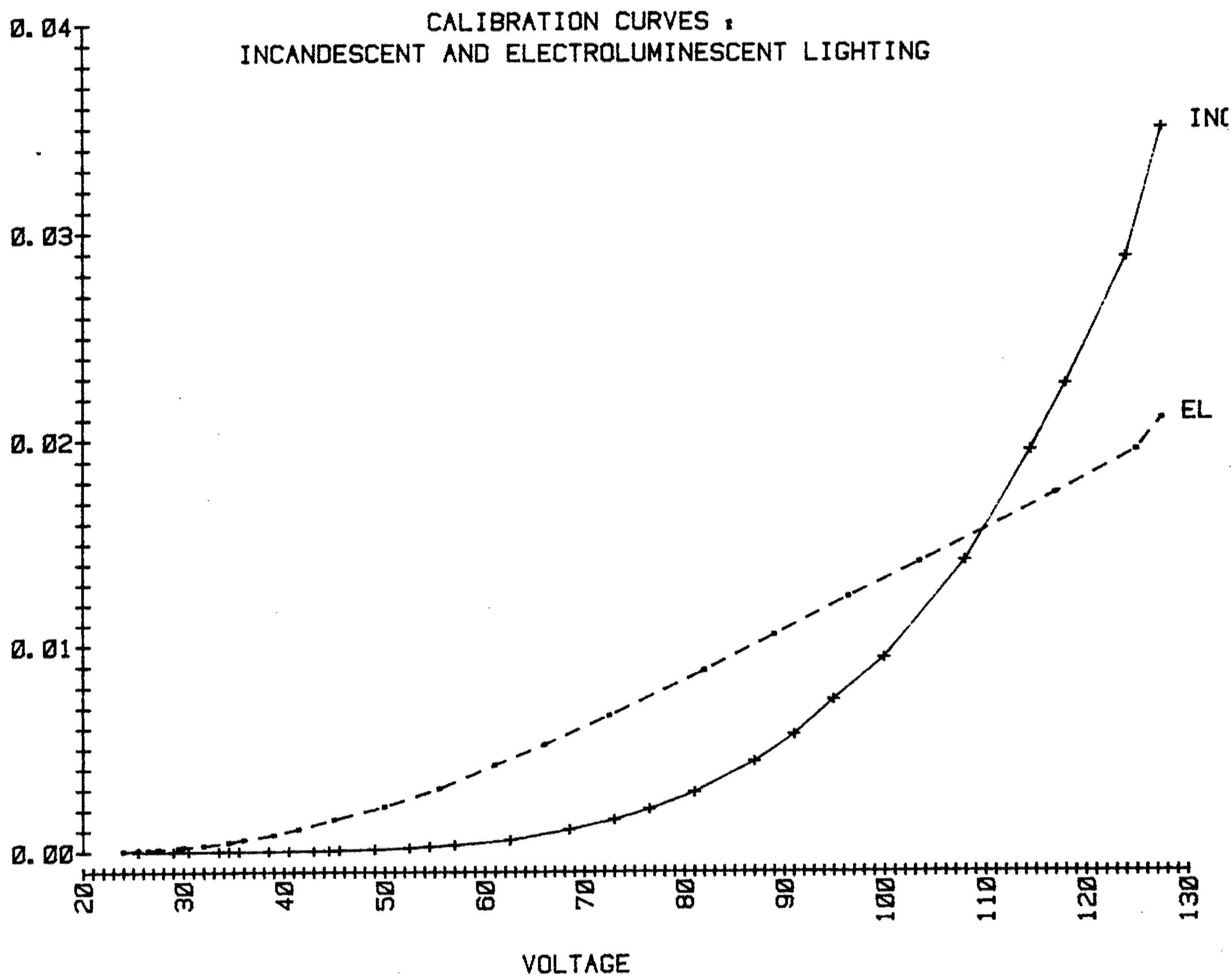

Figure 8. Calibration Curves

CHAPTER IV

CONCLUSIONS AND RECOMMENDATIONS

Introduction

In this chapter, the findings discussed in Chapter III are evaluated in light of the initial hypotheses specified in Chapter I. Each of the hypotheses is restated and considered below. Because this research effort was a preliminary investigation into the differences of incandescent versus electroluminescent light sources, some recommendations for future study are provided.

Conclusions

The first hypothesis dealt with the absolute threshold of dark adaptation of the human eye. It stated:

> An EL light source affects the adaptation threshold of the human eye in the same manner as an incandescent light source.

The experimental data and the subsequent analysis provided no evidence to reject the above-stated hypothesis at the .05 alpha level.

The second hypothesis was concerned with the resolution of a square wave grating of a predetermined spatial frequency. It stated:

> An EL light source affects the ability of the human eye to resolve a square wave grating at a predetermined spatial frequency in the same manner as an incandescent light source.

The experimental data and subsequent analysis again provided no evidence to reject this hypothesis at the .05 alpha level. The significant difference noted when an ANOVA was conducted on the EL versus INC portion of the grating resolution portion of the experiment was attributed to the very large differences between subjects. To compensate for the large disparity, additional analysis relaxed the assumption of a normal population and tested the equality of the variances. Analysis established that no significant differences were present. Based on these findings, it was concluded that the ability of the human eye to resolve a square wave grating is not dependent on the type of light source.

The final hypothesis was concerned with a subjective evaluation of the amount of light required to fly a normal mission by rated Air Force officers. It stated:

> Rated Air Force personnel select the same or greater cockpit luminance levels when using an EL light source than when using an incandescent light source.

The experimental data and subsequent analysis led to the rejection of the above-stated hypothesis. A significant difference was noted between the two light sources. An interesting discovery not tested during this experiment was the difference in luminance levels based on aeronautical rating. The three pilots in the group invariably selected lower luminance levels than did the navigators. This fact may be of importance to aircraft cockpit lighting designers, especially in two-place cockpits such as the FB-111.

Recommendations

This study has been an initial investigation of the claims that electroluminescent light is somehow perceived differently by the human eye than is incandescent light. Therefore, it is difficult to generalize the findings herein over the wide range of the entire cockpit luminance problem. However, even though the actual scope of this study was confined to a small population, certain recommendations can be made which could aid in defining the overall cockpit lighting criteria.

Research completed for this study indicates that EL light should not be selected for cockpit lighting based on its effect on dark adaptation alone. There may be many other reasons, i.e., power consumption, cost, life span, weight, etc., to select EL light, but its effect on dark adaptation and square wave grating resolution is no different than incandescent lighting.

With respect to the comfort portion of the test, additional research to control the dynamics of the experiment may resolve the differences found in this experiment. One suggestion for further study is to preset the luminance of the incandescent light source and have the subject adjust the EL source to match the luminance levels. In this manner the effect of the two different luminance curves and the relative positioning of the Variac could be eliminated as a cause of those differences.

An additional area for further research is the difference in comfort levels between pilots and navigators. Research into this area may provide verification of the differences found in this preliminary study. This effect may be of some importance in designing future aircraft cockpit lighting systems.

The substantial variability that exists between subjects is worthy of note even in this small sample size. Additional research is required to determine the extent and relevance of this variability as it applies to different light sources.

APPENDICES

APPENDIX A

DEFINITION OF SPATIAL FREQUENCY

SPATIAL FREQUENCY

A square wave grating is a repeated sequence of light and dark bars. The width of one light and one dark bar of a grating is one cycle or the period of the grating. The reciprocal of the period is the spatial frequency--the number of cycles of the grating that occur over a specified distance. The spatial frequency of an object can be expressed in cycles per degree (cpd) of visual angle. The square wave grating relates to an individual's visual acuity. For example, a square wave grating consisting of 80 cycles per inch equals 10 cycles per degree. Ten cycles per degree is equivalent to 3 minutes of arc or 20/60 vision.

APPENDIX B

EXPERIMENTAL PROCEDURE

EXPERIMENTAL PROCEDURE

Dark Adaptation of Rated Air Force Officers Using Electroluminescent versus Incandescent Light Sources

You are invited to participate in an experiment entitled, "Dark Adaptation of Rated Air Force Officers using Electroluminescent versus Incandescent Light Sources." We hope to study and measure any difference in these lighting systems.

If you decide to participate, you will be asked to take part in three phases of the experiment. The first phase will be standard dark adaptation measurements using the same type of device used in an ophthalmologist's office. You will be asked to sit in a dark room for about 30 minutes and asked to identify a striped slide as your eyes adapt to the dark.

The second phase will consist of spatial threshold measurements. You will be asked to view a slide under dark environment conditions. The slide will be retro-illuminated with the amount of light slowly increasing. You will be asked (a) when you see any luminance, and then (b) to identify the target on the slide. The light will then be decreased to the initial conditions and the measurements repeated.

In the third phase you will be asked to sit in front of a simulated cockpit panel and increase the lighting until you feel it to be at a comfortable working level, i.e., you can readily identify the information on the dials and gauges. You will then be measured for dark adaptation as before.

Your confidentiality as a participant in this program will be protected. Your name will not be revealed without your written permission. Statistical data collected during the test program may be published in scientific literature without identifying individual subjects. You will be asked to participate for one session that will last no more than 2 hours with approximately 30 minutes for initial dark adaptation. There will be about a 5 minute break each half hour.

You will receive no monetary benefits for participating in the study. No alternative exists to obtain the required information. Your decision to participate will not prejudice your future relations with the Air Force Aerospace Medical Research Laboratory. If you decide to participate, you are still free to withdraw your consent and to discontinue participation at any time without prejudice. If you have any questions, we expect you to ask us. If you have additional questions later, Dr. Lee Task, Lt. Col. Genco, or Capt. Blouin (255-6623) will be happy to answer them. Any medical questions will be referred to Dr. Wolf.

YOU WILL BE GIVEN A COPY OF THIS FORM TO KEEP.

__________ ____________________
Date VOLUNTEER'S INITIALS

APPENDIX C

CONSENT FORM

CONSENT FORM

Dark Adaptation of Rated Air Force Officers Using Electroluminescent versus Incandescent Light Sources

I, ______________________________, having full capacity to consent, do hereby volunteer to participate in a research study entitled, "Dark Adaptation of Rated Air Force Officers Using Electroluminescent versus Incandescent Light Sources" under the direction of Dr. Lee Task, Lt. Col. Lou Genco, and Capt. George K. Blouin. The implications of my voluntary participation, the nature, duration, and purpose, the methods and means by which it is to be conducted, and inconveniences and hazards which may reasonably be expected have been explained to me by ______________________________ and are set forth on the reverse side of this agreement, which I have initialed. I have been given the opportunity to ask questions concerning this research project, and any such questions have been answered to full and complete satisfaction. I understand that I may at any time during the course of this project revoke my consent, and withdraw from the project without prejudice.

I FULLY UNDERSTAND THAT I AM MAKING A DECISION WHETHER OR NOT TO PARTICIPATE. MY SIGNATURE INDICATES I HAVE DECIDED TO PARTICIPATE HAVING READ THE INFORMATION PROVIDED ABOVE.

AM
PM

____
Signature Date Time

I was present during the explanation referred to above, as well as the volunteer's opportunity for questions, and hereby witness the signature.

____
Signature Date

I have briefed the volunteer and answered questions concerning the research project.

____
Signature Date

APPENDIX D

DARK ADAPTATION CURVES

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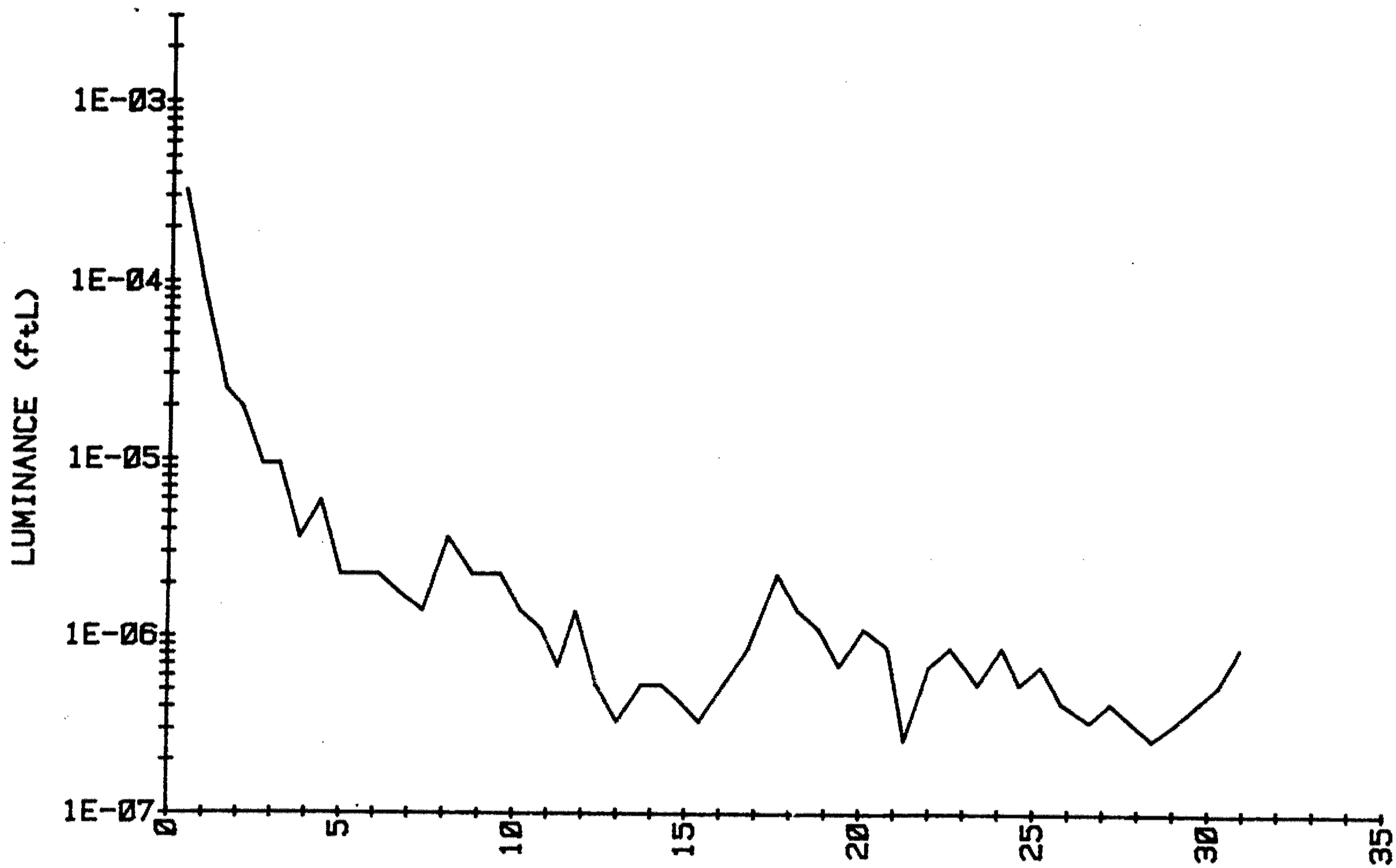
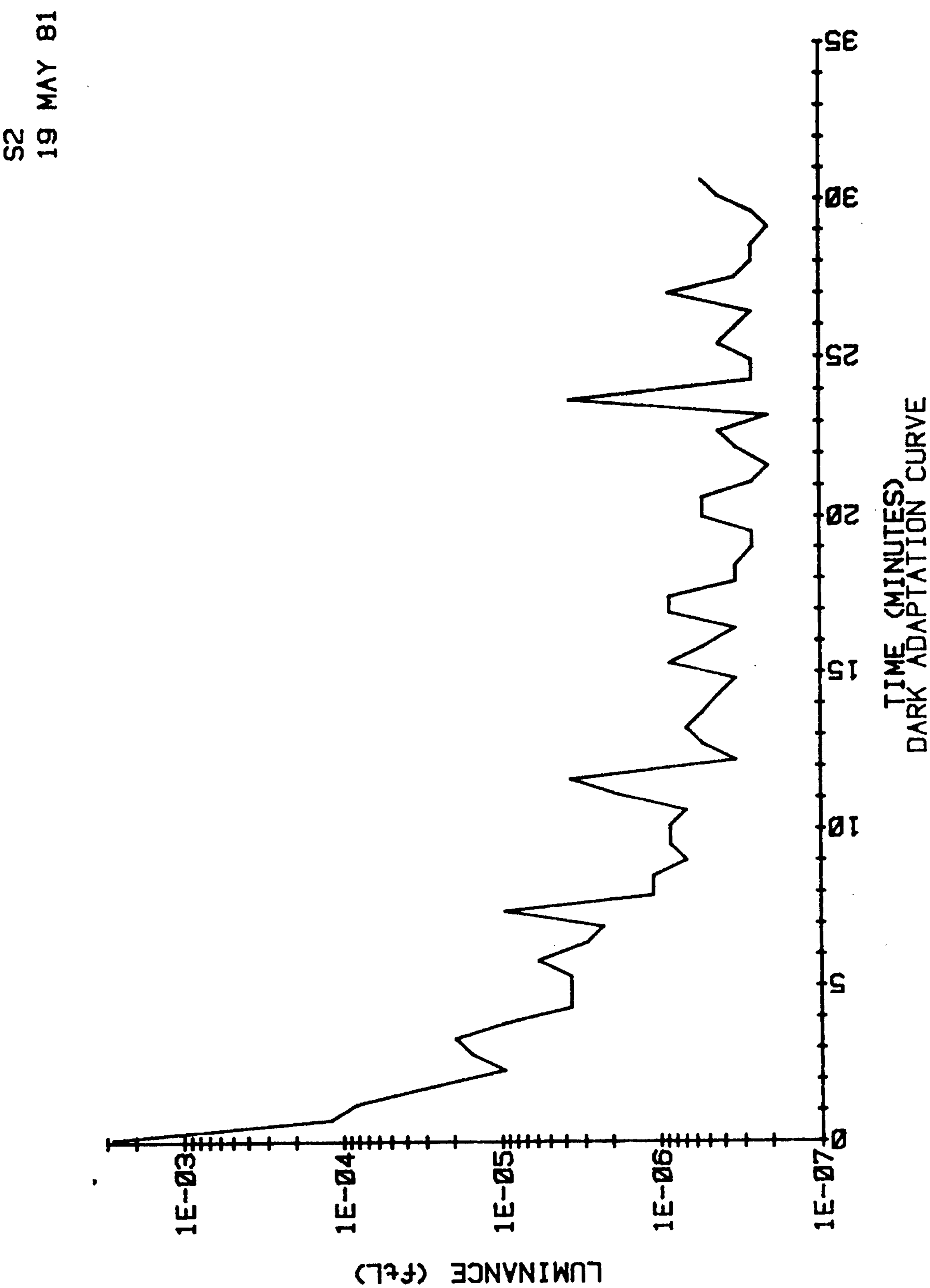


DARK ADAPTATION CURVE



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1E-04
1E-05
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1E-07
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10
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25
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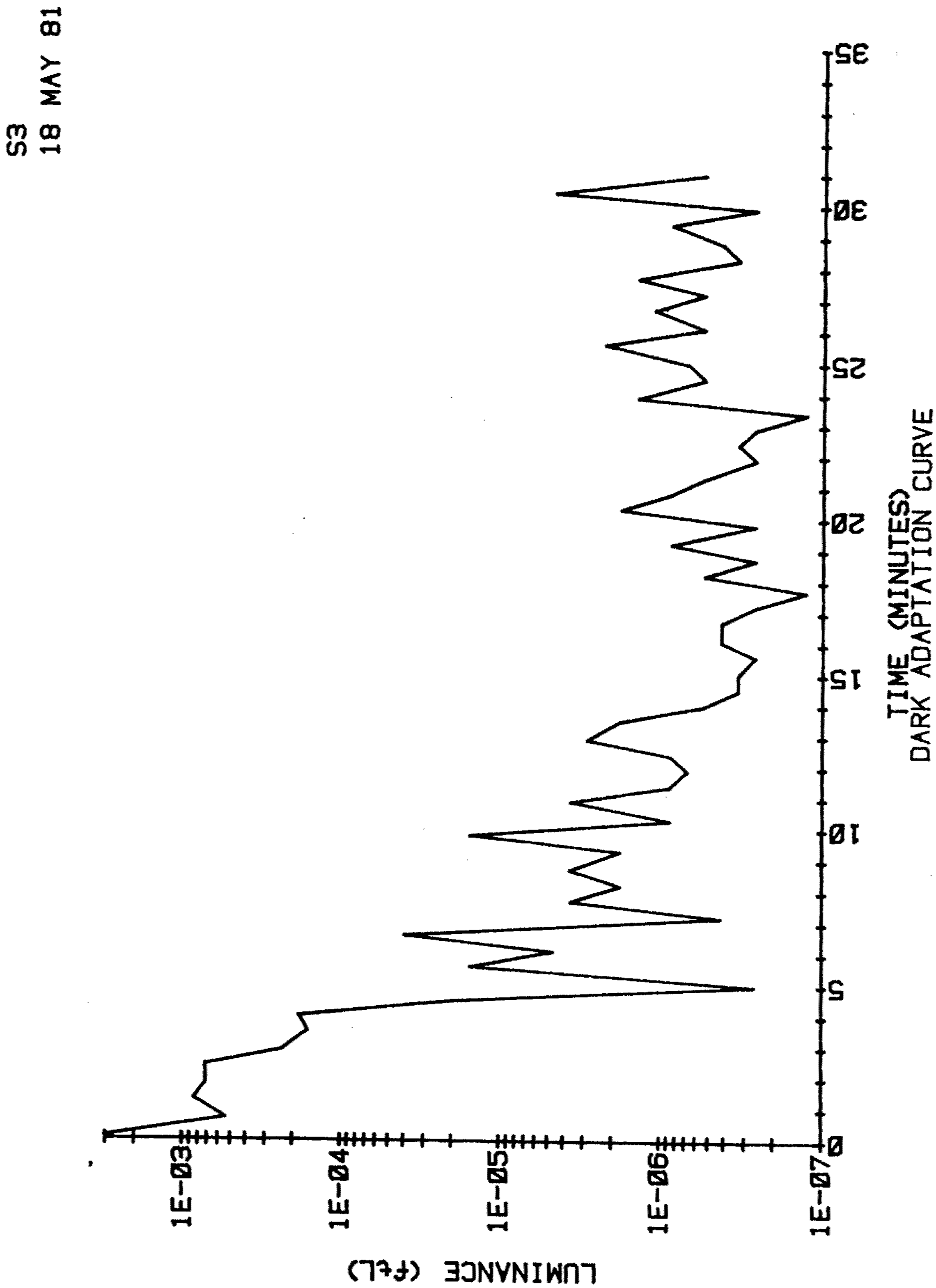
35
TIME (MINUTES)
DARK ADAPTATION CURVE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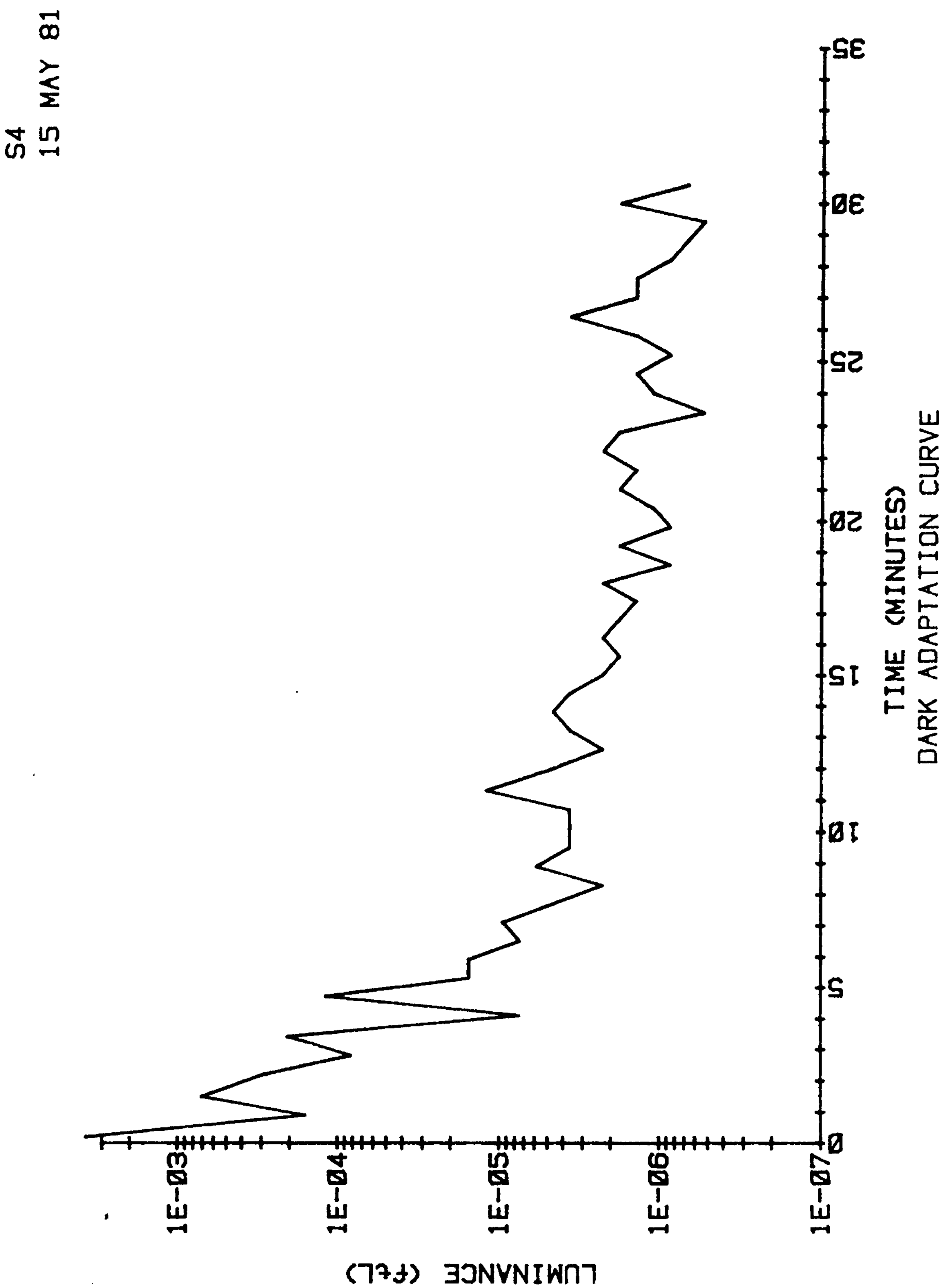
DARK ADAPTATION CURVE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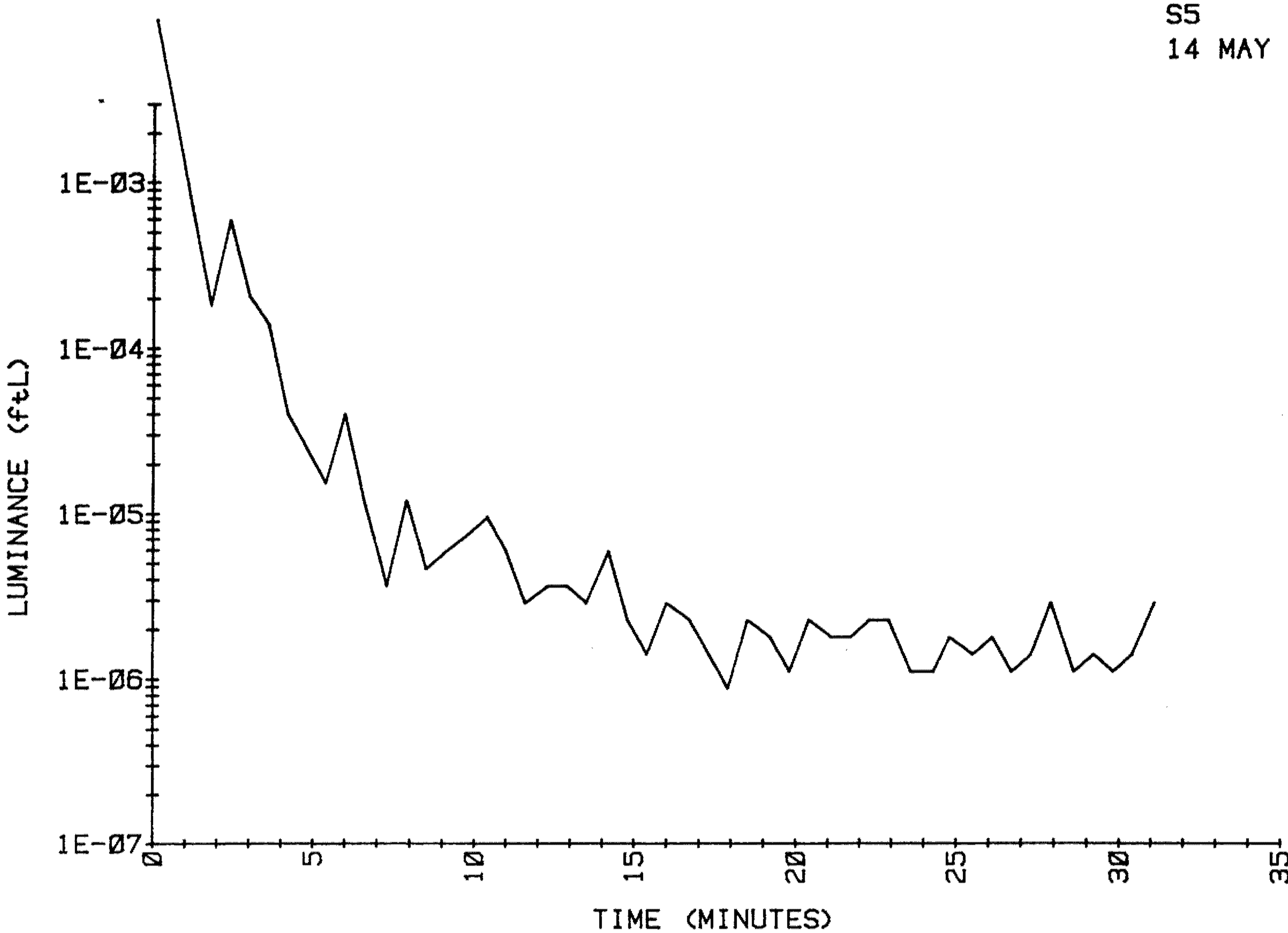
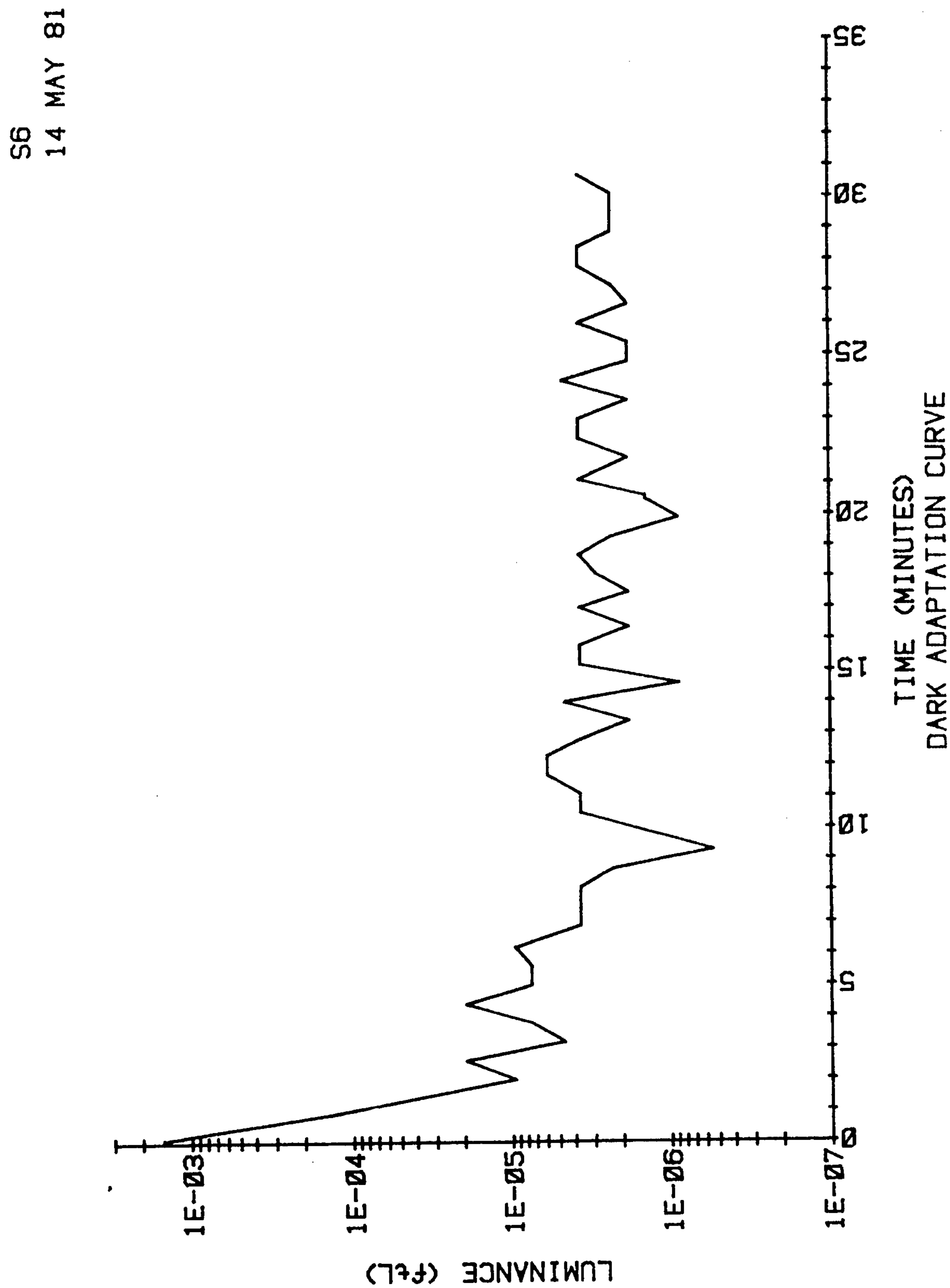
25
30
35
TIME (MINUTES)
DARK ADAPTATION CURVE

S5
14 MAY 81



DARK ADAPTATION CURVE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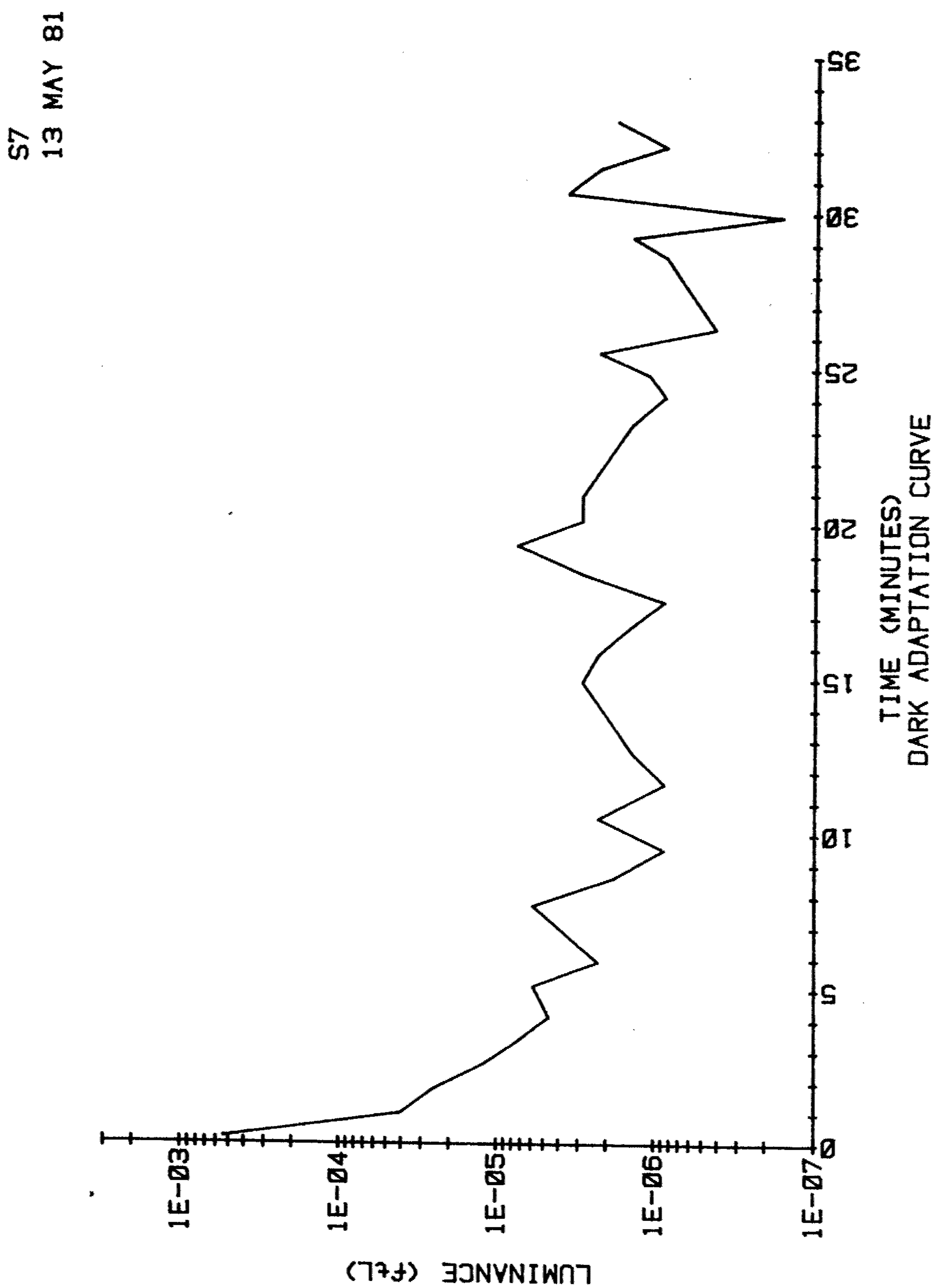
TIME (MINUTES)
DARK ADAPTATION CURVE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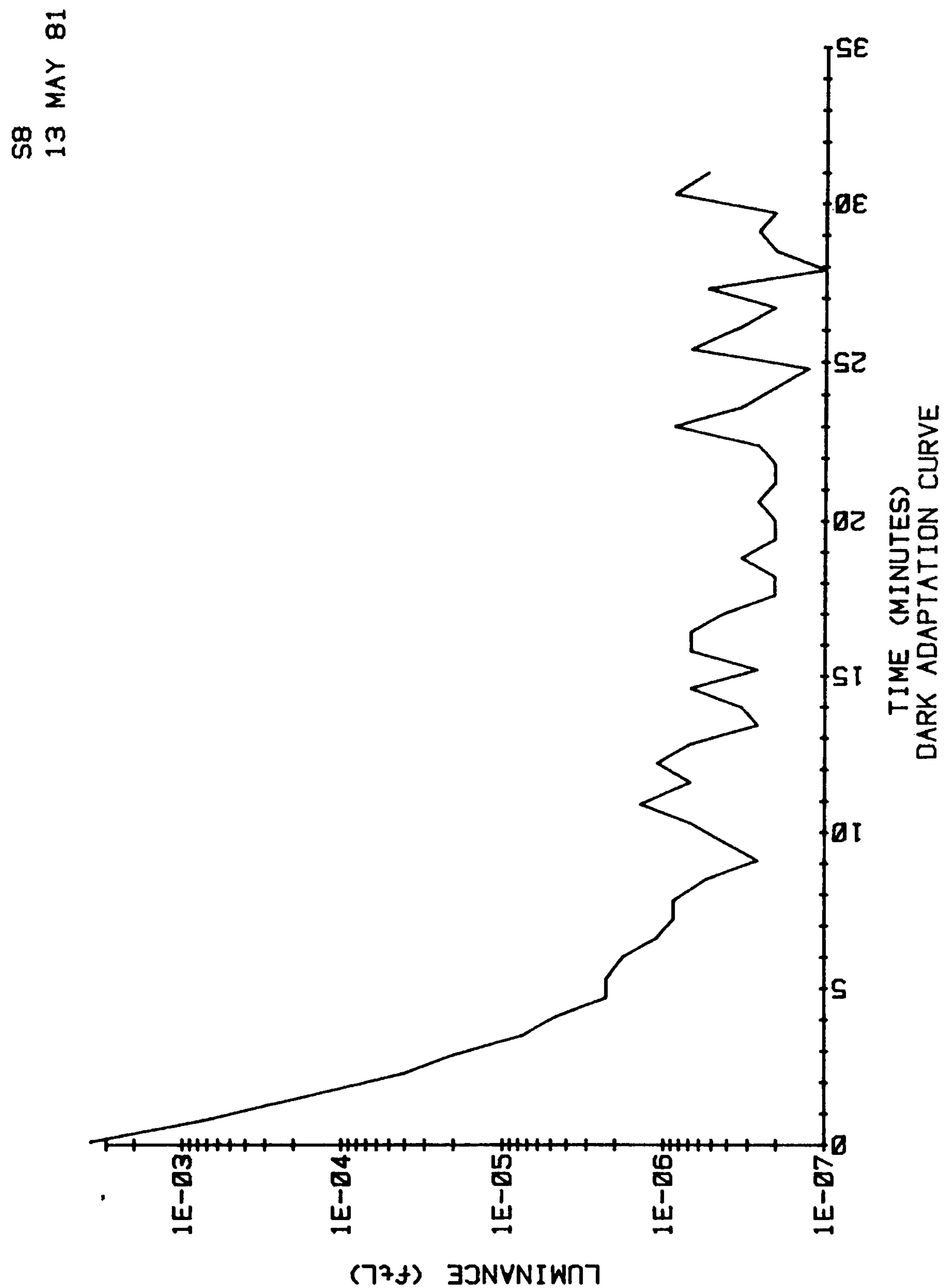
TIME (MINUTES)
DARK ADAPTATION CURVE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1E-Ø7
Ø
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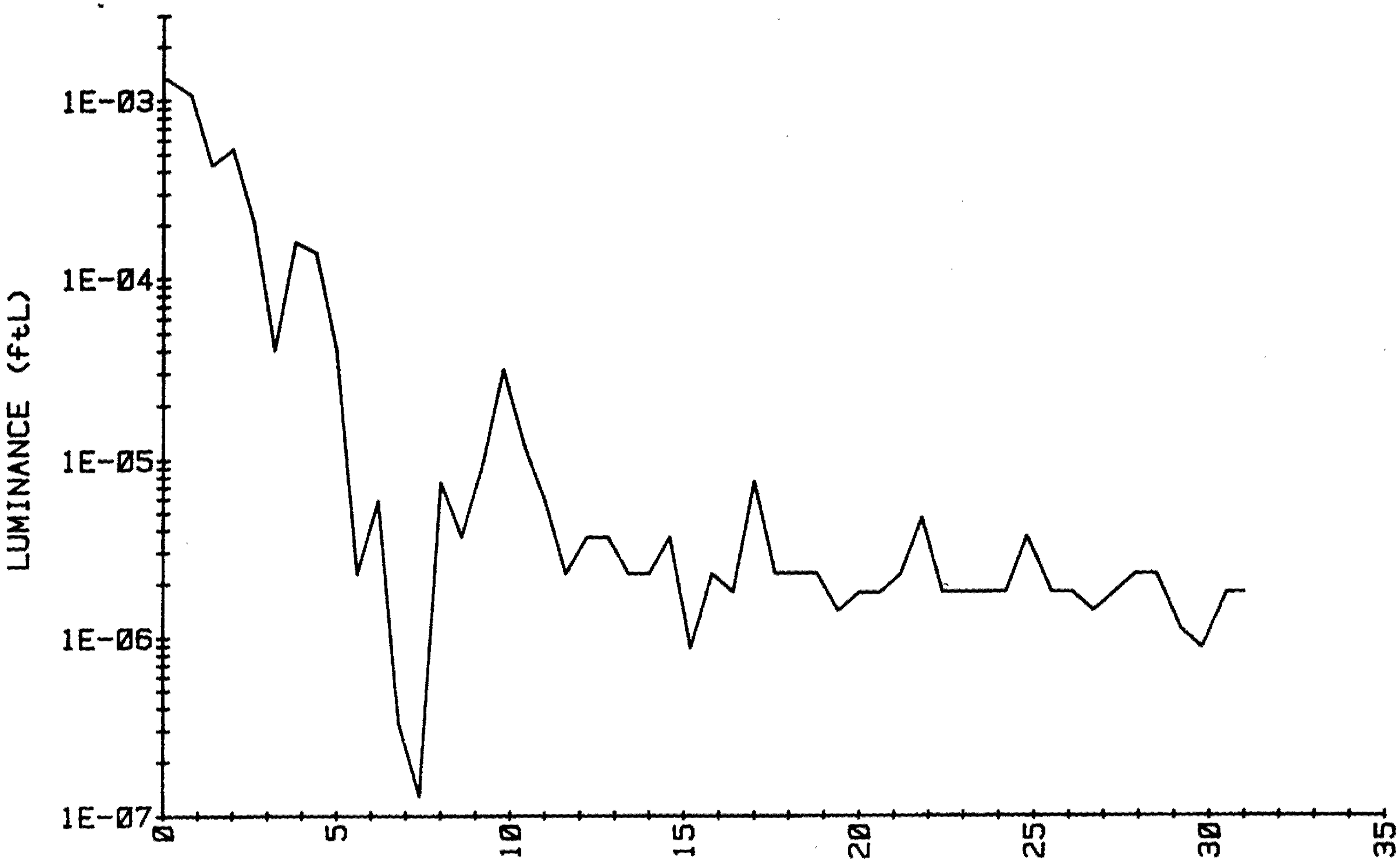
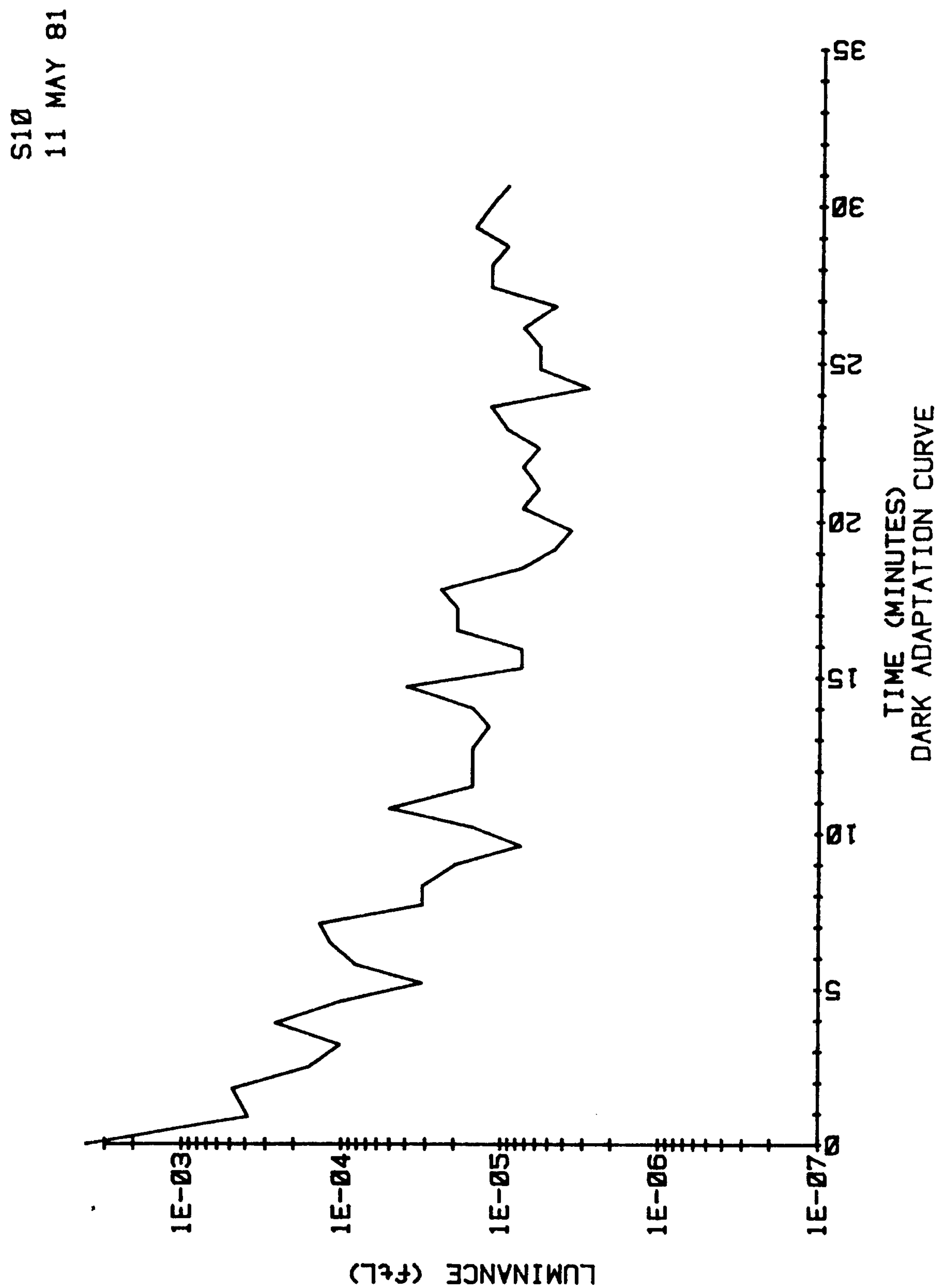
1Ø
15
2Ø
25
3Ø
35
TIME (MINUTES)
DARK ADAPTATION CURVE

S9
11 MAY 81

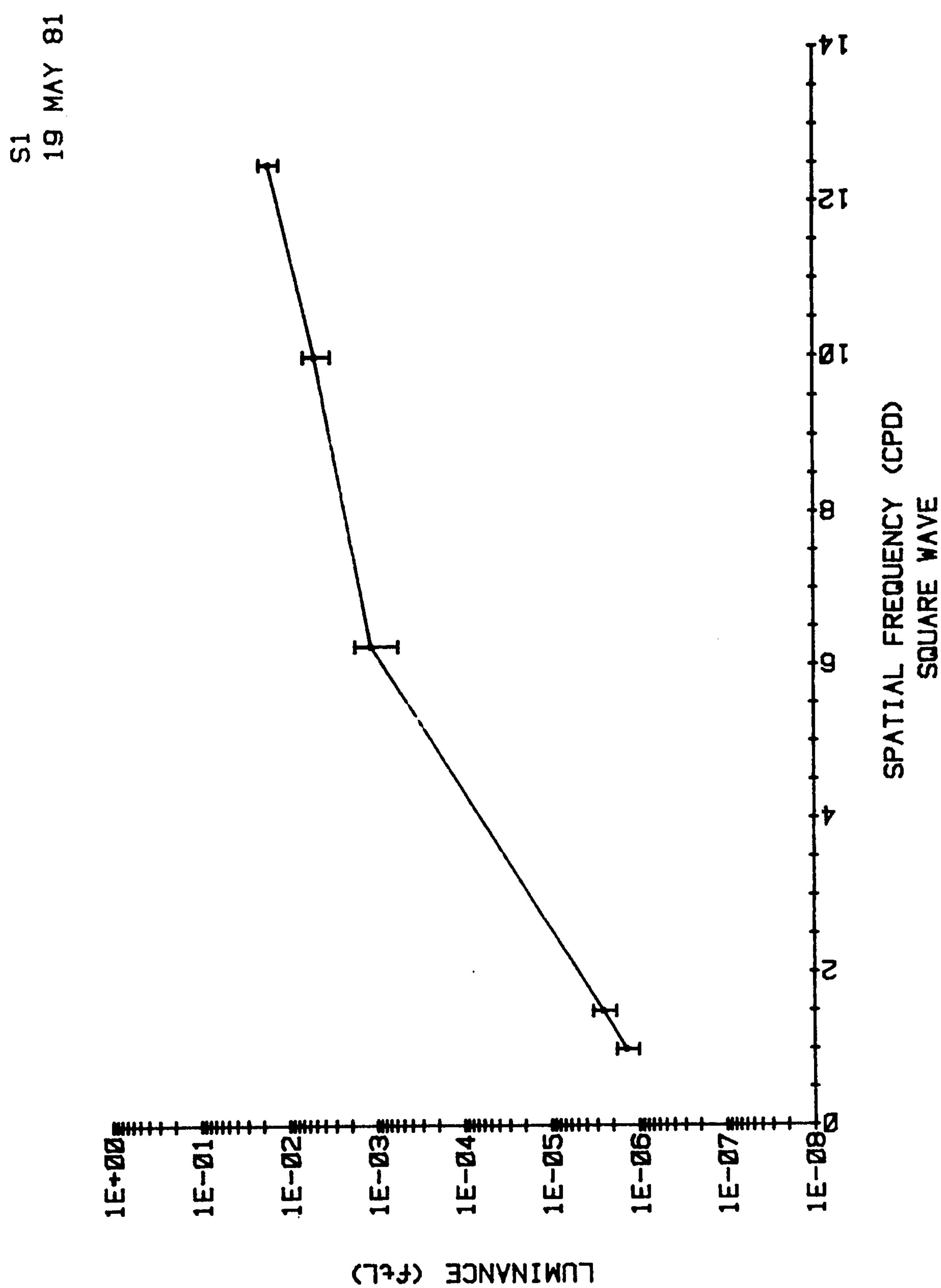


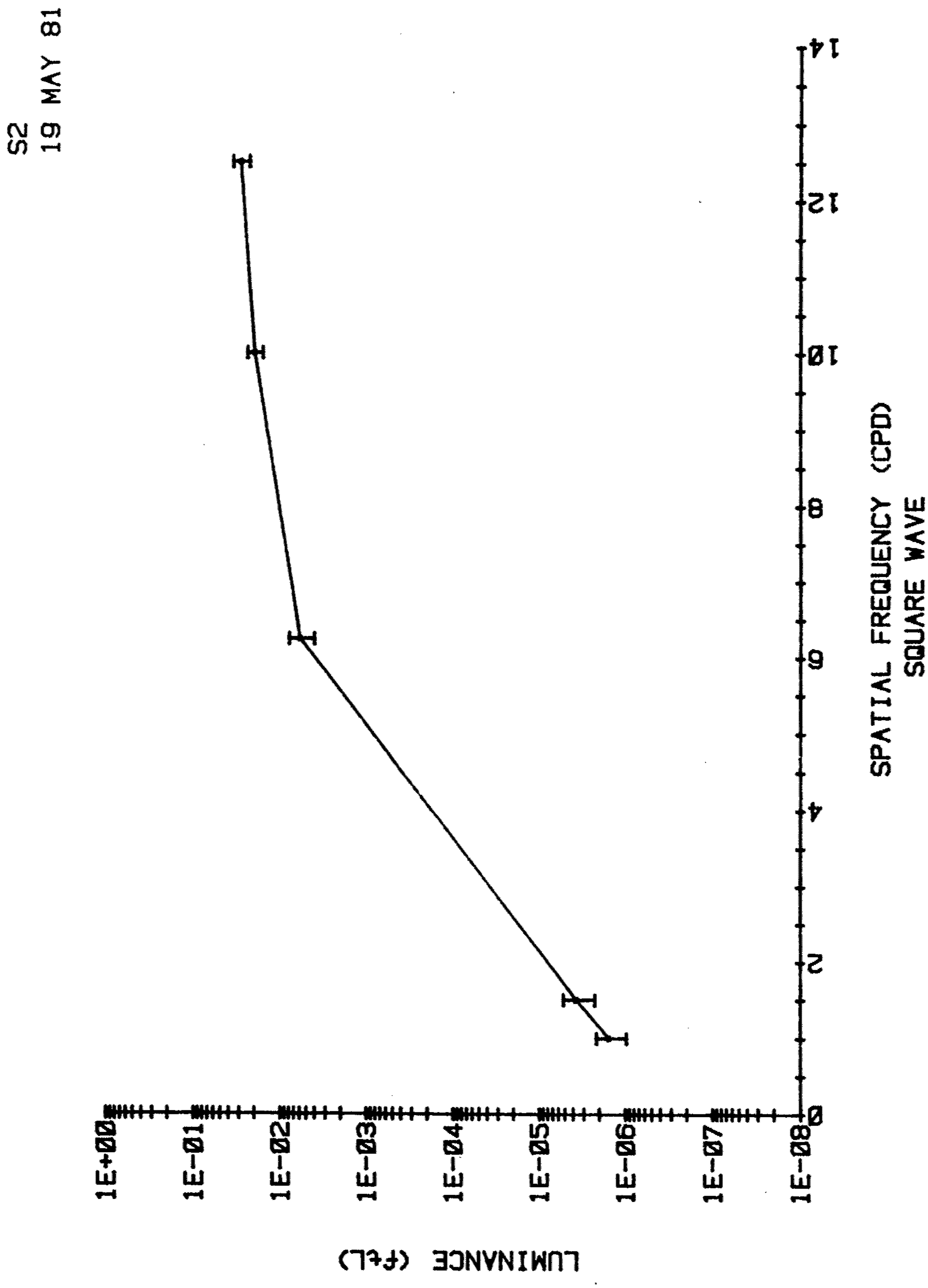
DARK ADAPTATION CURVE

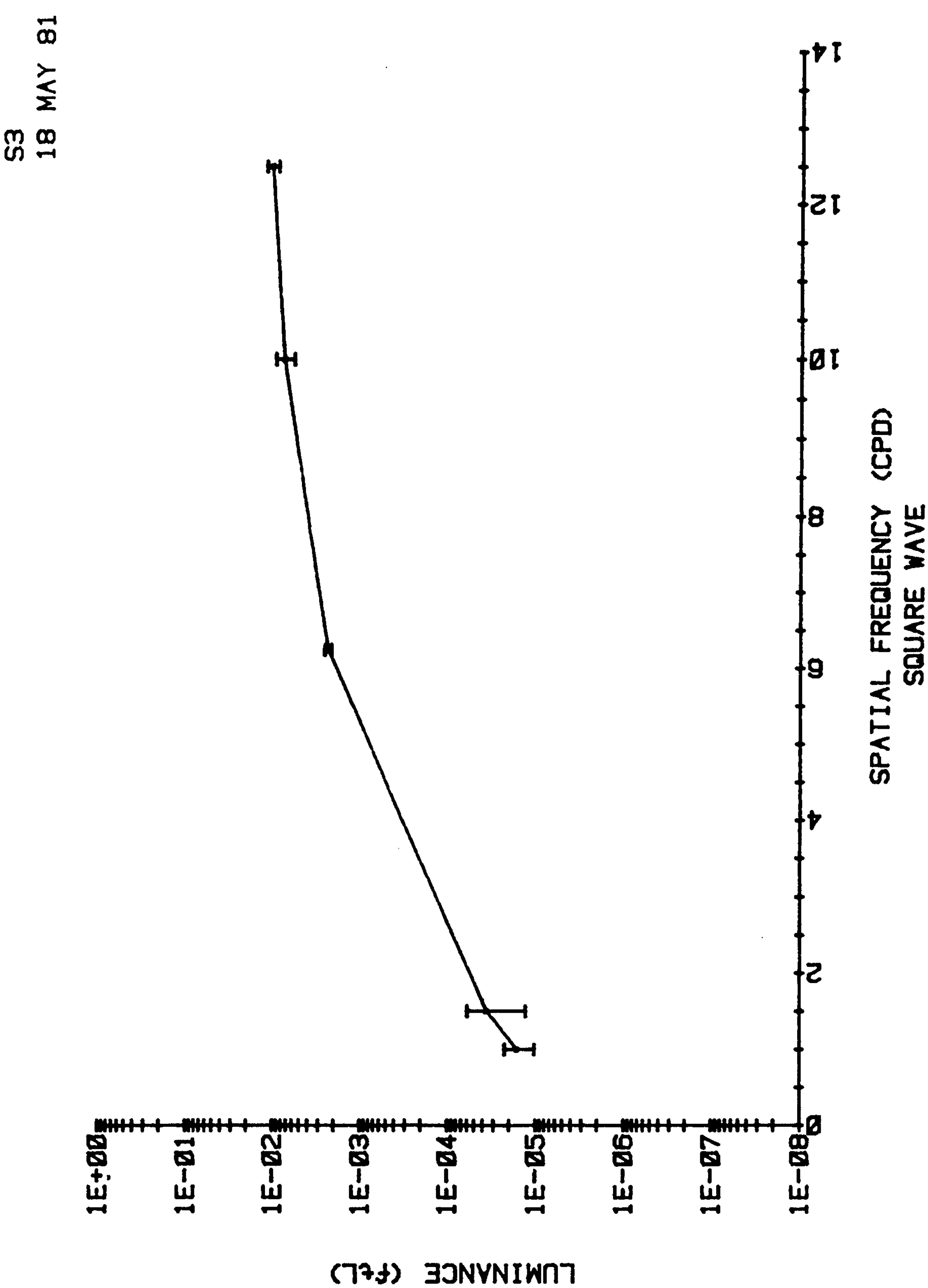

S1Ø
11 MAY 81
LUMINANCE
1E-Ø3
1E-Ø4
1E-Ø5
1E-Ø6
1E-Ø7
Ø
5
1Ø
15
2Ø
25
3Ø
35
TIME (MINUTES)
DARK ADAPTATION CURVE

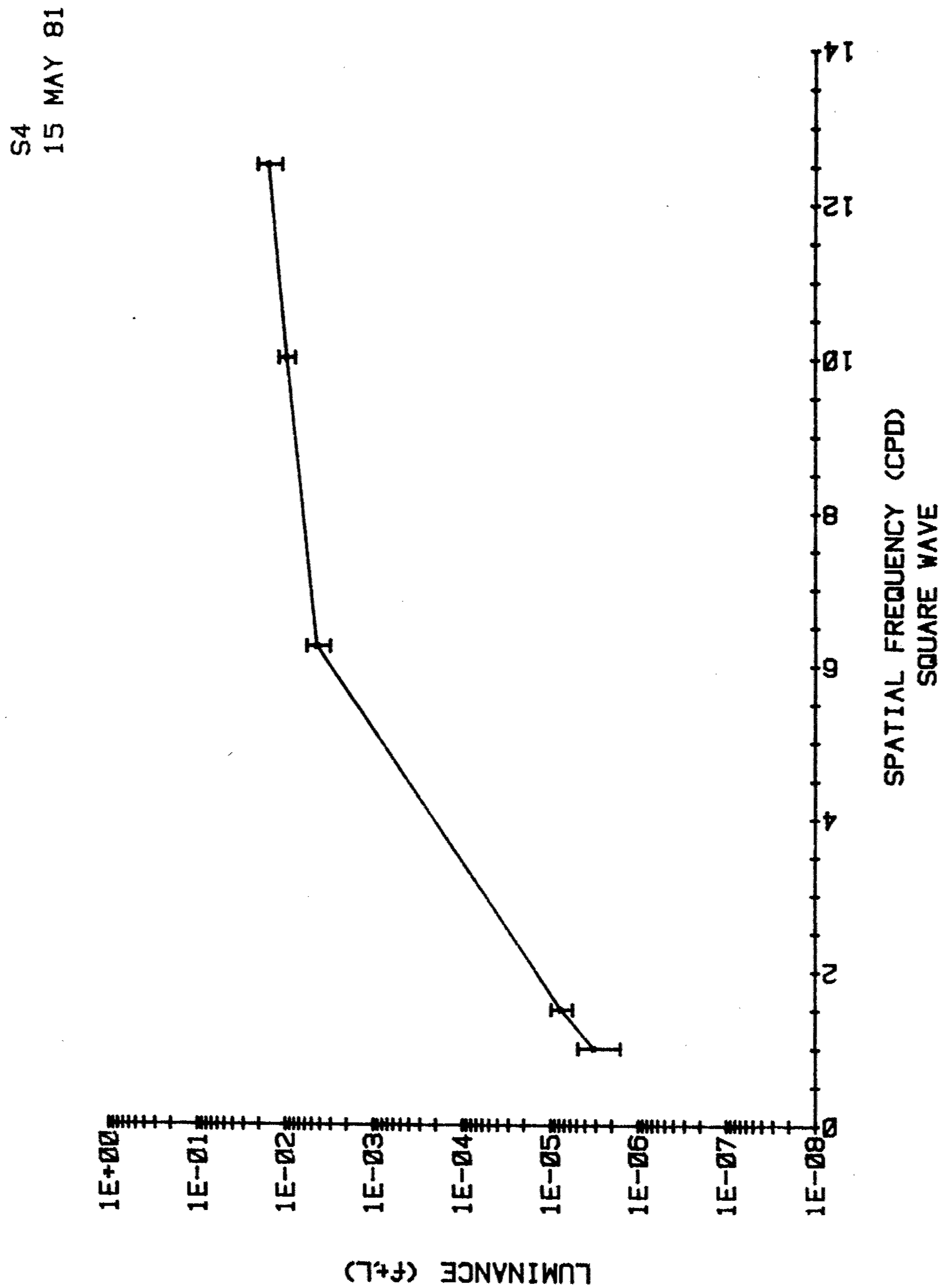
APPENDIX E

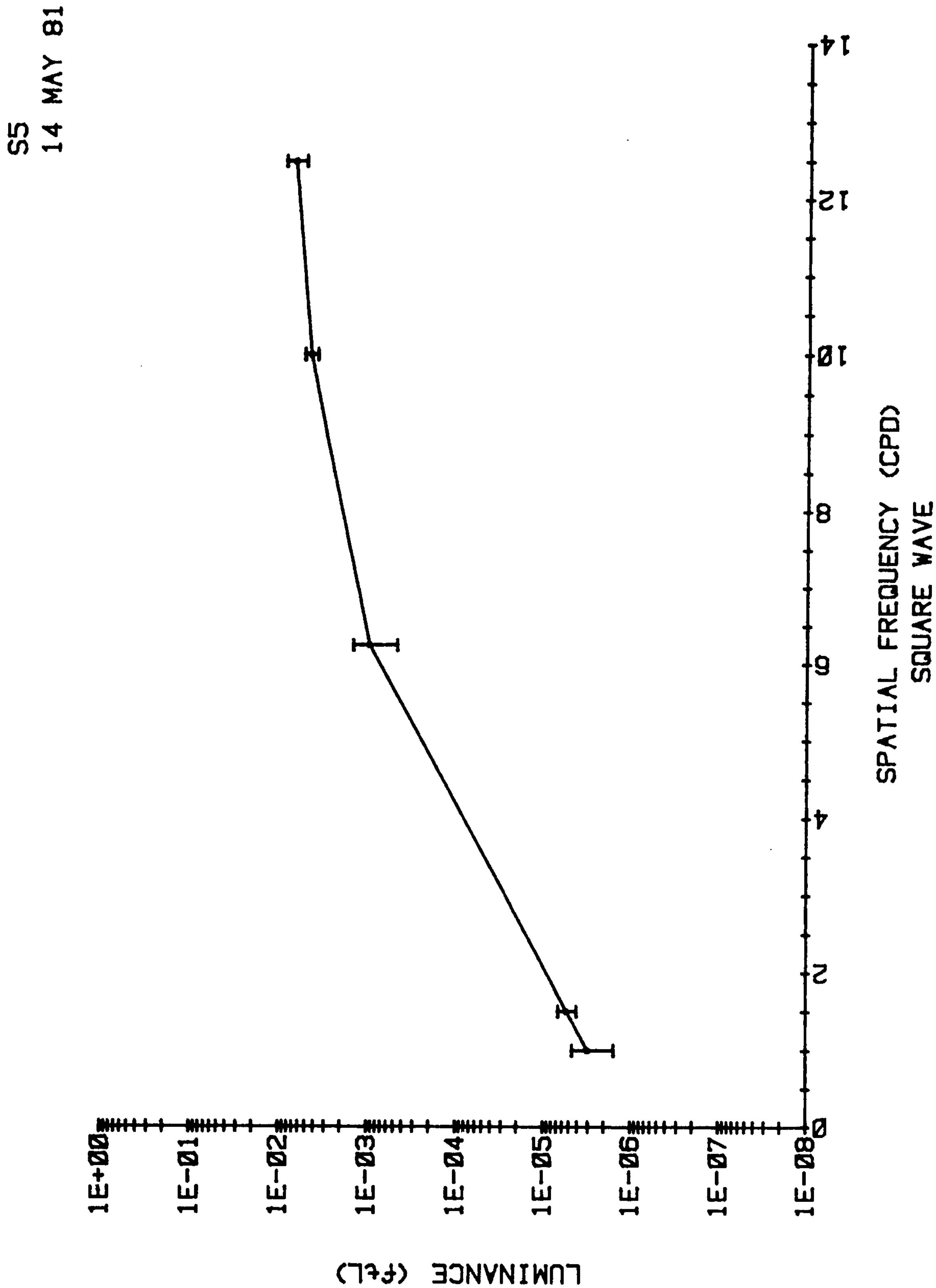
SQUARE WAVE SPATIAL FREQUENCY GRAPHS

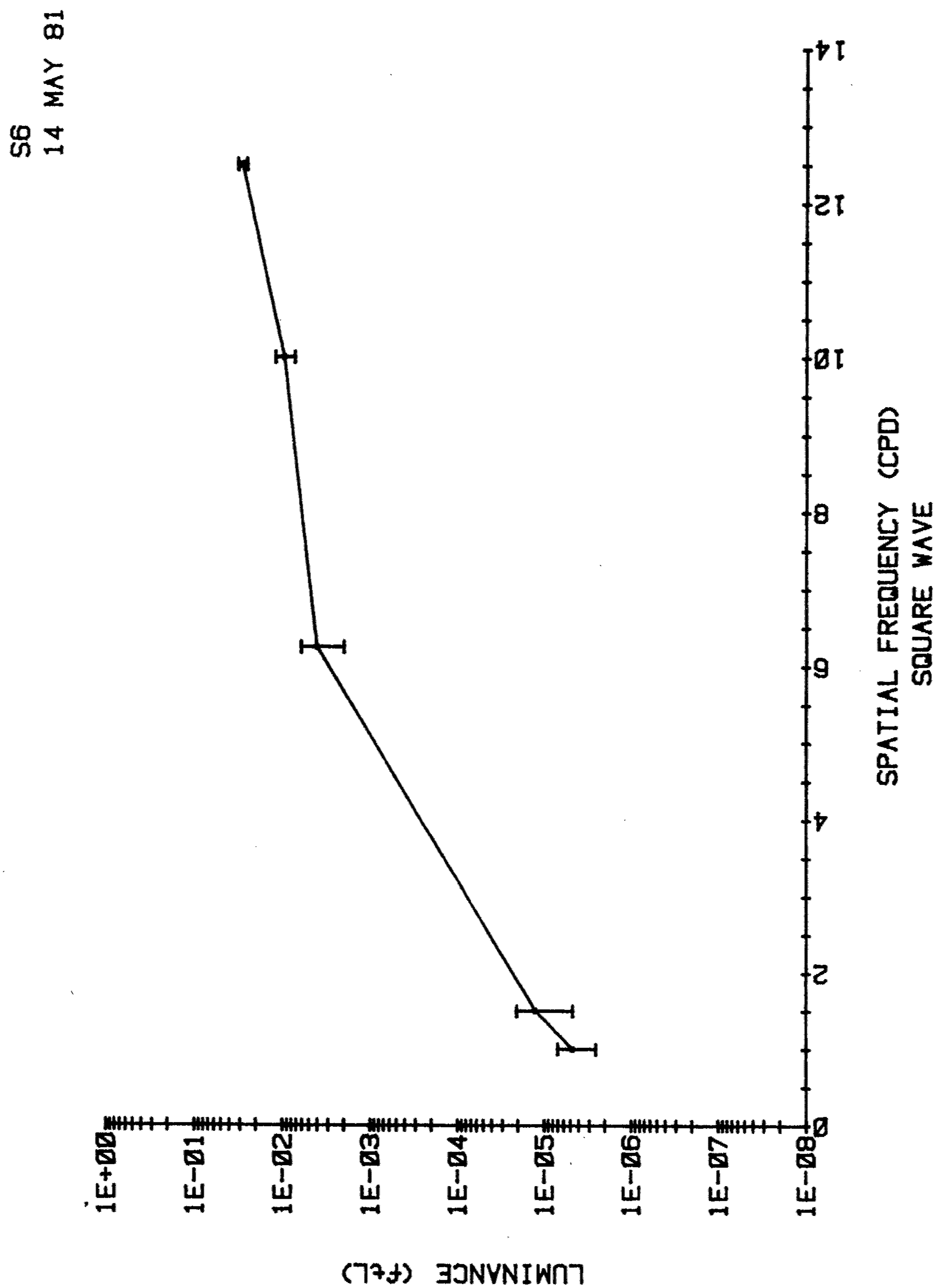

S1
19 MAY 81
LUMINANCE (ftL)
1E+00
1E-01
1E-02
1E-03
1E-04
1E-05
1E-06
1E-07
1E-08
0
2
4
6
8
10
12
14
SPATIAL FREQUENCY (CPD)
SQUARE WAVE

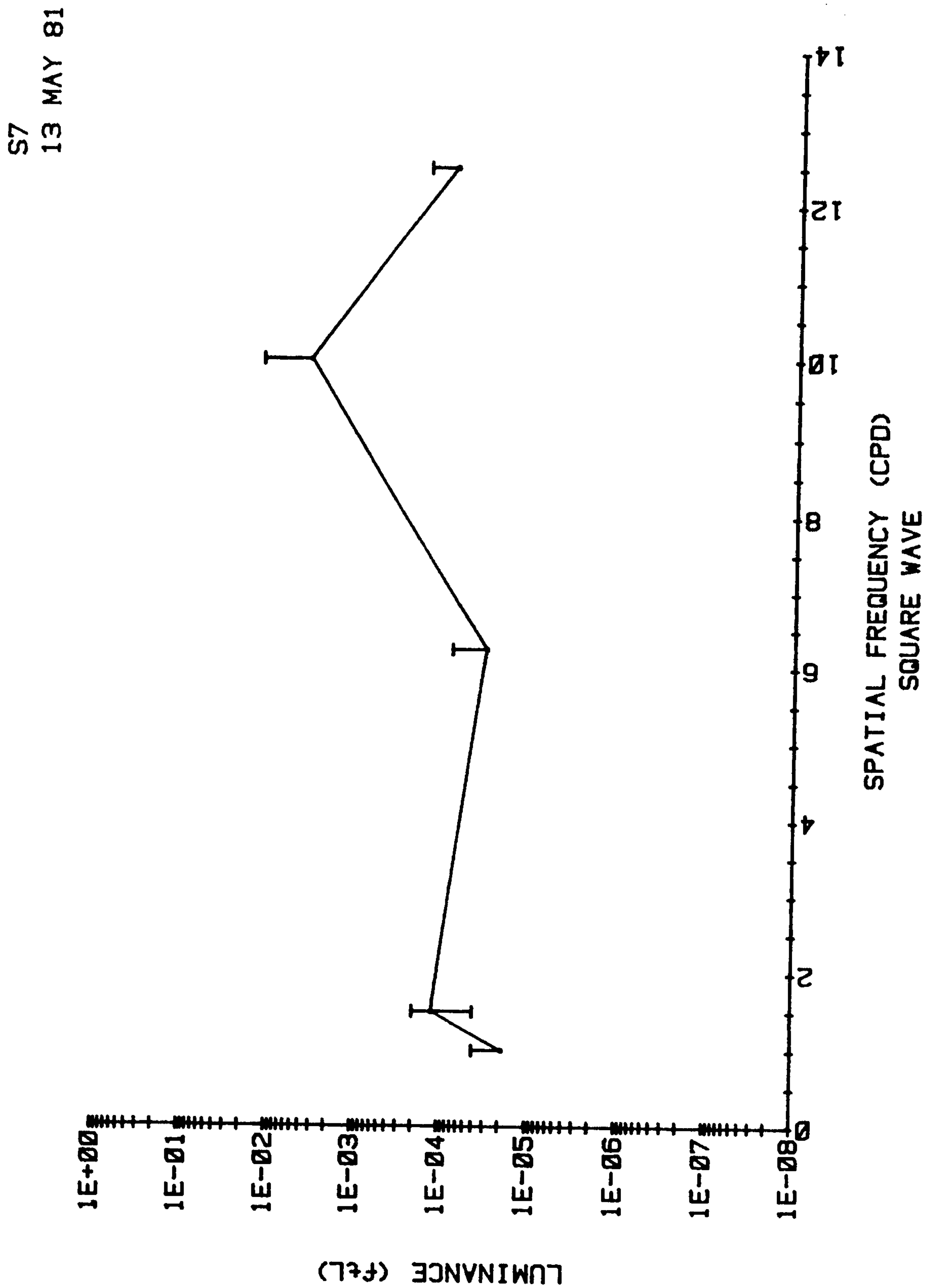

S2
19 MAY 81
LUMINANCE (ftL)
1E+00
1E-01
1E-02
1E-03
1E-04
1E-05
1E-06
1E-07
1E-08
0
2
4
6
8
10
12
14
SPATIAL FREQUENCY (CPD)
SQUARE WAVE

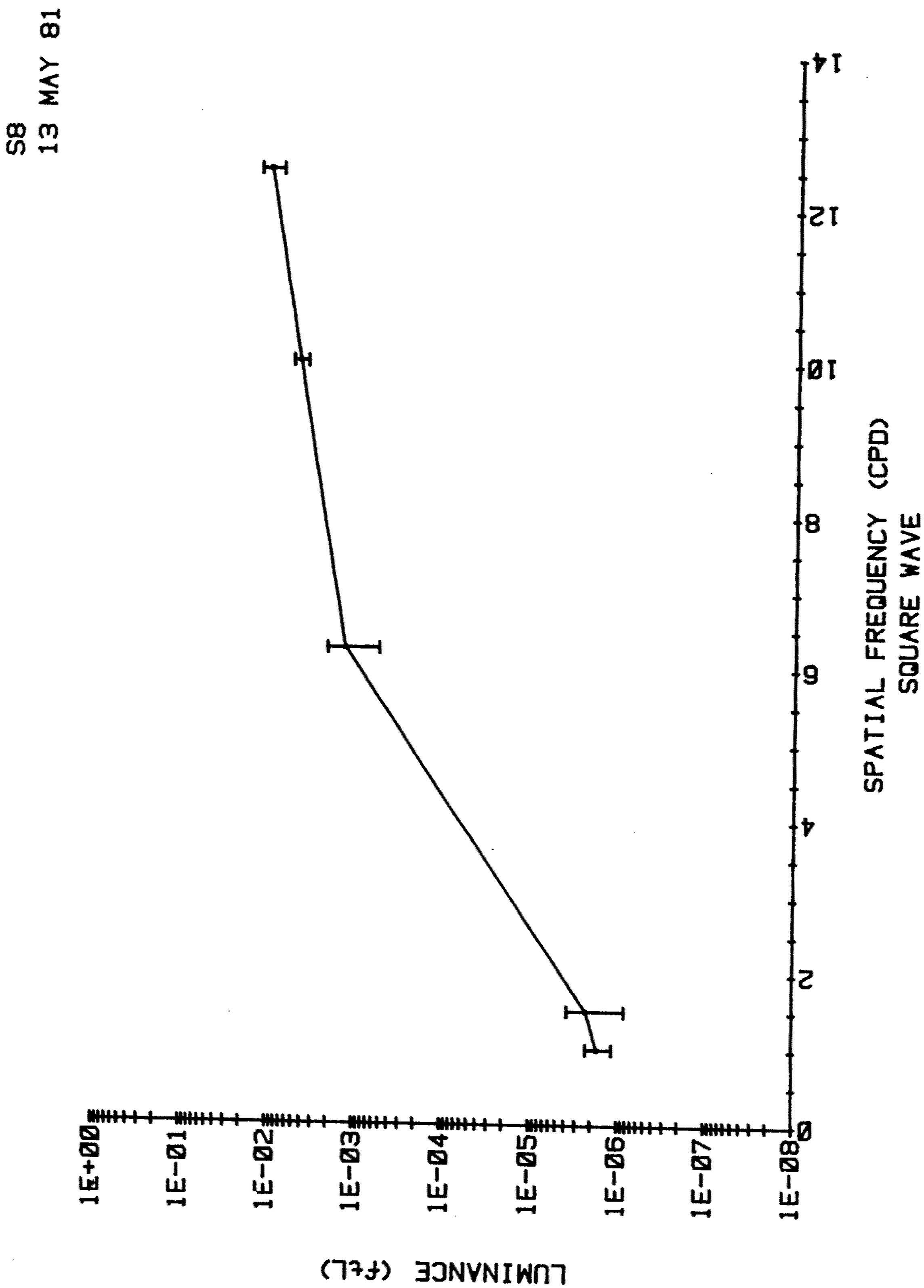

S3
18 MAY 81
LUMINANCE (ftL)
1E+00
1E-01
1E-02
1E-03
1E-04
1E-05
1E-06
1E-07
1E-08
0
2
4
6
8
10
12
14
SPATIAL FREQUENCY (CPD)
SQUARE WAVE


S4
15 MAY 81
LUMINANCE (f+L)
1E+ØØ
1E-Ø1
1E-Ø2
1E-Ø3
1E-Ø4
1E-Ø5
1E-Ø6
1E-Ø7
1E-Ø8
Ø
2
4
6
8
1Ø
12
14
SPATIAL FREQUENCY (CPD)
SQUARE WAVE

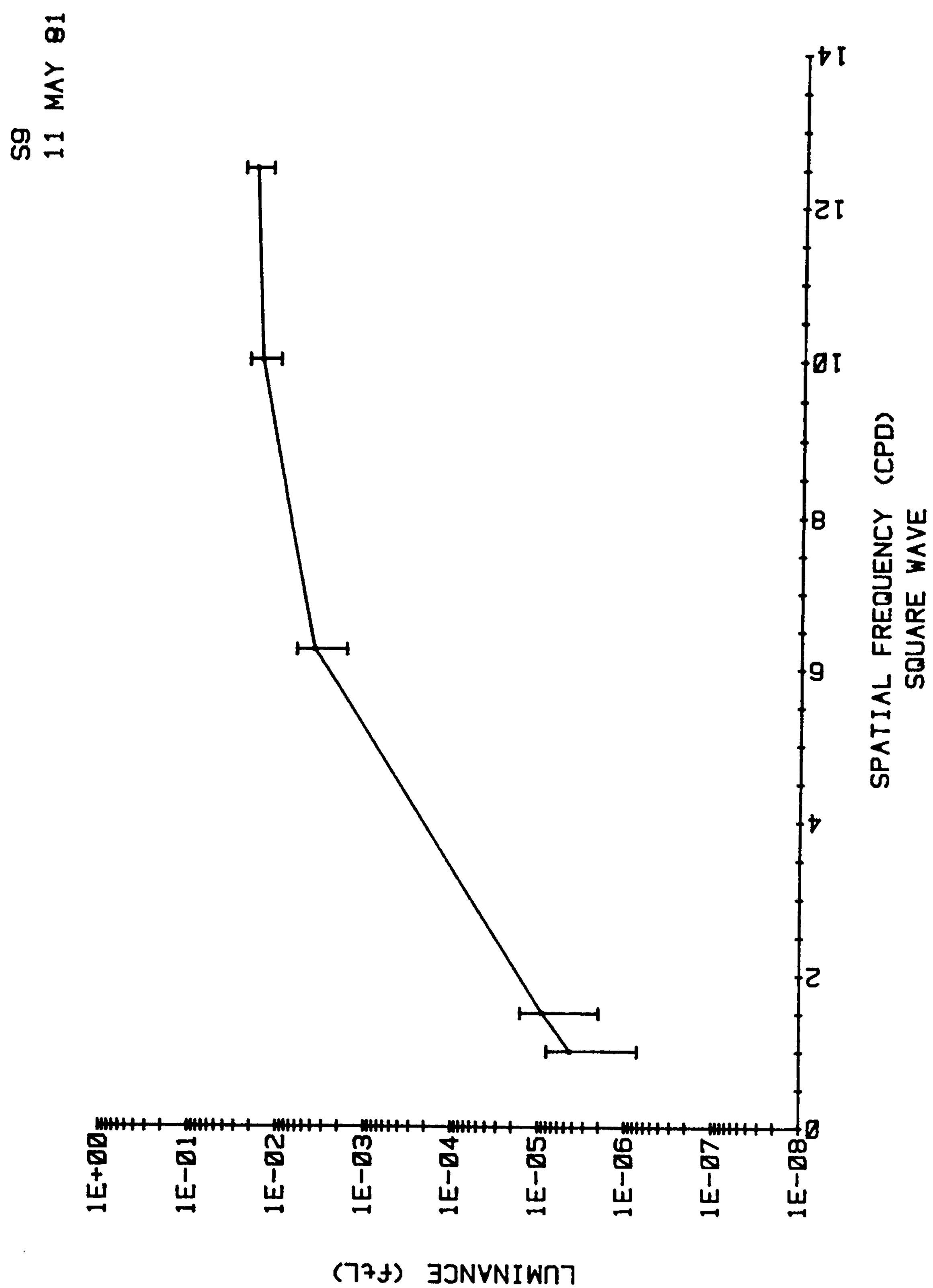

S5
14 MAY 81
LUMINANCE (ft-L)
1E+00
1E-01
1E-02
1E-03
1E-04
1E-05
1E-06
1E-07
1E-08
0
2
4
6
8
10
12
14
SPATIAL FREQUENCY (CPD)
SQUARE WAVE


S6
14 MAY 81
LUMINANCE (fL)
1E+00
1E-01
1E-02
1E-03
1E-04
1E-05
1E-06
1E-07
1E-08
0
2
4
6
8
10
12
14
SPATIAL FREQUENCY (CPD)
SQUARE WAVE

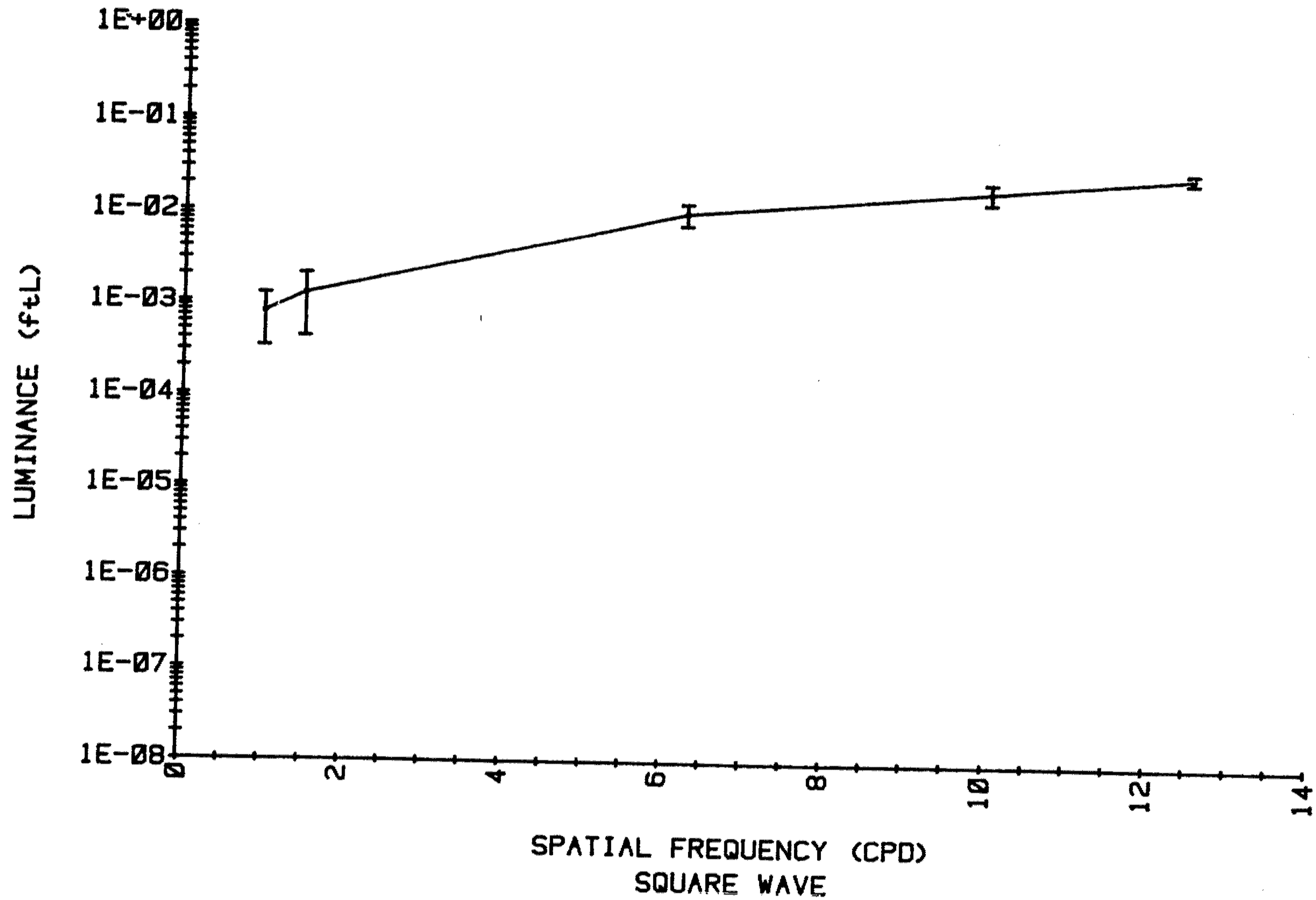

S7
13 MAY 81
SPATIAL FREQUENCY (CPD)
SQUARE WAVE
LUMINANCE (ftL)
1E+00
1E-01
1E-02
1E-03
1E-04
1E-05
1E-06
1E-07
1E-08
0
2
4
6
8
10
12
14



S8
13 MAY 81
LUMINANCE (f+L)
1E+00
1E-01
1E-02
1E-03
1E-04
1E-05
1E-06
1E-07
1E-08
0
2
4
6
8
10
12
14
SPATIAL FREQUENCY (CPD)
SQUARE WAVE


SG
11 MAY 81
1E+00
1E-01
1E-02
1E-03
1E-04
1E-05
1E-06
1E-07
1E-08
LUMINANCE (ftL)
0
2
4
6
8
10
12
14
SPATIAL FREQUENCY (CPD)
SQUARE WAVE

S1Ø
11 MAY 81



1E+ØØ
1E-Ø1
1E-Ø2
1E-Ø3
1E-Ø4
1E-Ø5
1E-Ø6
1E-Ø7
1E-Ø8
LUMINANCE (ftL)
Ø
2
4
6
8
1Ø
12
14
SPATIAL FREQUENCY (CPD)
SQUARE WAVE

APPENDIX F

TASK 3
RESPONSE DATA

ABSOLUTE THRESHOLD

10 cpd

Subject	Pretreatment		Posttreatment			
			EL		INC	
	$\bar{X}$	SD	$\bar{X}$	SD	$\bar{X}$	SD
1	5.323	4.340	3.33	2.62	2.94	2.84
2	21.30	55.56	87.75	57.39	70.42	90.53
3	74.99	109.40	50.0	46.99	28.66	15.33
4	4.793	3.203	19.67	20.10	21.69	16.11
5	2.793	1.434	18.96	14.38	22.08	14.06
6	2.851	1.396	380.75	434.03	417.12	546.43
7	192.1	524.8	8.04	7.73	6.99	2.97
8	0.7288	0.1199	4.59	4.66	7.07	13.27
9	2.023	0.9256	6.69	1.11	6.77	2.72
10	9.743	9.471	24.0	13.06	47.90	43.08
$\bar{\bar{X}}$	31.67		60.38		63.16	
SD	60.66		115.56		126.17	

NOTE: All values are in 10^{-6} ftL. Subjects 6 and 7 data not included in statistical analysis.

GRATING RESOLUTION THRESHOLD

10 cpd

Subject	Pretreatment		Posttreatment			
			EL		INC	
	$\bar{X}$	SD	$\bar{X}$	SD	$\bar{X}$	SD
1	4.92	1.68	4.11	1.95	3.86	1.51
2	19.16	3.83	13.87	3.84	13.96	2.41
3	7.47	1.78	7.67	4.47	5.38	3.62
4	9.53	2.03	10.94	2.63	9.56	2.79
5	4.52	0.77	5.73	0.91	4.77	1.37
6	9.47	2.40	14.08	2.74	12.44	4.03
7	3.51	9.11	0.25	0.47	0.26	0.32
8	4.66	0.90	4.19	1.39	3.72	0.70
9	16.14	6.27	9.09	3.51	8.84	3.21
10	17.99	4.51	26.38	4.03	27.29	5.76
$\bar{\bar{X}}$	9.74		9.63		9.01	
SD	5.95		7.36		7.70	

NOTE: All values are in 10^{-3} ftL. Subjects 7's data not included in statistical analysis.

APPENDIX G

TASK 4
COMFORT DATA

COMFORT TEST

Subject		EL		INC	
		$\bar{X}$	SD	$\bar{X}$	SD
1		20.56	0.0	34.82	0.703
2		6.17	2.59	14.32	9.62
3		19.05	0.130	24.12	0.726
4		17.70	3.69	20.68	6.35
5		3.13	1.51	4.47	2.99
6		16.16	2.26	24.45	8.02
7		5.33	2.96	5.80	3.49
8		0.6265	0.230	0.8093	0.274
9		0.4335	0.153	0.4399	0.188
10		17.35	2.58	25.47	2.46
	$\bar{\bar{X}}$	10.65		15.54	
	SD	8.19		12.08	

NOTE: All values are in 10^{-3} ftL.
Subject 7's data not included in the statistical analysis.

APPENDIX H

SUMMARY OF ANOVA TABLES

ONE-WAY ANOVAS WITH REPEATED MEASURES

Absolute Threshold

Source of Variation	Degrees of Freedom	Sums of Squares	Mean Square	F-Ratio	Significance Level
Absolute Threshold Condition	2	670.850	335.43	1.192	0.3585
Subjects	7	10020.707	--	--	--
Condition x Subjects	14	3940.765	281.48	--	--
Total	23	14632.322	--	--	--

ONE-WAY ANOVAS WITH REPEATED MEASURES

Grating Resolution

Source of Variation	Degrees of Freedom	Sums of Squares	Mean Square	F-Ratio	Significance Level
Grating Threshold Condition	2	58.781	29.39	2.131	0.1812
Subjects	8	391.362	--	--	--
Condition x Subjects	16	220.706	13.79	--	--
Total	26	670.849	--	--	--

ONE-WAY ANOVAS WITH REPEATED MEASURES

Comfort Condition

Source of Variation	Degrees of Freedom	Sums of Squares	Mean Square	F-Ratio	Significance Level
Comfort	1	130.138	130.14	11.531	0.0094
Subjects	8	1690.04	--	--	--
Condition x Subjects	8	90.284	11.29	--	--
Total	17	1910.462	--	--	--

APPENDIX I

ABSOLUTE THRESHOLD
ANOVA TABLES

CARNEGIE MELLON UNIVERSITY ANOVA PROGRAM

by

William A. Leaf

ABSOLUTE THRESHOLD 10 CPD

FORMAT = (3F5.2)

LEVELS OF FACTORS: 0 0 0 0 3 0 0 0

MAX OBS/CELL: 8 UNEQUAL N SWITCH: 0
PRINT MEANS SWITCH: 1 PRINT DATA SWITCH: 0

SUMS OF SQUARES

22.679

GRAND MEAN

15.221
26.874
25.941

J
SUM OF SQUARES = 670.850

*S
SUM OF SQUARES = 10020.707

J *S
SUM OF SQUARES = 3940.765

ERROR TERMS

	SUMS OF SQUARES	MEAN SQUARE	DF
1	10029.71	1431.53	7
2	3940.76	281.48	14

SOURCES OF VARIANCE	SUMS OF SQUARES	MEAN SQUARES
J	670.85	335.43

DF	ERROR	F- RATIOS
2	2	1.192

TOTAL SUM OF SQUARES = 14632.321

CARNEGIE MELLON UNIVERSITY ANOVA PROGRAM

by

William A. Leaf

ABSOLUTE THRESHOLD 10 CPD, BEFORE VS AFTER INC

FORMAT = (2F5.2)

LEVELS OF FACTORS: 0 0 0 0 2 0 0 0

MAX OBS/CELL: 8 UNEQUAL N SWITCH: 0
PRINT MEANS SWITCH: 1 PRINT DATA SWITCH: 0

SUMS OF SQUARES

20.581

GRAND MEAN

15.221
25.941

J
SUM OF SQUARES = 459.674

*S
SUM OF SQUARES = 5232.998

J *S
SUM OF SQUARES = 2906.692

ERROR TERMS

	SUMS OF SQUARES	MEAN SQUARE	DF
1	5233.00	747.57	7
2	2906.69	415.24	7

SOURCES OF VARIANCE	SUMS OF SQUARES	MEAN SQUARES
J	459.67	459.67

DF	ERROR	F- RATIOS
1	2	1.107

TOTAL SUM OF SQUARES = 8599.364

CARNEGIE MELLON UNIVERSITY ANOVA PROGRAM

by

William A. Leaf

ABSOLUTE THRESHOLD 10 CPD, BEFORE VS AFTER EL

FORMAT = (2F5.2)

LEVELS OF FACTORS: 0 0 0 0 2 0 0 0

MAX OBS/CELL: 8 UNEQUAL N SWITCH: 0
PRINT MEANS SWITCH: 1 PRINT DATA SWITCH: 0

SUMS OF SQUARES

21.047

GRAND MEAN

15.221
26.874

J
SUM OF SQUARES = 543.123

*S
SUM OF SQUARES = 7873.429

J *S
SUM OF SQUARES = 2334.401

ERROR TERMS

	SUMS OF SQUARES	MEAN SQUARE	DF
1	7873.43	1124.78	7
2	2334.40	333.49	7

SOURCES OF VARIANCE	SUMS OF SQUARES	MEAN SQUARES
J	543.12	543.12

DF	ERROR	F- RATIOS
1	2	1.629

TOTAL SUM OF SQUARES = 10750.953

CARNEGIE MELLON UNIVERSITY ANOVA PROGRAM

by

William A. Leaf

ABSOLUTE THRESHOLD 10 CPD, EL VS INC

FORMAT = (2F5.2)

LEVELS OF FACTORS: 0 0 0 0 2 0 0 0

MAX OBS/CELL: 8 UNEQUAL N SWITCH: 0
PRINT MEANS SWITCH: 1 PRINT DATA SWITCH: 0

SUMS OF SQUARES

26.407

GRAND MEAN

26.874
25.941

J
SUM OF SQUARES = 3.478

*S
SUM OF SQUARES = 8905.366

J *S
SUM OF SQUARES = 670.051

ERROR TERMS

	SUMS OF SQUARES	MEAN SQUARE	DF
1	8905.37	1272.20	7
2	670.05	95.72	7

SOURCES OF VARIANCE	SUMS OF SQUARES	MEAN SQUARES
J	3.48	3.48

DF	ERROR	F- RATIOS
1	2	.036

TOTAL SUM OF SQUARES = 9578.896

APPENDIX J

GRATING RESOLUTION
ANOVA TABLES

CARNEGIE MELLON UNIVERSITY ANOVA PROGRAM

by

William A. Leaf

GRATING THRESHOLD 10 CPD

FORMAT = (3F5.3)

LEVELS OF FACTORS: 0 0 0 0 3 0 0 0

MAX OBS/CELL: 9 UNEQUAL N SWITCH: 0
PRINT MEANS SWITCH: 1 PRINT DATA SWITCH: 0

SUMS OF SQUARES

8.394

GRAND MEAN

10.429
7.773
6.979

J
SUM OF SQUARES = 58.781

*S
SUM OF SQUARES = 391.362

J *S
SUM OF SQUARES = 220.706

ERROR TERMS

	SUMS OF SQUARES	MEAN SQUARE	DF
1	391.36	48.92	8
2	220.71	13.79	16

SOURCES OF VARIANCE	SUMS OF SQUARES	MEAN SQUARES
J	58.78	29.39

DF	ERROR	F- RATIOS
2	2	2.131

TOTAL SUM OF SQUARES = 670.848

CARNEGIE MELLON UNIVERSITY ANOVA PROGRAM

by

William A. Leaf

GRATING THRESHOLD 10 CPD, BEFORE VS AFTER INC

FORMAT = (2F5.3)

LEVELS OF FACTORS: 0 0 0 0 2 0 0 0

MAX OBS/CELL: 9 UNEQUAL N SWITCH: 0
PRINT MEANS SWITCH: 1 PRINT DATA SWITCH: 0

SUMS OF SQUARES

8.704

GRAND MEAN

10.429
6.979

J
SUM OF SQUARES = 53.575

*S
SUM OF SQUARES = 285.187

J *S
SUM OF SQUARES = 151.248

ERROR TERMS

	SUMS OF SQUARES	MEAN SQUARE	DF
1	285.19	35.65	8
2	151.25	18.91	8

SOURCES OF VARIANCE	SUMS OF SQUARES	MEAN SQUARES
J	53.58	53.58

DF	ERROR	F- RATIOS
1	2	2.834

TOTAL SUM OF SQUARES = 490.011

CARNEGIE MELLON UNIVERSITY ANOVA PROGRAM

by

William A. Leaf

GRATING THRESHOLD 10 CPD, BEFORE VS AFTER EL

FORMAT = (2F5.3)

LEVELS OF FACTORS: 0 0 0 0 2 0 0 0

MAX OBS/CELL: 9 UNEQUAL N SWITCH: 0
PRINT MEANS SWITCH: 1 PRINT DATA SWITCH: 0

SUMS OF SQUARES

9.101

GRAND MEAN

10.429
7.773

J
SUM OF SQUARES = 31.760

*S
SUM OF SQUARES = 273.571

J *S
SUM OF SQUARES = 177.087

ERROR TERMS

	SUMS OF SQUARES	MEAN SQUARE	DF
1	273.57	34.20	8
2	177.09	22.14	8

SOURCES OF VARIANCE	SUMS OF SQUARES	MEAN SQUARES
J	31.76	31.76

DF	ERROR	F- RATIOS
1	2	1.435

TOTAL SUM OF SQUARES = 482.418

CARNEGIE MELLON UNIVERSITY ANOVA PROGRAM

by

William A. Leaf

GRATING THRESHOLD 10 CPD, EL VS INC

FORMAT = (2F5.3)

LEVELS OF FACTORS: 0 0 0 0 2 0 0 0

MAX OBS/CELL: 9 UNEQUAL N SWITCH: 0
PRINT MEANS SWITCH: 1 PRINT DATA SWITCH: 0

SUMS OF SQUARES

7.376

GRAND MEAN

7.773
6.979

J
SUM OF SQUARES = 2.835

*S
SUM OF SQUARES = 334.319

J *S
SUM OF SQUARES = 2.723

ERROR TERMS

	SUMS OF SQUARES	MEAN SQUARE	DF
1	334.32	41.79	8
2	2.72	.34	8

SOURCES OF VARIANCE	SUMS OF SQUARES	MEAN SQUARES
J	2.84	2.84

DF	ERROR	F- RATIOS
1	2	8.331

TOTAL SUM OF SQUARES = 339.877

APPENDIX K

GRATING RESOLUTION
SIEGEL-TUKEY TEST CALCULATIONS

GRATING RESOLUTION THRESHOLD 10 CPD

INC VS EL
SIEGEL-TUKEY TEST

TEST H_O: VAR(INC) = VAR(INC) = VAR(EL) $\alpha = 0.05$

H_A: VAR(INC) $\neq$ VAR(EL)

Rank the scores as follows:

INC	EL	Rank
	2.64	1
2.73		4
37.21		5
38.64		8
	41.12	9
	41.93	12
47.73		13
53.81		16
	57.27	17
	76.66	18
88.39		15
	90.93	14
95.58		11
	109.43	10
124.38		7
	138.73	6
139.64		3
	140.84	2

$$\gamma_{INC} = 4 + 5 + 8 + 13 + 16 + 15 + 1 + 7 + 3 = 82$$

$$T_{INC} = (10)(10) + \frac{(10)(11)}{2} - 82 = 73$$

$$T_{EL} = 100 - 73 = 27$$

$$U = \text{Min}\ (T_{EL} T_{INC}) = 27$$

$$Z_{.05} = 1.65 \qquad Z_{\frac{\alpha}{2}} = Z_{.025} = 1.96$$

$$d = \frac{1}{2}\left[(10(10) + 1 - 1.96\sqrt{\frac{10(10)\ \ (10+10+1)}{3}}\right] = 24.57$$

$27 \nless 24.57$ ∴ cannot reject H_O and conclude the variances are equal.

APPENDIX L

COMFORT TEST
ANOVA TABLE

CARNEGIE MELLON UNIVERSITY ANOVA PROGRAM

by

William A. Leaf

COMFORT TEST

FORMAT = (2F6.4)

LEVELS OF FACTORS: 0 0 0 0 2 0 0 0

MAX OBS/CELL: 9 UNEQUAL N SWITCH: 0
PRINT MEANS SWITCH: 1 PRINT DATA SWITCH: 0

SUMS OF SQUARES

13.931

GRAND MEAN

16.620
11.242

J
SUM OF SQUARES = 130.138

*S
SUM OF SQUARES = 1690.040

J *S
SUM OF SQUARES = 90.284

ERROR TERMS

	SUMS OF SQUARES	MEAN SQUARE	DF
1	1690.04	211.26	8
2	90.28	11.29	8

SOURCES OF VARIANCE	SUMS OF SQUARES	MEAN SQUARES
J	130.14	130.14

DF	ERROR	F- RATIOS
1	2	11.531

TOTAL SUM OF SQUARES = 1910.462

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ADVISORY GROUP FOR AEROSPACE RESEARCH AND DEVELOPMENT

(ORGANISATION DU TRAITE DE L'ATLANTIQUE NORD)

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ADVANCED AVIONICS AND THE MILITARY AIRCRAFT MAN/MACHINE INTERFACE

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ELECTROLUMINESCENT LIGHTING AND OTHER TECHNIQUES FOR IMPROVING NIGHT VISION GOGGLES COMPATIBILITY WITH COCKPIT DISPLAYS

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SUMMARY

Standard night lighting for most aircraft cockpits results in a lighting configuration that is not compatible with the use of night vision goggles. One specific example discussed in this paper is the US Air Force PAVE LOW III helicopter; a modified version of the HH-53H. Both wavelength and geometric light control techniques were developed and applied to this cockpit to make it compatible with the night vision goggles. A combination of light control film (3-M micro-louvre), color filters, infra-red blocking filters, electroluminescent light and anti-flare baffles were used to successfully retrofit the cockpit for night vision goggle use. In addition, some of the techniques are applicable to reducing windscreen reflection, thus, improving unaided night vision through the windscreen.

1. INTRODUCTION

The work described in this paper was done in support of the US Air Force PAVE LOW III helicopter. The PAVE LOW III is a modified version of the HH-53H helicopter (see Figure 1). The modifications included

Figure 1. PAVE LOW III helicopter

a moveable infra-red imaging sensor mounted to the forward nose section and a radar altimeter to allow night and adverse weather low level flight. These and other modifications were done to facilitate the helicopter's night/day air rescue mission. After delivery of the initial aircraft, a decision was made to use night vision goggles to obtain lower night flying capability. Unfortunately, the cockpit lighting and displays were not originally designed for night vision goggle compatibility. The authors were requested to assist in developing techniques to reconfigure the cockpit lighting to alleviate this problem. The desired night flying configuration was for the pilot to wear the night vision goggles for piloting the aircraft while the copilot did not wear goggles so that he could monitor the aircraft instruments and the infra-red video display. In this configuration it was impossible to achieve sufficient lighting for the copilot to do his job while allowing the pilot to also do his job of viewing outside with the night vision goggles. Infra-red light from the incandescent lighting system and console displays caused reflections in the windscreen and other scattered light that made it impossible for the pilot to see outside with the goggles, even when the lights were turned so low that the copilot could barely see to do his job. The objective of this effort was to develop light control techniques that could be easily retrofit to the cockpit and would allow both crew members to do their assigned jobs.

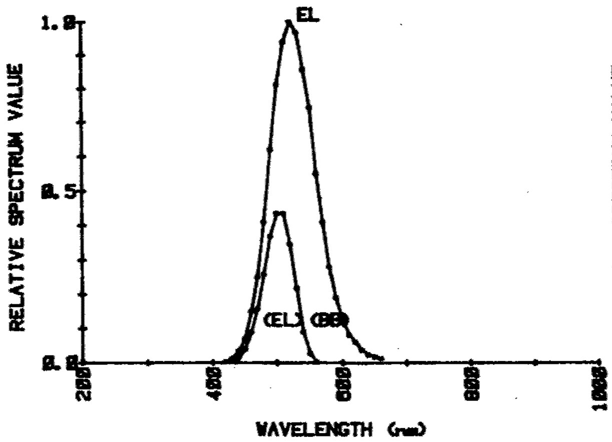
2. LIGHT CONTROL TECHNIQUES

Basically, the light control techniques that were employed fell into two general categories: wavelength control and geometric control. The wavelength control techniques involve the judicious use of various filters to separate the visual sensitivity spectrum from the night vision goggle sensitivity spectrum. The geometric control involves the use of techniques to direct the light so that it only goes in desired directions.

2.1 Wavelength Control Techniques

The US Army AN/PVS-5 night vision goggles (NVGs) are sensitive to light in the spectral region from about 350nm to 900nm. This includes the visible wavelength region of '30nm to 700nm as well as a small portion of the near infra-red. Incandescent lighting normally used in aircraft cockpits for night operations emits considerable energy in this near infra-red band from 700nm to 900nm. The result is that reflections in the aircraft windscreen of instrument lights, that are annoying to the unaided eye, render the NVG's nearly useless.

The approach taken by the authors was to use electroluminescent lighting and color filters to separate the night lighting required for unaided vision from the sensitivity region of the modified NVGs. This was done by turning off all possible incandescent lamps and floodlighting the instrument panels with blue-green filtered electroluminescent light. Infra-red transmissive red filters were placed over the NVGs to reduce their sensitivity to the blue-green light. Since the electroluminescent light emits essentially no energy in the infra-red, it makes an ideal light source for the NVG compatibility. Figure 2 shows the emission spectrum of the electroluminescent light used before filtering (upper curve) and after a blue-green filter was used to "shape" its wavelength output. Similarly, Figure 3 shows the



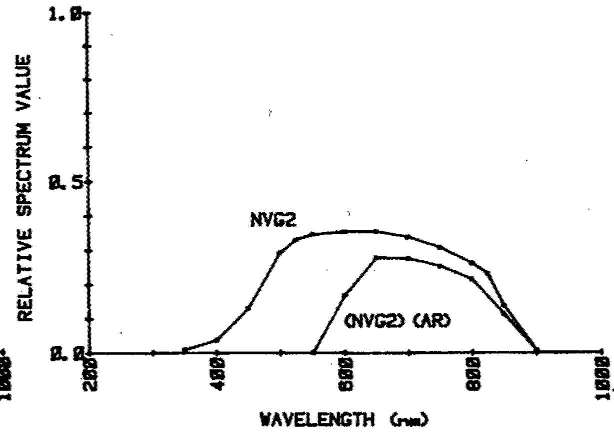


Figure 2. Emission spectrum of the yellow-green electroluminescent lights without blue-green filter (EL-upper curve) and with filter (EL-BB-lower curve).

Figure 3. Relative sensitivity spectrum of the US Army second generation might vision goggles without filter (NVG2-upper curve) and with a red/infra-red transmissive filter (NVG2-AR-lower curve).

sensitivity of the so-called second generation NVGs before (upper curve) and after wavelength filtering. The result (see Figure 4) is that the two wavelength distributions have very little overlap.

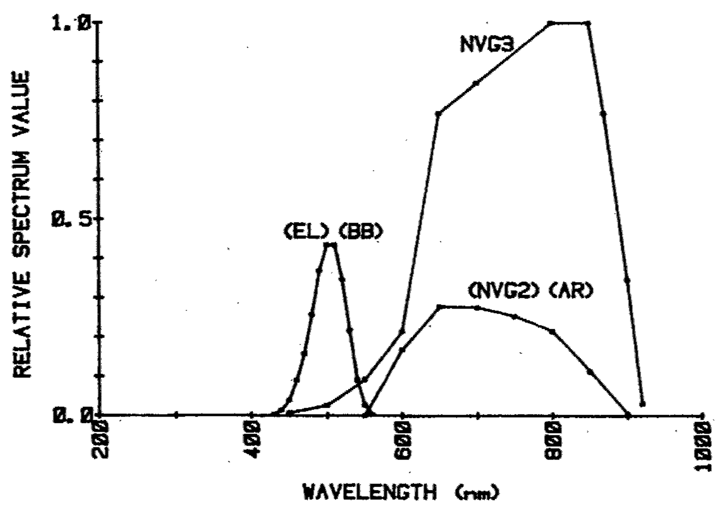


Figure 4. Comparison of emission and sensitivity spectra for the electroluminescent light with blue-green filter (EL-BB), the US Army second generation night vision goggles with red/infra-red filter (NVG2-AR) and the US Army third generation night vision goggles without filters (NVG3). Note that the spectra for the filtered EL light and the filtered NVG2s barely overlap.

This means that the NVGs can easily "see through" any spurious windscreen reflections that occur from the electroluminescent lighting.

The PAVE LOW III cockpit has two 5" by 7" video displays for presenting infra-red imagery (see Figure 5).

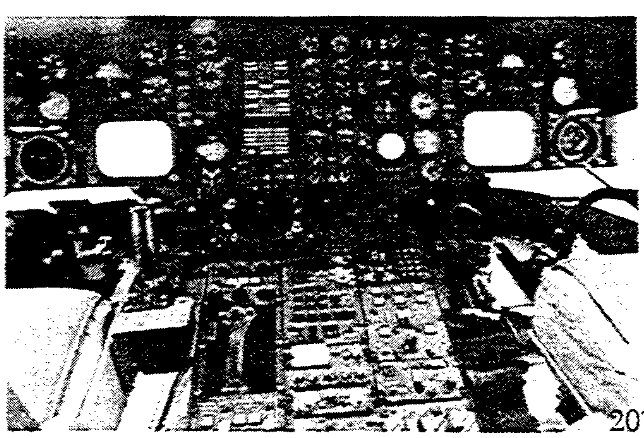


Figure 5. Front instrument panel and center console of the PAVE LOW III helicopter. Note the video displays located in front of the copilot seats. Light switches and instruments on the center console are a major source of windscreen reflections.

These displays use a P-4 white phosphor and are normally covered with a red filter for night flying. This results in incompatibility with the use of the NVG's since the red filtered displays are filling the cockpit with red light to which the NVGs are sensitive. Figure 6 shows the overlap with wavelength distributions for the display (P-4) and the unfiltered NVGs. By using the same combination of blue-green filters

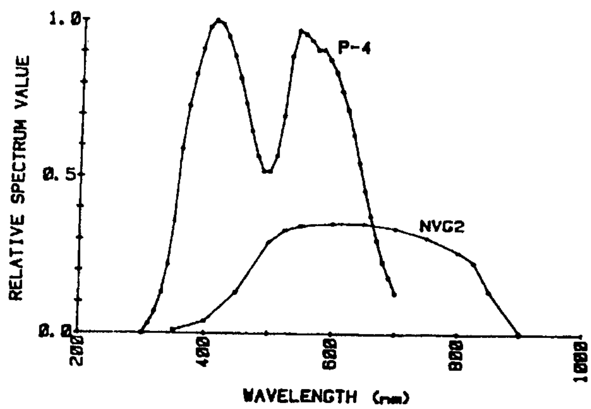


Figure 6. Comparison of the emission spectrum of the P-4 phosphor on the video displays and the sensitivity spectrum of the night vision goggles (NVG2). Note the considerable overlap of these two curves out to and including the red region of the spectrum (600-700nm) used for conventional red light lighting.

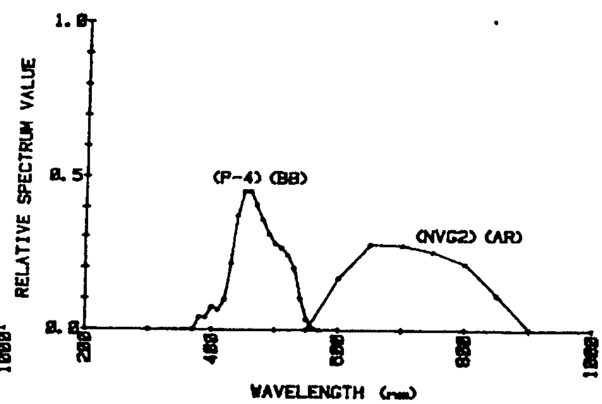


Figure 7. Comparison of the same two spectra described in Figure 6 but with appropriate filters placed over the display and the NVGs. Note that there is very little overlap between the two distributions.

described previously, it is possible to separate these two wavelength distributions as shown in Figure 7.

There has been some concern expressed about using blue-green lighting and blue-green filters over the display from the standpoint of its effect on the dark adaptation state of the crew members. It should be noted that the crew members that are not wearing the goggles are focussing their attention on the displays and instruments inside the cockpit. It is, therefore, not necesaary for them to be absolutely dark adapted.

Some instrument lights in the cockpit cannot be turned off. The incandescent infra-red light from several of these lights located in the center console (see Figure 5) resulted in direct reflections in the windscreens. To reduce this adverse effect, these lights were covered with an infra-red blocking material that transmitted most of the visible light. This thin plastic material was originally developed for laser safety goggles but worked very well for this application.

2.2 Geometric Control Techniques

Geometric control was accomplished by simply devising means to direct the instrument lighting in desired directions and blocking it from going in undesired directions.

Many instrument lights consist of an incandescent lamp with a diffusing (sometimes colored) filter over the top with a printed legend on it. This diffusing filter distributes the light in all directions, including toward the windscreen. This results in unwanted reflections of these lights in the windscreen. To combat this problem, a product developed by 3-M Corporation called micro-louvre was used to direct the light away from the windscreen. The micro-louvre is a relatively thin plastic material with extremely small slats or louvres imbedded within. It is available with different slat spacing and orientation. It acts very similarly to a miniature venetian blind.

By selecting the appropriate angle of micro-louvre, it is possible to direct the instrument lights toward the aircrew members and away from the windscreen. This allows full viewability of the instruments and displays by the aircrew members but prevents the light from reaching the windscreen and causing a reflection. Figure 8 shows a laboratory example of this effect for visible light. A back illuminated lettered text in the lower portion of Figure 8 was positioned so that a reflection of it could be seen in a thin piece of clear plastic (windscreen) in the upper portion of Figure 8. A small section of micro-louvre set for a 30° angle was placed on the lettered text so that it directs the light toward the louvres and away from the windscreen. Note that it is difficult to see through the windscreen in the area of the reflection except for the rectangular area covered by the micro-louvre. This technique was used considerably throughout the PAVE LOW III cockpit.

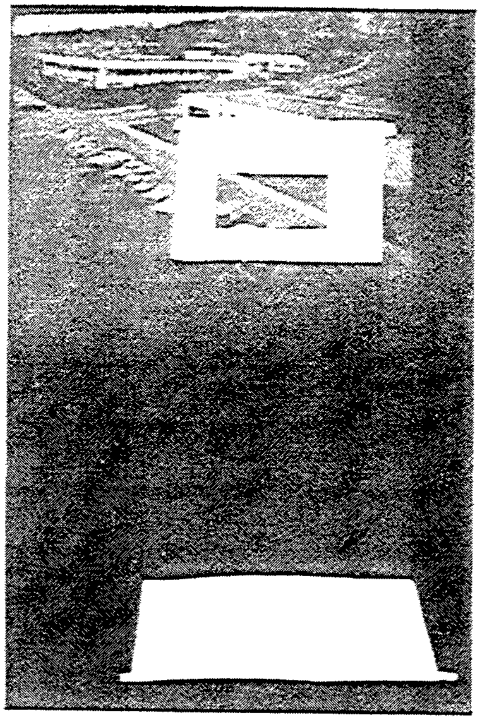


Figure 8. Laboratory example of the effectiveness of the 3-M Corporation micro-louvre in directing the light from display screens. The lower part of the photograph shows a back illuminated screen with a rectangular piece of micro-louvre placed over the center of the text. The upper part of the photograph shows the reflection of the text in a sheet of plastic simulating a windscreen. A background scene consisting of buildings and cars in a parking area is easily visible except for where the display reflection washes it out. But the area of the text display covered by the micro-louvre does not reflect in the windscreen, permitting easy visibility of the outside scene. Note also that there is no detrimental effect caused by the micro-louvre in reading the text display in the lower portion of the photograph.

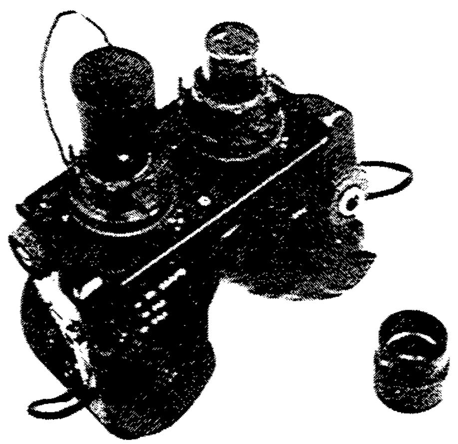


Figure 9. US Army second generation night vision goggles with anti-flare baffle (lower right).

A second geometric control technique was to attach a small flare baffle to the objective lens housing of the night vision goggles. These baffles (see Figure 9) reduced the flare produced in the objective lens caused by relatively bright light sources outside of the field of view of the goggles. The baffles also made a convenient mounting location for the red/infra-red filters previously mentioned.

The final light control technique was a recommendation that the flight crews wear black or dark infra-red absorbing clothing and, to a maximum degree, the interior of the cockpit be painted with a black-matte finish. The geometry of the cockpit was such that the pilot and copilot could see a reflection of their knees in the windscreen. In other cockpit configurations, i.e., C-130 aircraft, many of which have a cream colored control column, the light colored objects are clearly reflected in the windscreen at low (one quarter foot-Lambert) ambient light conditions. By reducing the stray light in the cockpit and minimizing the reflectance coefficient of the clothing, this reflection source was considerably reduced.

3.0 EVALUATION OF LIGHT CONTROL TECHNIQUES IN THE PAVE LOW III HELICOPTER COCKPIT

All of the previously discussed light control techniques were installed in the cockpit of a PAVE LOW III helicopter for evaluation. Several instructor pilots viewed the modified cockpit and provided a critical assessment. In general, the comments concerning the modifications were extremely positive. Reflections in the windscreen were greatly reduced, even for the visible spectrum, which improved outside visibility for both the copilot (without the goggles) and the pilot (with the goggles). It was not possible to make photometric measurements of the improvements because of the relatively low light levels involved. However, photographs were taken to document the improvements. Figure 10 shows a picture taken through the night vision goggles of the forward field of view of an unmodified cockpit. The lower row of lights are runway lights seen outside. The collection of lights in the upper portion of the picture is from reflections

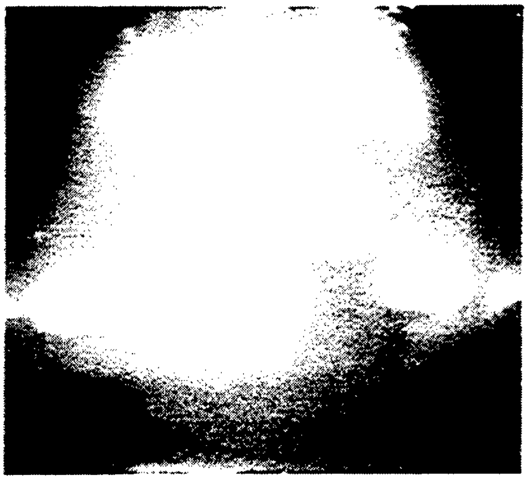


Figure 10. Photograph taken through the night vision goggles of the forward field of view seen from an unmodified PAVE LOW III cockpit. The lower row of lights are runway lights from a nearby airstrip The upper secton of lights are reflections in the windscreen from the center console. Note that some of the reflections are as intense as some of the runway lights.

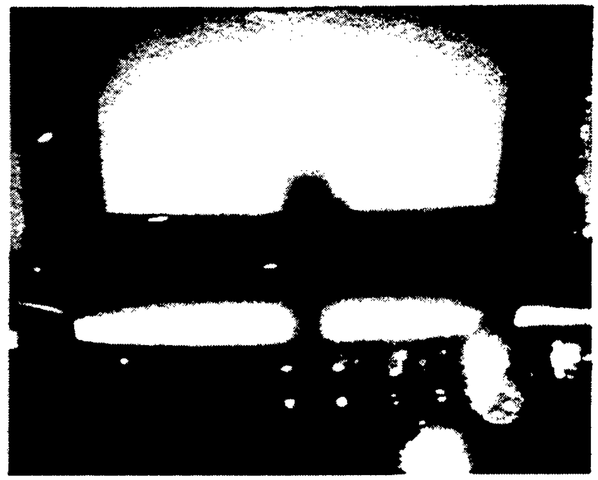


Figure 11. Photograph taken through the night vision goggles of the light control modified cockpit Note the absence of reflections except for two minor light leaks reflected from the center console. The rectangular strips of light toward the lower part of the photograph are the electroluminescent lights mounted under the glare shield to illuminate the forward instrument panel.

of center console instruments in the windscreen. Note that the intensity of some of these reflections is comparable to the outside runway lights. For comparison, Figure 11 shows the forward view out of a helicopter cockpit that was modified with the light control techniques. Except for two small reflections caused by inadequately covered instrument lights, the view is clear of unwanted reflections. With the reflections gone, the night vision goggles' gain was increased to a level that it was possible to see the sky glow of a nearby city that was masked in the view from the unmodified cockpit.

4.0 CONCLUSIONS AND RECOMMENDATIONS

The light control concepts discussed in this paper were quite successful in providing lighting conditions compatible with the use of night vision goggles. However, several problems still exist in developing materials and installation techniques that will be suitable for aircraft retrofit. It is extremely difficult to locate electroluminescent floodlighting to adequately illuminate all areas requiring illumination without involving expensive modifications to the cockpit lighting. It is considerably easier to provide for electroluminescent lighting when designing the original cockpit than to devise acceptable ways to retrofit this lighting in the cockpit. The micro-louvre does an excellent job of directing the light as desired but it is unfortunately cast in a relatively soft plastic that is susceptible to both warping from heat and loss of effectiveness from scratching and wear. It would be highly desirable to develop a tougher version of the micro-louvre, but as of this writing, there are no known efforts in effect to do this. The laser safety material used for blocking the infra-red radiation from critical incandescent instrument lights needs to be improved to pass more visible light in the red region (630nm) and to block the light better toward the far red and infra-red region (650nm to 900nm). Use of the material over red warning lights reduced the visible level to a degree which rendered them unsatisfactory for daytime use in the helicopter. With the indicated needed improvements, this problem should be alleviated.

Even with these shortcomings from the materials standpoint, interest and work in this light control area for night vision goggle compatibility is progressing rapidly. Other USAF aircraft that have been modified and tested with these light control techniques are the UH-1N and HH-53C rotary wing aircraft for MAC/AARS (Air Rescue and Recovery Service) and two special mission C-130E/H fixed wing aircraft for TAC. In all cases, the wavelength separation and light control techniques were pursued, as appropriate to the individual cockpit configuration and aircraft mission, with very good to excellent results through ground evaluation and flight test.

Yet to be tested is an all electroluminescent lighting system for the interior and exterior of six A-10 single seat attack aircraft for TAC. NVG compatibility is not a requirement with these ten aircraft, rather, a complete emphasis on unaided night visibility inside the cockpit and through the transparencies and improved lighting for formation flying and night refueling is needed.

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PAVE LOW III: Interior Lighting Reconfiguration for Night Lighting and Night Vision Goggle Compatibility

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The PAVE LOW III aircraft is a modified HH-53H helicopter that has a low altitude—below 30.48 m (100 ft)—night/day rescue mission. The desired night flying configuration is for the pilot to wear night vision goggles (NVGs) to fly the aircraft while the copilot, without NVGs, observes the video display and monitors the aircraft instruments. The problems of NVG incompatibility in the cockpit were successfully countered using several light control techniques. The light control modifications were evaluated on the ground in the PAVE LOW III helicopter at Kirtland AFB in April, 1980, by PAVE LOW instructor pilots. The evaluation results were extremely positive.

THE PAVE LOW III aircraft is a modified version of the HH-53H helicopter. Its primary mission is day/night air rescue. The mission profile of this aircraft is to fly extremely low for day/night search and rescue of downed pilots. The original PAVE LOW III modifications included a forward-looking infrared (FLIR) imaging sensor mounted on a moveable gimbal at the forward section of the aircraft. This FLIR provided night, infrared imagery via two 5 × 7 in cathode ray tubes (CRTs) mounted in the instrument panel in front of the pilot and copilot. Additionally, to support night and adverse weather navigation, a radar altimeter and terrain avoidance/terrain following radar was installed. However, as the PAVE LOW III aircraft was undergoing acceptance testing and required participation in Red Flag '79 tactical air combat exercise, the requirement for low-altitude flight was extended beyond the design capabilities of the radar. It was felt by those familiar with the helicopter that lower altitudes could be achieved at night if the pilot used the U.S. Army developed, second-generation night vision goggles (NVGs).

In initial tests with the night vision goggles, it was determined that the interior lighting for night flight interfered severely with their useful operation. The night illumination, even adjusted to a low level, emits considerable energy in the near infrared, where the NVGs are most sensitive. A first attempt to reduce this problem was conducted by the PRAM (Productibility, Reliability, Availability, Maintainability) PO (Program Office) at Wright-Patterson AFB in cooperation with the Military Airlift Command (MAC) and the Air Rescue and Recovery Service (ARRS). This initial test involved turning off all possible interior lights and floodlighting the instrument panel with yellow-green electro-luminescent lighting. Electro-luminescent (E-L) light emits almost all of its energy in the visible region and, essentially, none in the infrared. This "cold light" effect makes the E-L light much more compatible with the use of NVGs than the traditional incandescent lighting.

At a meeting late in 1979, the authors were asked by PRAM and MAC to address the problem of making the interior lighting of the PAVE LOW III helicopter compatible with the use of the NVGs. The desired operating condition was for the pilot to wear the NVGs to fly the helicopter while observing the outside world, and for the copilot to monitor the FLIR video display and the aircraft instruments. Thus the fundamental problem was to design a means of lighting such that the copilot had sufficient light to monitor the cockpit instruments but insure that the lighting did not interfere with the pilot's NVGs. A review of the aircraft interior lighting and the windscreen/instrument geometry revealed two sources of lighting difficulty. First, several illuminated instruments on the center and overhead console reflected directly in the windscreen from the pilot's and copilot's

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eye positions as well as the flight engineer's nominal eye position. This problem makes night flight, even without the NVGs, difficult and distracting and almost totally disallowed the use of NVGs. Second, the stray light in the cockpit illuminated other surfaces (like the pilot's knees and hands) such that their reflections in the windscreen were highly visible and distracting when using the NVGs. To improve the NVG utility, it was necessary to eliminate the direct reflecting sources and reduce or control the scattered light.

APPROACH

Several lighting and light control techniques were recommended to alleviate the NVG incompatibility problem:

1. Use blue-green E-L flood-lighting and turn off all possible incandescent lamp sources.
2. Use blue filters, instead of red, over the CRT display and place a red filter over the NVGs.
3. Use light baffles to control stray light.
4. Use anti-flare baffles on NVGs to reduce flare.
5. Use flat-black flight clothing and helmets to reduce stray light and reflections.

As a result of the meeting with MAC and PRAM, the authors were requested to implement the above recommendations on a PAVE LOW III helicopter for a full-up ground evaluation. The following sections describe each of these recommendations in detail.

Electro-Luminescent Flood Lighting: The main reason for using E-L light is that, unlike incandescent lighting, it emits little or no light in the near infrared region (4). The NVGs are highly sensitive to light from about 450-850 mm wavelength (1,2). By limiting the interior lighting to blue-green visible wavelengths only, considerable adverse interaction between the lighting system and the NVGs was eliminated.

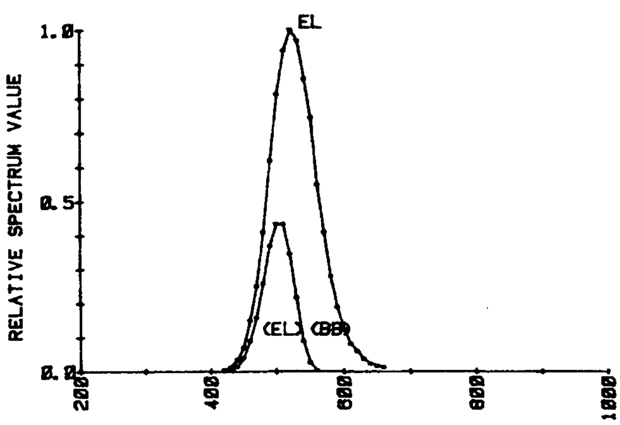

Fig. 1. Wavelength emission spectrum of the electro-luminescent lamp without filter (E-L) and with a blue filter (BB).

Fig. 1 shows the emission spectrum of the E-L lamps used. The upper curve is the E-L lamp without filter and the lower curve shows the lamp with a blue filter (BB) used to shift the peak of the emission spectrum further into the blue region.

The E-L lamps were placed under the glare shield to illuminate the front instrument panel and center console. They were also placed on the backs of the pilot's and copilot's seats, directed upwards, to illuminate the overhead panels. It was not possible under the constraints placed on this retrofit (no holes drilled or permanent modifications allowed) to properly illuminate the far forward section of the overhead panels or the rear section of the center console. Thus to provide a means of "portable" illumination, and E-L light wand was provided that the copilot could use for map reading or close-up instrument tasks, such as setting radio frequencies. In an ideal situation, these areas would be locally illuminated with E-L light built into the instrument or its immediate surround.

Blue/Red Filters: The CRT FLIR displays on the helicopter use a P-4 white phosphor. Although this emits no infrared light, it does emit over the full visible region. The standard night operation required the white CRT screen to be covered with a red filter. This left a display emission spectrum in the visible region from about 600-650 nm. This spectrum is in the center of the sensitivity region of the NVGs. Fig. 2 shows the relative sensitivity

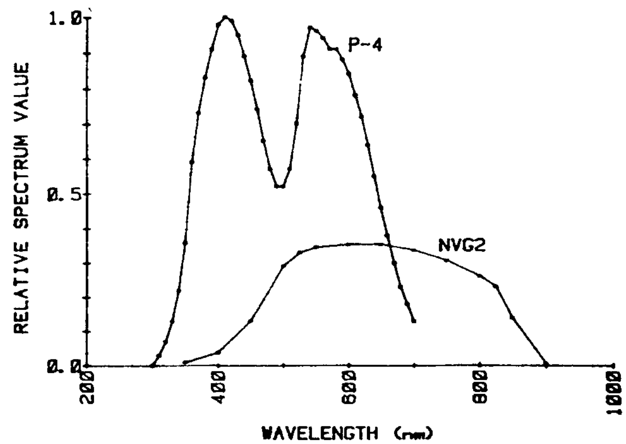

Fig. 2. Composition of the display P-4 phosphor spectrum and the night vision goggle (NVG 2) sensitivity curves.

of the second generation night visions goggles (NVG2) compared with the emission spectrum of the P-4 phosphor.

By using a blue filter (BB) over the P-4 phosphur screen, it is possible to shift the peak of the emission spectrum toward the blue, where the NVG is not quite as sensitive. This still results in considerable overlap. To reduce the overlap still further, a red plastic filter that was also highly transmissive in the near infra-red was placed over the NVGs. This resulted in the curves shown in Fig. 3. Under these conditions, the emission of the display and the sensitivity of the NVG have almost no overlap, thus effectively eliminating the interference of the display with proper operation of the NVGs (3). The red/infrared filter over the NVGs also significantly reduced the sensitivity of the NVG to the blue-green E-L, thereby eliminating that source of interference.

The red/infrared filter reduces the overall sensitivity of the NVGs. However, since most of the natural night illumination is in the near infrared i.e. 800-1000 nm, the effective reduction in night sensitivity is relatively small.

Baffles for Light Control: It is not possible to turn off all incandescent lights in the cockpit since some are

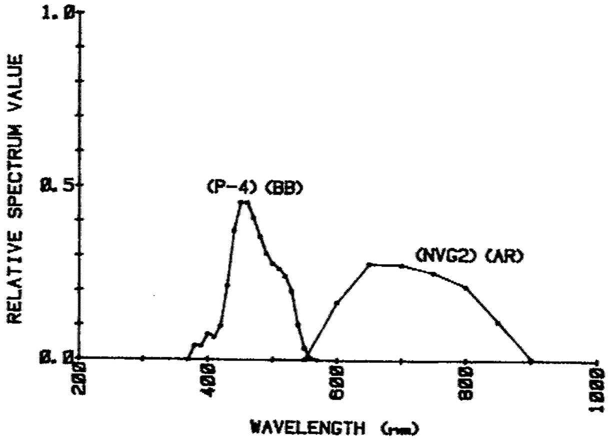

Fig. 3. Comparison of P-4 phosphor with blue filter and night vision goggle sensitivity with red filter. Note lack of overlap.

required instrument status lights. Several such lights were, unfortunately, located in the center console. Most of the center console was directly visible in the windscreen due to the reflection geometry. To control these reflections, a material developed by 3-M Corp. was applied wherever possible. This material, called Micro-Louver (ML), is like a miniature venetian blind cast in a thin plastic layer. It is about 1/16-in. thick and can be obtained in various configurations. By varying the "slat" spacing and tilt, the fan of light that is allowed through the material can be controlled. The material comes in three "fan widths" of 48°, 60°, and 90°; and several tilt angles: 0°, 18°, 30°, and 45°. The tilt angle refers to the direction with respect to the vertical. Thus a 48° fan at 0° tilt results in a 48° light distribution spread that is emitted vertically, with respect to surface of material.

By placing appropriately chosen ML sections over the lights and displays, the light can be directed away from the windscreen toward the pilot, copilot, and flight engineer. This reduces or eliminates the direct reflection of instruments in the windscreen. Fig. 4 shows a section of ML that is a 48° fan, 0° tilt mounted over a vugraph. Note the clarity of the vugraph beneath the ML. Fig. 5

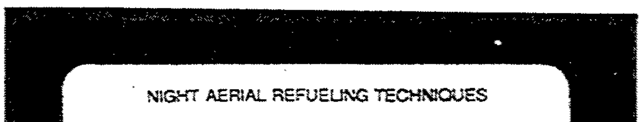

Fig. 4. The 48° fan, 0° tilt micro-louver viewed directly.

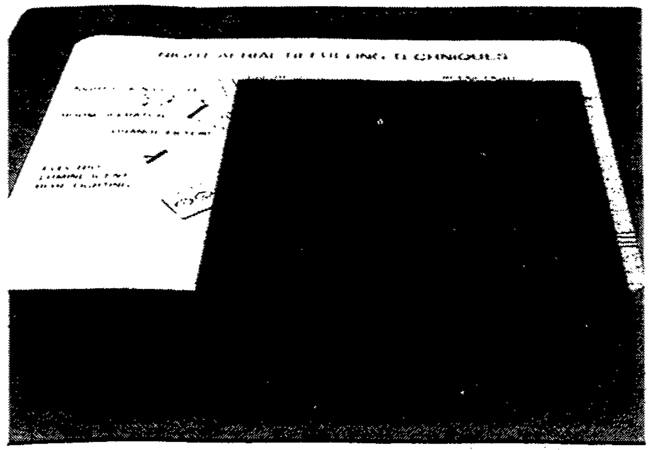

Fig. 5. The 48° fan, 0° tilt micro-louver viewed from an angle of about 60°.

shows this same vugraph and material, but from a different angle. The vugraph light has been directed in a fan upward.

This technique of using ML baffles was successfully employed over several indicator lamps and displays including the incandescent lamp illuminated moving map display located in the center console. The ML was oriented to provide a horizontal fan of light directed away from the forward windscreen toward the pilot, copilot, and flight engineer positions.

Although this technique was highly successful for the visible light reflections, it was not totally successful with the IR reflections. The ML plastic was partially transmissive in the IR, and IR from the lamps was so strong that it caused scattering within the ML material. To combat this problem, a thin, plastic material was borrowed from the laser safety industry. The original purpose of this material was to provide laser safety and protection at the near IR wavelengths. Thus the material passed a large portion of the visible spectrum but absorbed light in the near IR. This IR-blocking material (IRBM) was used in conjunction with the ML material to provide fairly effective control of both visible and IR radiation. The IRBM was a "Glendale Green" filter material obtained from Glendale Optical Co. The published photopic transmissivity of the IRBM is about 45%. It does have a definite green tint and affects the red end of the visible radiation much more severely than the green.

Anti-Flare Baffles on NVG: Another source of stray light that can affect the NVG operation is caused by flare. The NVGs have a 40° field of view (FOV), 1:1 optical imaging system. However, bright light sources just outside of this FOV can still illuminate the objective lens of the NVG. Although this illumination is not imaged through the optical system, since it is outside the FOV, it still scatters in the lens causing a veiling luminance at the image plane that reduces contrast. This condition can be partly alleviated by providing an antiflare baffle outside of the objective lens. The baffle "shades" the objective lens from bright light sources outside the FOV and provides a housing to mount the red/IR filters to the NVGs.

Black Flight Clothing: To further reduce stray light, it was recommended that the flight crew wear dark clothing to absorb any stray light instead of reemitting it. Due to the geometry of the windscreen and pilot/copilot seats, the knees and hands of the pilot/copilot were reflected and highly visible in the windscreen to the NVG wearer. By wearing dark clothing, the intensity of the reflections was greatly reduced.

GROUND EVALUATION RESULTS

All of the light control techniques herein described were applied to the PAVE LOW III aircraft and evaluated by several instructor pilots during a day/night ground evaluation. Overall, the evaluation results were extremely good. The copilot had sufficient light to do his job, but the lighting did not adversely affect the pilot's NVGs. Several specific problems were identified by the evaluating instructor pilots.

In general, the use of the IRBM tended to make some of the indicator lights too dim to the unaided eye in daytime. In particular, the moving navigation map display was only marginally acceptable in daytime when sufficient IRBM was applied to block the IR emissions for night use. During the night evaluation, several other sources of incandescent or neon light IR emissions were identified as requiring applications of the light control techniques. These sources were not identified originally because the other sources totally masked their light. However, with the original problem lights effectively controlled, these "secondary" sources of light control problems became evident.

What need to be solved before these techniques can be applied are the long-term materials problems associated with the ML and the IRBM. The ML is a soft plastic; it is susceptible to scratching and can be warped by the heat of incandescent lamps. These same concerns apply to the IRBM as well.

If an aircraft cockpit used E-L panel lighting instead of incandescent, then the heat problem associated with the ML application would be solved. Also, this would eliminate the need for the IRBM since the E-L emits no IR.

An additional bonus of an all E-L cockpit light system or application of the techniques described is that the emission of IR from the cockpit is greatly reduced or eliminated. This should make the craft less visible and vulnerable to IR sensing and seeking devices.

CONCLUSIONS

The light control techniques described were successfully applied to the PAVE LOW III helicopter to make the interior lighting system compatible with the use of night vision goggles. From the ground evaluation, it is evident that these techniques provide a simple, inexpensive, and useful means to improve night visibility looking out of the cockpit with or without night vision goggles. The materials problems encountered should be addressed, and these techniques should be considered in the design of new cockpit layouts for interior night lighting.

Since this effort, similar efforts have begun for light control of the C-130 and UH-1 aircrafts.

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AAMRL-TR-85-055

INSTRUMENT LIGHTING LEVELS AND AN/AVS-6 USAGE

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Two experimental investigations were performed to determine the effects of the AN/AVS-6 Aviators Night Vision Imaging System (ANVIS) display luminance on the setting of instrument lighting levels. In a laboratory study using a simulated A-10 night lighting mockup, eight subjects adjusted instrument lighting levels to what they judged to be the minimum required for safe readability of instruments. Prior to the adjustment of instrument lighting, the subjects were preadapted to various ambient lighting conditions, including a simulated ground luminance of a full moonlit night and two simulated ANVIS display luminances. Results show primary instrument lighting levels were set higher, by a factor of 1.6 following adaptation to the 1.0 foot lambert (ft-L) ANVIS luminance test condition when compared to lighting levels set following adaptation to a 0.00065 ft-L ambient luminance condition.

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A field study was performed to determine instrument lighting levls used on board C-14 C-130, HH-53 and the OH-6 aircraft. Pilots set instrument lighting levels in flight on the ground while using ANVIS. Instrument luminances were measured in the 0.003 to 0.086 ft-L range. The average luminance calculated from measurements of a front instrument panel remained below 0.06 ft-L.

SUMMARY

The purposes of this study were to determine the effects of various preadapting luminance conditions on the setting of instrument lighting levels and to determine minimum luminance levels required for the readability of instruments when preadapted to the AN/AVS-6 Aviator's Night Vision Imaging System (ANVIS) display luminance. The approach to answering these questions consisted of two separate efforts:

A laboratory study investigated the effect of the ANVIS display luminance on instrument lighting levels required to read aircraft instruments. Eight subjects adjusted lighting levels to what they judged to be the minimum required for safe readability of instruments. Prior to adjusting the luminance levels, the subjects were preadapted to various ambient lighting conditions, including a simulated ground luminance of a full moonlit night and two simulated ANVIS luminances. All three of the preadapting lighting conditions were considered representative of actual operational conditions. Instrument lighting levels, set by the subjects after preadaptation to the ANVIS test conditions, were generally higher than lighting levels set after preadaptation to the ground luminance test condition. Increasing the preadapting luminance by roughly a factor of 300 (0.00065 ft-L ground luminance condition to a 0.2 ft-L ANVIS condition) resulted in an increase of instrument lighting levels by a factor of approximately 1.5.

A field study was performed on board operational aircraft to determine instrument lighting levels that are currently used with ANVIS. Photometric measurements were made at various locations on the front instrument panel of a C-141, C-130, and HH-53 Air Force aircraft. Additional lighting measurements were made on board an OH-6 National Guard aircraft. Pilots set instrument lighting levels in flight or on the ground, following adaptation to an ANVIS display luminance. No specific instructions describing how to set instrument lighting levels were given. Instrument luminance levels were in the 0.003 to 0.086 ft-L range. The average luminance of a single front instrument panel remained below 0.06 ft-L.

This report documents the methods and results of each study in separate sections. A single section will be used for discussion of the results of both the laboratory and field studies.

PREFACE

This report was prepared by the Crew Systems Effectiveness Branch of the Human Engineering Division, Armstrong Aerospace Medical Research Laboratory (AAMRL), Wright Patterson Air Force Base under Work Unit 7184-12-15.

The author wishes to thank Dr. Diana Nelson, of Systems Research Laboratories, Inc. for consultation provided during the course of this effort. The author also wishes to thank Mr. Dave Ramer, Mr. Mike Gifford, and Ms. Annette Wilber for construction of various hardware elements.

INTRODUCTION

GENERAL BACKGROUND

In recent years the military aviator's night operation capability has been enhanced by the use of Night Vision Goggles (NVGs). This device is used primarily for visual navigation in low level flight. NVGs are employed for terrain avoidance, terrain identification, landings, and takeoffs. The proven effectiveness of NVGs as a visual aid to the aviator has resulted in a plan for increased military use.

The AN/AVS-6 Aviator's Night Vision Imaging System (ANVIS) is an NVG currently being procured by the military for use on board aircraft. This electro-optical device (Figure 1) weighs approximately 16 ounces and is mounted on the front of a pilot's flight helmet. A battery power supply is mounted on the back of the helmet. ANVIS functions as an image intensifer by amplification of red and near-infrared components of moonlight and starlight. Looking through the eyepieces, the user views a binocular image of the real world on green monochrome displays. The "look under" design feature of ANVIS allows the pilot to view cockpit instruments with the unaided eye and to obtain an intensified nighttime image of the world external to the aircraft without a mechanical adjustment of focus.

Basic changes to the design of aircraft interior lighting are required to accommodate the use of ANVIS in the cockpit. Aircraft lighting traditionally consists of multicolor incandescent sources with spectral emissions in the infrared and visible wavelength region. Because ANVIS is extremely sensitive to the near-infrared and visible-red components of these lights, traditional aircraft lighting causes severe interference with the operation of ANVIS. To use ANVIS, all of the interior lighting must be redesigned. The white incandescent sources, typically located throughout the cockpit, must be replaced with "cold" green lighting that contains very little or no red and near-infrared. Additional changes in warning, caution, and advisory lighting are also required. These changes restrict the use of color coding. Geometrical considerations also play an important role in the design of ANVIS-compatible lighting. Location of light sources, with respect to ANVIS and the windscreen, must be such as to minimize interference with ANVIS.

The procurement of ANVIS-compatible lighting is currently a problem. Both the design and specification must be based upon research and technical data, yet many human engineering questions regarding these basic changes in lighting design remain unanswered. The general purpose of this work is to provide technical data from which the accurate specification of ANVIS compatible interior lighting may be formulated.

In October 1984, AAMRL was tasked by the Joint Logistics Commanders (JLC) AD HOC group to perform night lighting and night vision research. Specific areas of study, as well as the scope of various efforts, were outlined initially by this group. Data provided by AAMRL are intended to be used as a basis for a Tri-Service specification of ANVIS-compatible interior lighting.

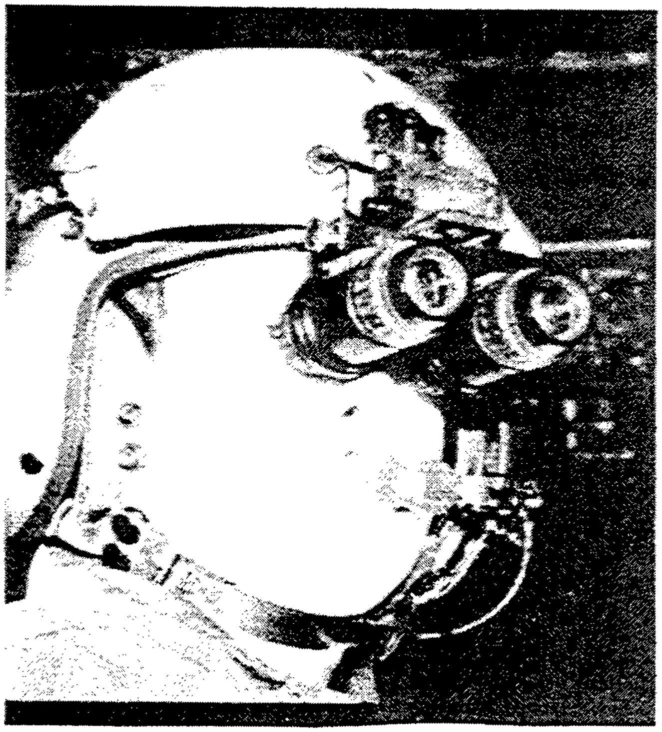

Figure 1. Pilot Wearing ANVIS.

RESEARCH QUESTION

The present research question investigates the use of ANVIS on aircraft and the effect of the ANVIS display luminance on visual adaptation and the setting of instrument lighting levels. Nighttime ambient lighting conditions (i.e. starlight, moonlight) range in luminance from 0.000001 to 0.001 ft-L. The output display luminance of ANVIS is within a range of 0.02 to 2.1 ft-L (reference 1). This "large" differential in preadapting luminance that occurs as a result of using ANVIS was expected to have some effect on the pilot's setting of instrument lighting levels. The specific objectives of this work were as follows:

1- To determine the effect of preadapting ANVIS luminances on the setting of instrument lighting levels by ANVIS users.

2- To define lighting levels required for reading aircraft instruments when adapted to ANVIS display luminance.

The specification of ANVIS-compatible lighting must use operating levels that are representative of an aviator's requirements for readability of instruments when adapted to ANVIS display luminances.

RELATED RESEARCH

A great deal of experimentation has been performed in the laboratory to quantify visual performance under conditions of low ambient lighting. A number of investigators have studied threshold luminances required for the discrimination of visual detail.

Kinney and Connors (reference 2) investigated the recovery of foveal acuity following exposure to various intensities and durations of light. The test stimulus was a circular grid 1 degree in diameter. Bars of the grid were alternately opaque and transparent and subtended 6 minutes of visual angle, corresponding to a visual acuity requirement of 20/120. Data collected with two subjects showed that, following complete foveal dark adaptation, the average luminance required to resolve the grating was 0.01 ft-L. Preadaptation to a 3.6 ft-L light source (45 second duration) resulted in a 20 second recovery time to resolve the 6 minute target. Preadaptation to a 0.36 ft-L light source showed no effect on foveal acuity (6 minute target) for any adaptation time period (1 to 45 second duration).

Brown (reference 3) examined the effect of preadapting luminance on the resolution of visual detail during dark adaptation. In the experiment, the subject was required to identify the orientation of a grating pattern. Luminance thresholds of two subjects were 0.3 mL (0.28 ft-L) and 0.03 mL (0.028 ft-L) for targets of 1.6 minute angle (20/32) and 4.0 minute angle (20/80) respectively. Results also indicated that a return to threshold luminance for the resolution of the 1.6 minute target following a 5 minute preadaptation to a 0.98 mL (0.91 ft-L) light source requires 2-4 minutes. Studies by Graham and Cook (reference 4), Brown, Graham, Leibowitz and Ranken (reference 5), and Diamond and Gilinsky (reference 6) showed similiar results regarding luminance thresholds for various acuities.

In each of the studies described above, the subject was presented with a grid pattern using a light flash of short duration. The stimulus was repeated at a constant interval until the subject could discern target orientation or striations. Note that these experimental presentations do not closely resemble those of a pilot's actual reading task.

Character size on aircraft instruments is designed for the maximum legibility permitted by space restrictions and range of illumination (reference 7). No minimum character size is defined by standards, however character sizes of instrument dials are designed typically for 2.0 (20/40) to 2.5 (20/50) minutes of arc visual angle as estimated for these non-Snellen characters.

In more current research that specifically deals with the readability of aircraft instrument dials, Bauer (reference 8) reports that instruments 2.8 inches in diameter are legible in the 0.02 mL (0.019 ft-L) to 0.05 mL (0.046 ft-L) range. It was also shown that pilot performance improved as display luminance increased from 0.01 mL (0.009 ft-L) to 0.1mL (0.09 ft-L). Bauer concluded that minimum luminance levels required for efficient pilot performance within the cockpit lie in the one log unit range of 0.01 to 0.1 mL (0.009 to 0.09 ft-L).

Results of a field study of operational instrument lighting levels by Dohrn (reference 9) differed from those of Bauer. With red and white instrument panel lighting, Dohrn found that luminance levels required for the legibility of instruments are in a 0.01 to 0.3 ft-L range. The minimum operational level for safe flight was observed to be in the 0.001 to 0.01 ft-L range. These values are based on the pilots' setting of instrument lighting levels in flight when preadapted to natural ambient lighting conditions. These studies did not involve the effects of preadapting luminances on the setting of instrument lighting levels.

LABORATORY STUDY METHODOLOGY

DESIGN VARIABLES

In the present study the effect of the ANVIS display and ambient luminance on the setting of instrument lighting levels was investigated by exposing the subject to various preadaptive lighting conditions. Before performing an instrument reading task, the subject preadapted to a lighting condition that was representative of a nighttime full moon ambient luminance or an ANVIS display luminance. The individual test conditions included a 0.00065 ft-L moonlight condition, a 0.2 ft-L ANVIS condition, and a 1.0 ft-L ANVIS condition.

The subject adjusted a single airspeed instrument light or a composite panel of instrument lights. The composite panel of instrument lights included primary instrument bezel lights, edge-lit panel lights, and glare shield flood lights.

This combination of three adaptation conditions and two instrument adjustment conditions resulted in a total of six treatment conditions (3 X 2).

SUBJECTS

Seven Air National Guard A-7 pilots and an Air Force C-130 pilot participated in the experiment. Subjects were administered refractive visual examinations and all had normal or corrected acuity of 20/25 or better. An AAMRL Night Vision Test (Appendix A) was also administered to evaluate the subject's visual performance under low light level conditions. All subjects were considered normal and "experienced" as pilots by their qualification to fly night missions.

TASK

The task was designed to emulate actual instrument reading tasks that a pilot performs when using ANVIS. This consisted of adjusting instrument lighting levels to read an airspeed instrument. The subject was required to glance down from the ANVIS display or ambient moonlight condition (screen external to the subject station) and read the instrument after adjusting instrument lighting.

The barrel readout and the pointer on the airspeed instrument (Figure 2) were read. The airspeed was recited by the subject with an accuracy of two knots.

APPARATUS

The major hardware components were: a subject's station, an experimenter's station, an ANVIS simulator, and an ambient light simulator.

SUBJECT'S STATION

The subject's station (Figure 3) was a night lighting mockup of an A-10 front instrument panel, containing four simulator instruments for the representation of primary flight instruments: Attitude Direction Indicator, Horizontal Situation Indicator, Airspeed Indicator, and Barometric Altitude Indicator. All other instruments were presented as flat pictures of instruments. White painted indicia elements on the pictures had the approximate reflectance characteristics of real instrument indicia.

Front instrument panel lighting was composed of three separate groups: primary instrument bezel lights, glare shield flood lights, and edge-lit panel lights. Each of the three lighting groups was separately adjusted by the subject.

Lighting for airspeed and altimeter instruments used full circular ring bezel lights. Lumicon(R) wedge lights were used for illumination of the attitude direction indicator and horizontal situation indicator instruments. General illumination of the front instrument panel was provided by flood lighting located beneath the instrument panel glare shield. Six edge-lit panel lights provided markings for the identification of front instrument panel controls and switches. Color coordinates of all of the lighting components were modified to meet the preliminary proposed ANVIS-compatible lighting specification (reference 10). Additional information concerning the front instrument panel lighting is included in Appendix B.

EXPERIMENTER'S STATION

The experimenter's station contained controls for presenting simulator instrument indicia and digital voltage displays for monitoring the luminance level of the three lighting groups and individual instrument bezel lights.

Controls for the selection of a single airspeed bezel light were also included at the experimenter's station. When a single bezel light was selected by the experimenter, the subject's potentiometer controlled only the airspeed instrument bezel light, while all other bezel lights were off.

ANVIS SIMULATOR

An ANVIS simulator (Figure 4) was used to adapt the subject to a display luminance of 1.0 or 0.2 ft-L, as determined by the test condition. This device provided the subject with a diffuse light source of uniform brightness (no image) and color over the display's entire 40-degree field of view. Light with chromaticity coordinates of a P-20 phosphor was obtained by filtering a tungsten source. The display luminance was adjusted with neutral density filters to within 15% of the desired test condition luminance.

AMBIENT LIGHT SIMULATOR

A projection screen in front of the subject was illuminated to simulate a condition of ground luminance on a full moonlit night (reference 11). The average 0.00065 ft-L (standard deviation of 1.9 for 9 measurements) luminance provided an ambient lighting condition to which the subject visually adapted. The light source consisted of a GE-7C7 incandescent light bulb, recessed in a cylindrical housing (2 inch diameter). A neutral density filter (ND=2.0) placed over the light source provided the desired luminance condition. The angular subtense or viewing angle of the screen was 34 degrees horizontally and 20 degrees vertically.

PROCEDURE

A set of instructions was read to each subject (Appendix C). They included the procedure for the experimental session and the events that would occur within a given trial.

A hypothetical mission segment of night-time low level navigation was described in which ANVIS would be used for visibility outside of the aircraft. It was emphasized that the subject should adjust instrument lighting to a minimum-safe level to avoid detection by adversaries.

The subject was seated 27 inches from the instrument panel. Features of the instrument panel lighting were pointed out. The function of the three lighting groups and corresponding dimmer controls was demonstrated.

The subject was dark adapted for 30 minutes prior to the start of the trial sequence. All other lights remained off during this period.

Preceding each trial the subject was exposed to a preadapting lighting condition for 1.5 minutes. The subject was required to look directly at the simulated ANVIS display or the simulated moonlight condition. The subject then adjusted the instrument lighting to a minimum level that he felt was necessary for readability of the airspeed instrument. In the first trial the subject adjusted the airspeed instrument bezel light to a level that he felt was necessary to read the pointer and barrel indicia. All other front instrument panel lights remained off. The subject was instructed to slowly increase the instrument lighting level until the instrument could be read following a brief glance down from the ANVIS display or the simulated moonlight condition. The subject was informed that reading the instrument should not require more than 2 seconds.

In the second trial the subject adjusted the luminance of three groups of the front instrument panel lighting. The subject performed the following sequence: 1- increased the primary instrument cluster lights until the airspeed instrument could be read by the method described above. 2- increased the edge-lit panel lights until the location of switches and knobs was referenced. 3- increased the flood lighting until the engine instrument cluster was adequately illuminated for the reading of gauge pointer positions. 4- made any necessary adjustments to the primary instrument cluster lights to compensate for the effects of the other two lighting groups.

The two trial sequences described above were performed in succession. All trials for a given preadapting lighting condition were performed consecutively. Five trials were given for each of the 6 experimental conditions. A total of 30 trials were given within the experimental session. One experimental session lasted approximately 2.25 hours and contained no rest breaks.

The three preadapting lighting conditions were counter-balanced to equalize the effects of fatigue and learning. For trials that followed a condition of higher preadapting luminance, an additional 10 minute dark adaptation period was given before testing under the lower luminance condition.

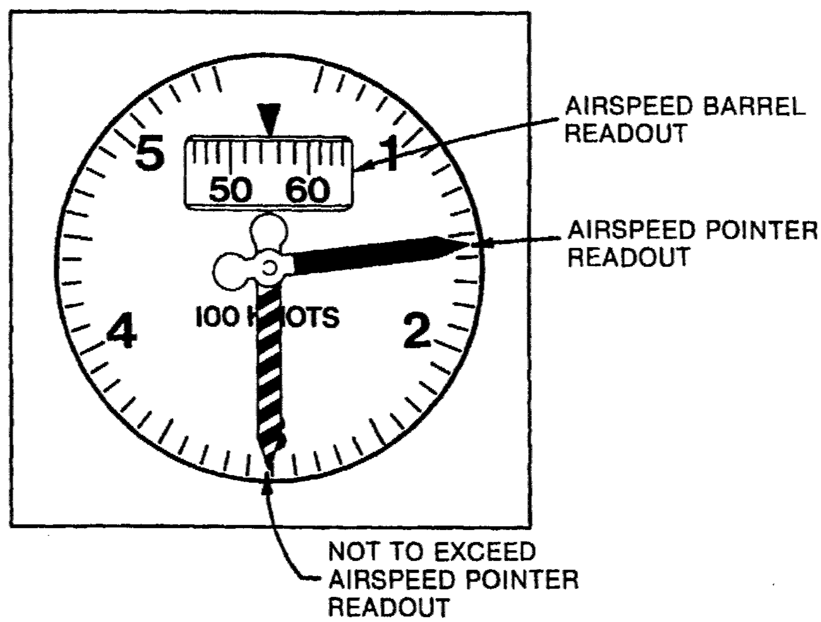

Figure 2. Diagram of Airspeed Simulator Instrument.

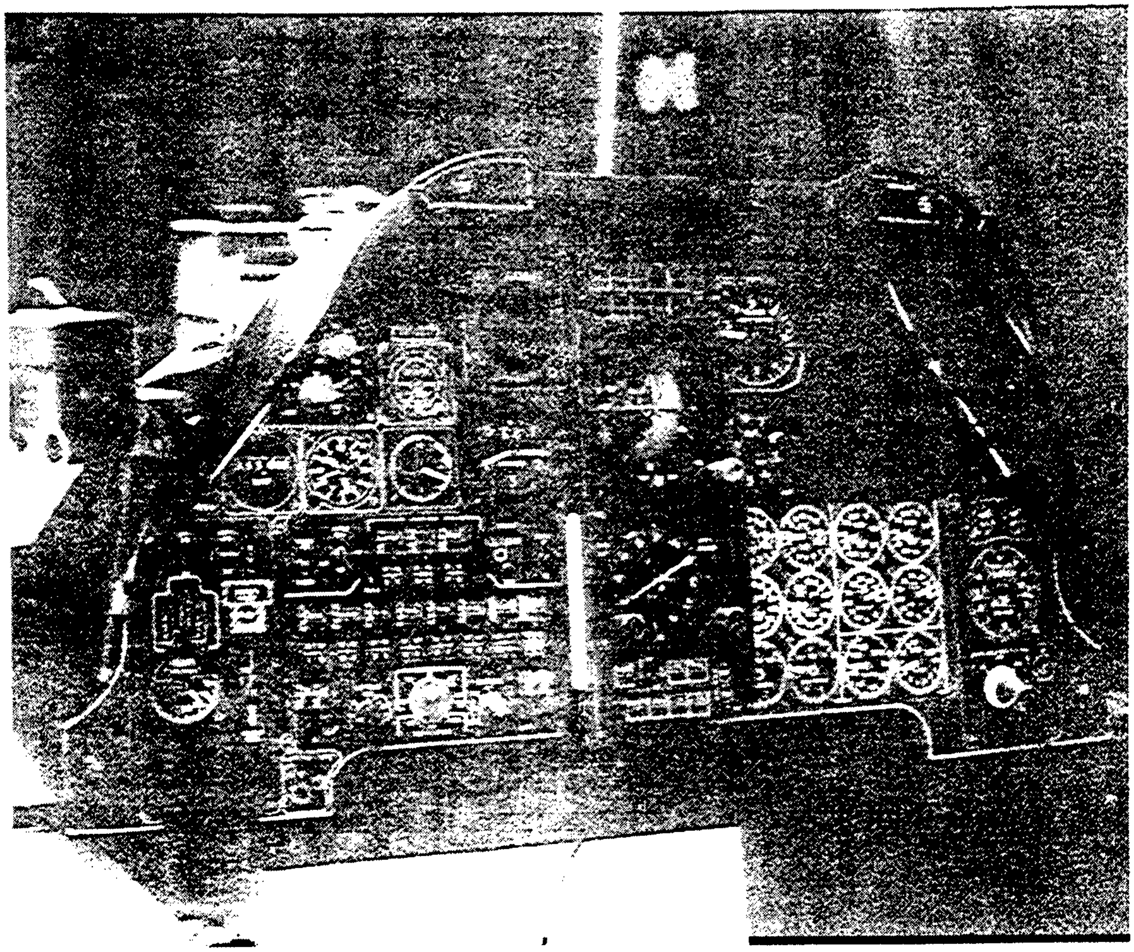

Figure 3. Subject's Station, consisting of an A-10 Front Instrument Panel Night Lighting Mockup. The Ambient Light Simulator is not present in the picture.

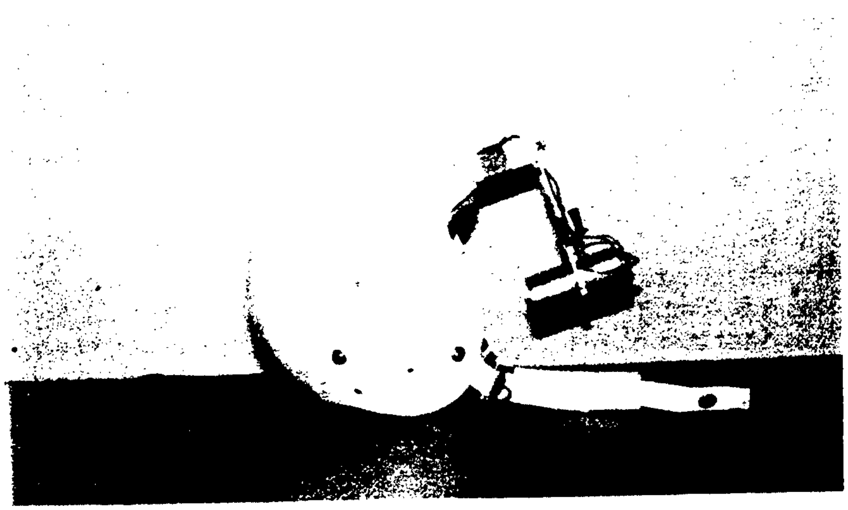

Figure 4. ANVIS Simulator with Helmet.

LABORATORY STUDY RESULTS

Tables 1 to 3 and Figures 5 to 7 summarize the results of the laboratory study. Tables 1 and 2 contain the mean luminance level setting and corresponding standard deviation for all 8 subjects combined, with 5 trials for each test condition. Measurement points for each lighting group are described in Appendix B.

Table 3 shows the mean luminance settings for the adjustment of the airspeed indicator light alone for individual subjects. All other lights remained off during this trial. Each luminance listed for an individual subject is an average of the 3 lighting conditions and the 5 trials of each condition. Substantial variability in individual subject's luminance settings are apparent. The mean values for subjects ranged from Ø.ØØ16 ft-L to Ø.Ø1Ø9 ft-L. The subject's age, night flying time in hours, and measured visual acuity are also included in this table.

An analysis of variance (ANOVA) was performed on the luminance data using the three adaptation conditions as factors. Results, shown in Tables 4 to 6, indicated that there was a significant difference in the adjustment of primary instrument lighting as a function of lighting condition ($p<.Ø1$). A Tukey's test indicated that lighting levels set by the subject to read the airspeed instrument, after adapting to the two ANVIS conditions, were significantly higher than those after adapting to the moonlight condition. However, comparison of the subject's setting of lighting levels following exposure to the two ANVIS conditions (1.Ø ft-L and the Ø.2 ft-L ANVIS) showed no significant differences. General results of the ANOVA were the same for trials involving the adjustment of the single airspeed instrument and for trials involving the composite panel of instrument lighting (primary lights, edge-lit panel lights, and flood lights).

A second and third ANOVA indicated that the subjects made no significant changes in edge-lit panel lighting or flood lighting levels as a result of preadaptation to the three lighting conditions. Tables 7 to 8 list results of these ANOVA.

Figure 5 illustrates the light level settings (mean of all subjects) for the three preadapting lighting conditions. It also compares airspeed instrument lighting levels for adjustment of the airspeed instrument light alone with that for the three lighting groups. The subjects' light level settings for trials involving the adjustment of a single airspeed instrument are approximately the same as those for trials involving the adjustment of the three lighting groups.

Mean luminance level settings as a function of subject age are shown in Figure 6. The product moment correlation coefficient, r, was $-$ Ø.41, which, for $n=8$ at the $p=Ø.1$ level is not statistically significant. A general trend for instrument lighting levels to decrease with increase in subject age is therefore not established statistically. Figure 6 also illustrates the somewhat broad range of luminance values set by individual subjects.

Figure 7 plots the subjects' mean airspeed luminance level settings (averaged for all three lighting conditions) against the subjects' night flying time. Six of the eight subjects had less than 500 hours of night flying time. For the eight subjects the product moment correlation coefficient between luminance settings and flight time was r=-0.19, which for p>0.1 is not statistically significant. Thus the apparent relationship of decreasing mean luminance levels with an increase in night flying experience is not established.

TABLE 1. MEAN LUMINANCE LEVEL SETTING FOR A SINGLE INSTRUMENT AND FOR A CLUSTER OF PRIMARY INSTRUMENTS WHEN PREADAPTED TO VARIOUS AMBIENT LIGHTING CONDITIONS.

	0.00065ft-L MOON	S	0.2ft-L ANVIS	S	1.0ft-L ANVIS	S
AIRSPEED ALONE	0.0043	(0.0029)*	0.0058	(0.0034)	0.0062	(0.0036)
AIRSPEED WITH CLUSTER	0.0044	(0.0028)	0.0064	(0.0037)	0.0073	(0.0042)

*STANDARD DEVIATION IN PARENTHESIS

TABLE 2. MEAN LUMINANCE LEVEL SETTING FOR THREE LIGHTING GROUPS WHEN PREADAPTED TO VARIOUS AMBIENT LIGHTING CONDITIONS.

	0.00065ft-L MOON	S	0.2ft-L ANVIS	S	1.0ft-L ANVIS	S
AIRSPEED-COMPENSATED	0.0040	(0.0026)	0.0061	(0.0034)	0.0065	(0.0039)
FLOODS	0.0138	(0.0175)	0.0155	(0.0156)	0.0202	(0.0160)
EDGE-LIT PANELS	0.0107	(0.0122)	0.0163	(0.0160)	0.0193	(0.0179)

*STANDARD DEVIATION IN PARENTHESIS

TABLE 3. MEAN LUMINANCE LEVEL SETTING ACROSS ALL THREE LIGHTING CONDITIONS FOR INDIVIDUAL SUBJECTS IN DECENDING ORDER OF LUMINANCE

SUBJECT NUMBER	LUMINANCE (ft-L)	AGE	NIGHT FLIGHT TIME (HOURS)	SNELLEN ACUITY RIGHT	SNELLEN ACUITY LEFT
7	0.0109	26	70	20/20	20/20
1	0.0086	34	100	20/25	20/25
6	0.0066	25	50	20/25	20/25
5	0.0060	36	350	20/15	20/15
8	0.0048	38	4700	20/20	20/15
4	0.0032	29	90	20/25	20/15
2	0.0020	34	1000	20/25	20/20
3	0.0016	34	270	20/20	20/20

TABLE 4. ANOVA FOR SINGLE AIRSPEED INSTRUMENT SETTINGS WHEN PREADAPTED TO VARIOUS AMBIENT LIGHTING CONDITIONS.

SOURCE	DF	MEAN SQUARE	F	P
SUBJECT	7	0.001543	42.0	0.0001
CONDITION	2	0.000443	12.0	0.0009
ERROR	14	0.000037		

TABLE 5. ANOVA FOR PRIMARY INSTRUMENT CLUSTER SETTINGS WHEN PREADAPTED TO VARIOUS AMBIENT CONDITIONS.

SOURCE	DF	MEAN SQUARE	F	P
SUBJECT	7	0.001710	34.2	0.0001
CONDITION	2	0.000787	15.8	0.0003
ERROR	14	0.000050		

TABLE 6. ANOVA FOR COMPENSATED PRIMARY INSTRUMENT CLUSTER SETTINGS WHEN PREADAPTED TO VARIOUS AMBIENT CONDITIONS.

SOURCE	DF	MEAN SQUARE	F	P
SUBJECT	7	0.001859	38.8	0.0001
CONDITION	2	0.000773	16.1	0.0002
ERROR	14	0.000048		

TABLE 7. ANOVA FOR EDGE-LIT PANEL LIGHTS WHEN PREADAPTED TO VARIOUS AMBIENT LIGHTING CONDITIONS.

SOURCE	DF	MEAN SQUARE	F	P
SUBJECT	7	0.000640	15.4	0.0001
CONDITION	2	0.000152	3.6	0.0551
ERROR	14	0.000042		

TABLE 8. ANOVA FOR FLOODLIGHTS WHEN PREADAPTED TO VARIOUS AMBIENT LIGHTING CONDITIONS.

SOURCE	DF	MEAN SQUARE	F	P
SUBJECT	7	0.010626	13.3	0.0001
CONDITION	2	0.002550	3.2	0.0724
ERROR	14	0.000800		

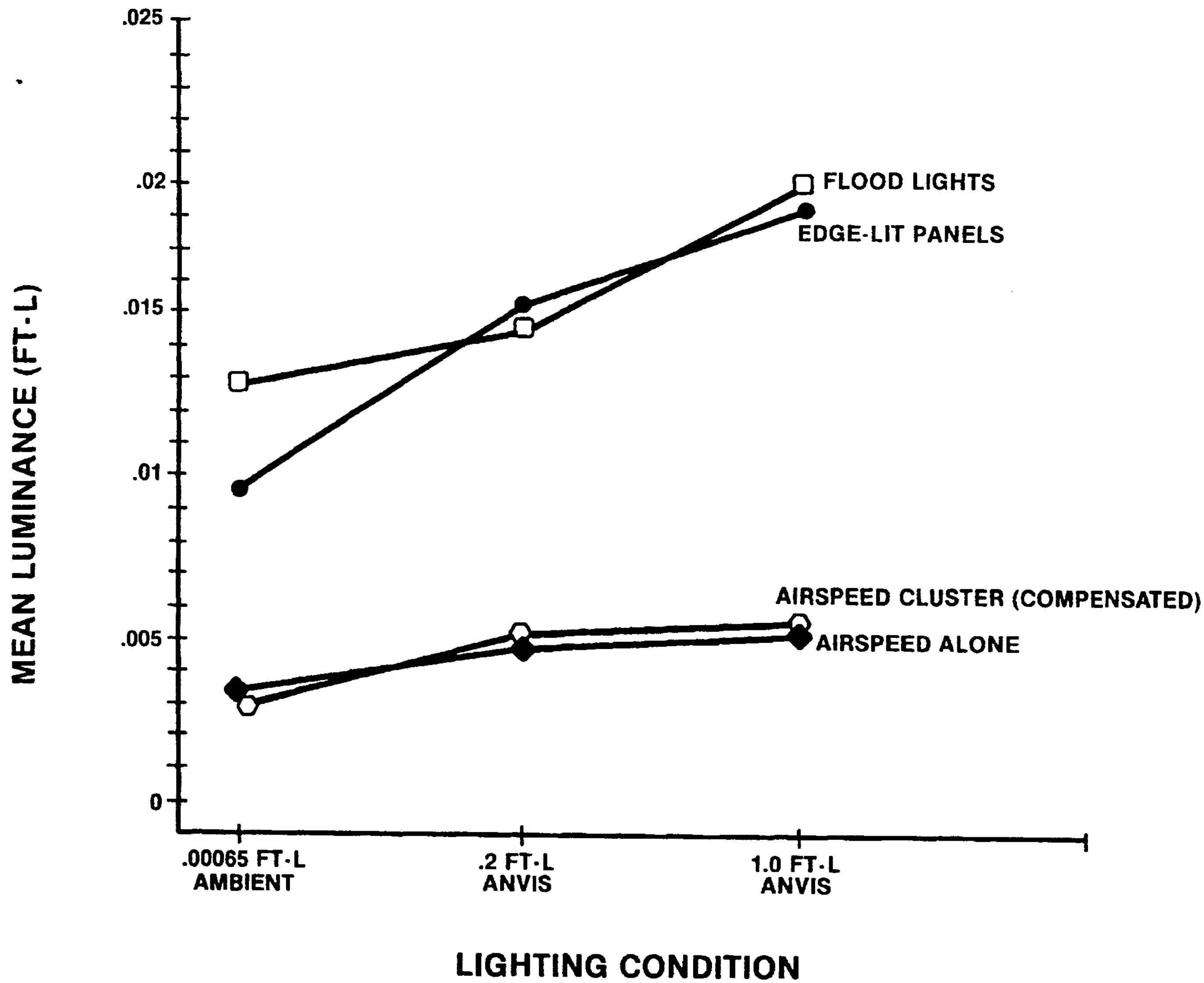

Figure 5. Mean Luminance Level Setting for the Three Lighting Groups and Airspeed Alone (Across All Subjects) as Function of Preadapting Lighting Conditions.

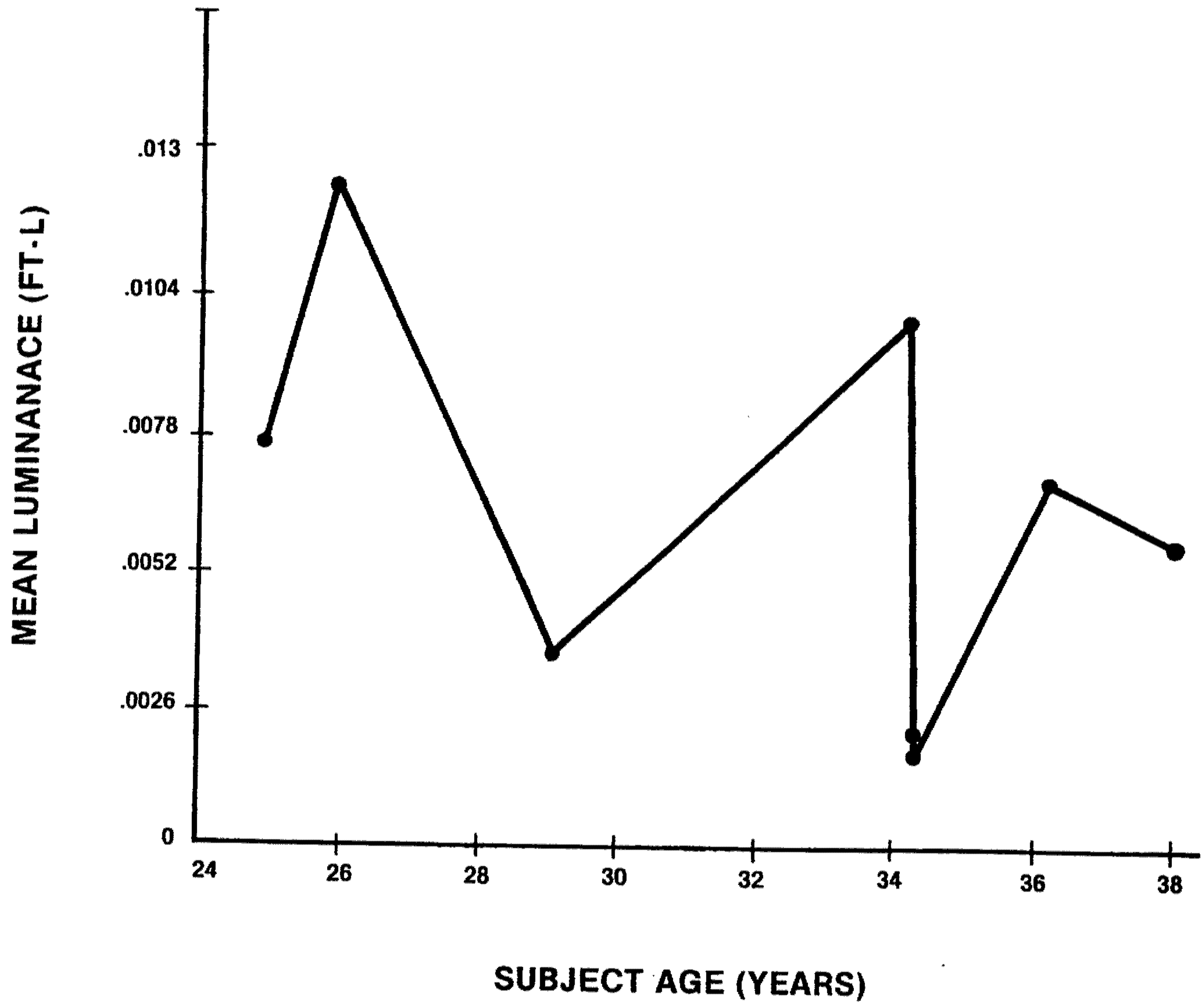

Figure 6. Mean Luminance Setting of Airspeed Indicator

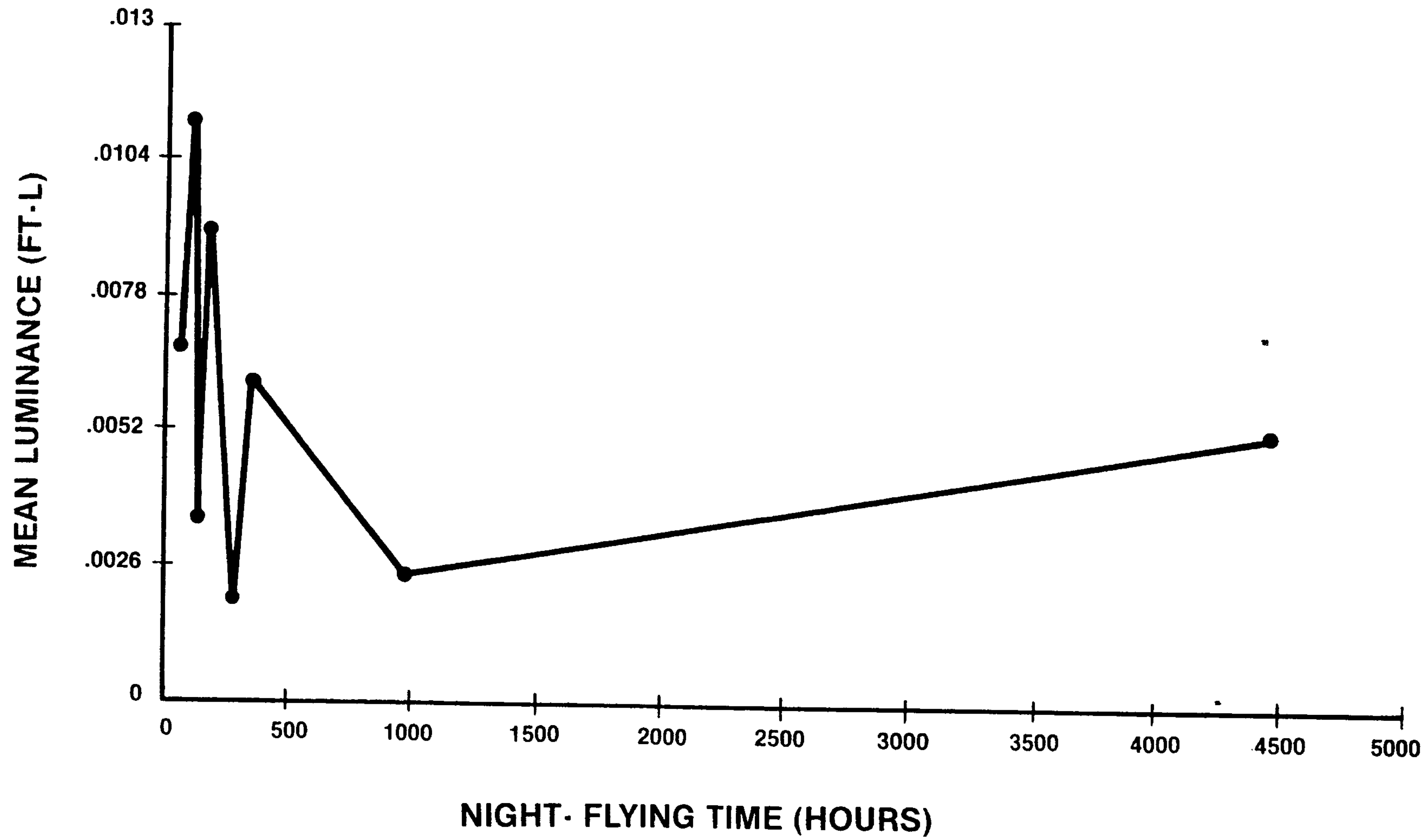

Figure 7. Mean Luminance Setting of the Airspeed Indicator Light as a Function of Night Flying Time.

FIELD STUDY METHODOLOGY

DESIGN VARIABLES

In the operational environment, many factors influence the pilot's setting of instrument lighting levels. The following variables are "independent variables" in the broad sense that each may influence the pilot's setting of instrument lighting levels. These variables are summarized as follows:

* Level of Dark Adaptation- Ambient light level (i.e. moonlight, starlight, ground light, etc.) determines the ANVIS display brightness, which in turn, is responsible for the human visual adaptation state.

* Individual Night Vision- Differences in an individual's night vision contribute to the setting of instrument lighting levels. Presently, pilot visual screening tests do not consider deficiencies in human night vision.

* Interference with NVGs- Current special operations lighting designs are, in some instances, reported to be only partially compatible with night vision goggles. As a result, pilots set instrument lighting levels to reduce or eliminate interference with the ANVIS displayed imagery (particularly reflections in the windscreen).

* Lighting/Crew Station Design- Many differences exist in lighting and crew stations for various operational aircraft, including the types of instruments, indicia, geometries, lighting componenets, etc. All influence instrument lighting levels.

* Training/Type of Mission- Special operations training requires that instrument lighting levels be set for minimum readability to reduce visibility from outside. This training can be related to a particular mission type.

The dependent variable in the field study was the luminance level of the instrument indicia set by the pilot.

AIRCRAFT AND EQUIPMENT

Lighting measurements were made on board three Air Force special operations aircraft: C-141, C-130, and HH-53. Each of these aircraft is equipped with lighting systems that are compatible with NVGs. The designs consist primarily of flood lighting located beneath the front instrument panel glare shield (reference 11). Additional measurements were made onboard a National Guard OH-6 aircraft. The lighting design for this aircraft consisted primarily of ring bezel lights or post lights located on individual instruments.

Measurements were made with a Pritchard 1980 photometer with close-up lens, a Spectra RS-1 barium sulfate plaque, and a tripod.

PROCEDURE

A verbal description of the lighting field study was given to crew members in the preflight briefing. This description included the purpose of the study, the time required for measurements, and the procedure for data collection. No specific instructions describing how to set instrument lighting levels were given. An alternate method of data collection was used when the method described conflicted with other mission requirements. The data collection sequence was performed as follows:

1- The aircraft landed at an austere airstrip and the pilot was instructed to remove his ANVIS.
2- After adapting to ambient lighting conditions, the pilot was instructed to adjust lighting levels to make aircraft instruments readable without ANVIS.
3- Photometric measurements of the front instrument panel were taken.
4- The pilot was instructed to put on ANVIS.
5- After visually adapting to the ANVIS display field, the pilot was instructed to adjust lighting levels to make aircraft instruments legible while utilizing the ANVIS look-under design.
6- Photometric measurements of the front instrument panel were taken.

The alternate method of data collection was as follows:

1- Lighting levels were set by the pilot in flight during a mission segment that typified ANVIS usage.
2- Photometric measurements of the front instrument panel were taken after the flight. Lighting levels set in flight were unchanged. Tarps were placed over the windscreens to block out parking area lights.

Because no additional instrument bezel lights were present on each of the three Air Force front instrument panel designs, illuminance measurements were the primary method of data collection. Direct luminance measurements were the method used for data collection on board the OH-6 aircraft. Lighting measurement techniques are described in Appendix D.

FIELD STUDY RESULTS

Data presented in Tables 9 to 11 are results of lighting measurements taken on board C-141, C-130, and the HH-53 special operations aircraft.

The tabular form of the illuminance data indicates the approximate physical location that measurements were made on the front instrument panel. The gradation of lighting, shown by measurements of the high, middle, and low position on the front instrument panel, is typical of a flood lighting distribution for lights mounted beneath the instrument panel glare shield. Illuminance data in Tables 9 to 11 indicate a rather broad range of lighting levels across each of the front instrument panels measured. Illuminance levels at the bottom of the panel (low position) ranged from 16% to 33% of the luminance levels at the top (high position) of the panel for any given crew position.

For data shown in Tables 9 and 10, the pilot adjusted instrument lighting levels, once when adapted to an ambient lighting condition (not wearing ANVIS) and again after adapting to the ANVIS display luminance. Table 11 lists lighting levels set by the pilot during a mission segment using ANVIS. Each illuminance measurement was taken in a position directly over the instrument face.

Table 12 lists results of lighting measurements taken onboard a National Guard OH-6 aircraft. Luminance of the white indicia ranged from 0.030 to 0.086 ft-L. The minimum measured instrument luminance was 35% of the maximum measured instrument luminance.

Tables 13 to 15 show the approximate luminances of white instrument indicia based on known reflectance characteristics of indicia paint. This data was calculated from illuminance data of Tables 9 to 11. MIL-L-27160C (reference 13) specifies white 37875, black 37038, and gray 36440 as the indicia colors. The reflectances of these paints as measured in the laboratory, were 86.3%, 5.5% and 46.8% respectively. Paint chips were provided in FED-STD-595 (reference 14). For the calculated lighting data shown in Tables 13 to 15 the range of luminance levels, set by pilots when using ANVIS, was 0.004 to 0.086 ft-L.

Mean luminances calculated for various instrument panel lighting data are listed in Table 16. A description of the data points used in the calculations as well as standard deviations are included in the table. The grading effect of flood lighting resulted in high standard deviations.

Figure 8 illustrates the effect of ANVIS use on instrument lighting levels for field data collected onboard the C-130 and C-141 aircraft. The graph shows that the pilots' setting of instrument lighting levels was higher when using ANVIS. Figure 8 also compares the pilot's ANVIS lighting levels with the copilot's non-ANVIS settings. It can be observed that the non-ANVIS copilot's ANVIS lighting levels are at approximately the same luminance level as the pilot's ANVIS lighting levels.

TABLE 9. PHOTOMETRIC MEASUREMENTS OF THE C-141 FRONT INSTRUMENT PANEL FOR PILOT WITH/WITHOUT ANVIS.

FLOOD LIGHT MEASUREMENTS, IN ft-C, NOT USING ANVIS

panel position	pilot console	center console	copilot console
high	0.005	0.024	0.044
middle	0.002	0.015	0.028
low	0.001	0.008	0.009

FLOOD LIGHT MEASUREMENTS, IN ft-C, USING ANVIS

panel position	pilot console
high	0.100
middle	0.050
low	0.025

(center and copilot level were unchanged)

ADI LUMINANCE LEVEL, IN ft-L, USING ANVIS

panel position	pilot console	copilot console
above horizon line	0.050	0.053
below horizon line	0.006	0.005

HSI LUMINANCE LEVEL, IN ft-L, USING ANVIS

panel position	pilot console	copilot console
pointer at 6 o'clock	0.021	0.011
black background	0.006	0.001

Notes: -Date Collected: 6/27/84
-Airplane: tail# 0131, Electroluminescent lighting
-Conditions: hazy, starlight, no ground lights

TABLE 1Ø. PHOTOMETRIC MEASUREMENTS OF THE C-13ØE (AWADS) FRONT INSTRUMENT PANEL FOR PILOT WITH/WITHOUT ANVIS.

FLOOD LIGHT MEASUREMENTS, IN ft-C, NOT USING ANVIS

panel position	pilot console	center console	copilot console
high	Ø.ØØ2	Ø.ØØ2	Ø.Ø82
middle	Ø.ØØ1	Ø.ØØ2	Ø.Ø34
low	Ø.ØØ1	Ø.Ø2Ø	Ø.Ø14

FLOOD LIGHT MEASUREMENTS, IN ft-C, USING ANVIS

panel position	pilot console
high	Ø.Ø12
middle	Ø.ØØ7 (center and copilot levels were unchanged)
low	Ø.ØØ4

ADI LUMINANCE LEVEL, IN ft-L, USING ANVIS

panel position	pilot console	copilot console
above horizon line	Ø.ØØ2	Ø.ØØ2
below horizon line	Ø.ØØØ3	Ø.ØØØ4

Notes: -Date Collected: 8/14/84
-Airplane: Tail# 1276, Electroluminescent lighting
-Location: Pope AFB, no ground lights
-Conditions: approximately 8Ø% full moon

TABLE 11. PHOTOMETRIC MEASUREMENTS OF THE HH-53 (PAVELOW) FRONT INSTRUMENT PANEL WITH ANVIS.

FLOOD LIGHT MEASUREMENTS, IN ft-C, USING ANVIS

panel position	pilot console		center console		copilot console	
high	Radar ALt	Ø.Ø74			Airspeed	Ø.Ø64
middle	ADI	Ø.Ø52			Radar Alt	Ø.Ø18
	VVI	Ø.Ø5Ø			ADI	Ø.Ø32
low	Rotor RPM	Ø.Ø22	clock	Ø.ØØ5	VVI	Ø.Ø18
			eng temp	Ø.ØØ9	Rotor RPM	Ø.Ø14

ADI LUMINANCE, IN ft-L, USING ANVIS

panel position	pilot console
above horizon line	Ø.Ø11
below horizon line	Ø.ØØ4

HSI LUMINANCE, IN ft-L, USING ANVIS

panel position	pilot console
bearing pointer	Ø.ØØ3

Notes: -Date Collected: 11/1/84
-Airplane: Tail# 165Ø, filtered incandescent flood lighting
-Location: parking area with tarps covering windscreens
-Conditions: 5Ø% moon, clear
-lighting levels were set during mission segments using NVGs
-both pilot and copilot were using ANVIS

TABLE 12. PHOTOMETRIC MEASUREMENTS OF THE OH-6A FRONT INSTRUMENT PANEL WITH ANVIS.

Instrument	White Pointer Luminance (ft-L)	Adjacent Black Luminance (ft-L)
Altimeter	0.063	0.006
Clock	0.031	0.002
RMI	0.086	0.003
Attitude Indicator	0.045	0.007
Rotor Tach	0.082	0.006
Airspeed	0.047	0.021
Torque	0.057	0.005
N. Tach	0.030	0.013

Notes:
- Date Collected: 4/2/85
- Airplane: Tail# 15188, incandescent bezel lights by Aerospace Optics
- Location: in hangar with tarps covering windscreens
- Conditions: full moon, clear
- Lighting levels were set in flight during a low level flight
- Only direct instrument measurements of instrument pointers were made (ft-L)
- Measurement data in the table is not ordered by position on the front instrument panel

TABLE 13. C-141 CALCULATED LUMINANCE, IN ft-L, FOR WHITE PAINTED INDICIA.

NOT USING ANVIS

panel position	pilot console	center console	copilot console
high	Ø.ØØ4	Ø.Ø21	Ø.Ø38
middle	Ø.ØØ2	Ø.Ø13	Ø.Ø24
low	Ø.ØØ1	Ø.ØØ7	Ø.ØØ8

USING ANVIS

panel position	pilot console
high	Ø.Ø86
middle	Ø.Ø43
low	Ø.Ø22

(center and copilot levels were unchanged)

TABLE 14. C-13Ø CALCULATED LUMINANCE, IN ft-L, FOR WHITE PAINTED INDICIA.

NOT USING ANVIS

panel position	pilot console	center console	copilot console
high	Ø.ØØ2	Ø.ØØ2	Ø.Ø71
middle	Ø.ØØ1	Ø.ØØ2	Ø.Ø29
low	Ø.ØØ1	Ø.Ø17	Ø.Ø12

USING ANVIS

panel position	pilot console
high	Ø.Ø1Ø
middle	Ø.ØØ6
low	Ø.ØØ3

(center and copilot levels were unchanged)

TABLE 15. HH-53 CALCUALATED LUMINANCE, IN ft-L, FOR WHITE PAINTED INDICIA.

USING ANVIS

panel position	pilot console		center console		copilot console	
high	Radar Alt	Ø.Ø64			Airspeed	Ø.Ø55
middle	ADI	Ø.Ø45			Radar Alt	Ø.Ø16
low	VVI	Ø.Ø43			ADI	Ø.Ø28
	Rotor RPM	Ø.Ø19	clock	Ø.ØØ4	VVI	Ø.Ø16
			eng temp	Ø.ØØ8	Rotor RPM	Ø.Ø12

TABLE 16. AVERAGE LUMINANCES CALCULATED FOR MEASUREMENTS ON AIRCRAFT.

Aircraft	Location/Condition	# of Measurements	Mean(ft-L)	S
C-141	all of panel/no ANVIS	9	Ø.Ø13	(Ø.Ø12)*
C-141	pilot station/no ANVIS	3	Ø.ØØ2	(Ø.ØØ2)
C-141	pilot station/with ANVIS	3	Ø.Ø5Ø	(Ø.Ø33)
C-13Ø	all of panel/no ANVIS	9	Ø.Ø15	(Ø.Ø23)
C-13Ø	pilot station/no ANVIS	3	Ø.ØØ1	(Ø.ØØ1)
C-13Ø	pilots station/with ANVIS	3	Ø.ØØ6	(Ø.ØØ4)
HH-53	pilot station/with ANVIS	4	Ø.Ø43	(Ø.Ø18)
HH-53	copilot station/with ANVIS	5	Ø.Ø25	(Ø.Ø18)
OH-6	pilot station/with ANVIS	8	Ø.Ø55	(Ø.Ø21)

*STANDARD DEVIATION IN PARENTHESIS

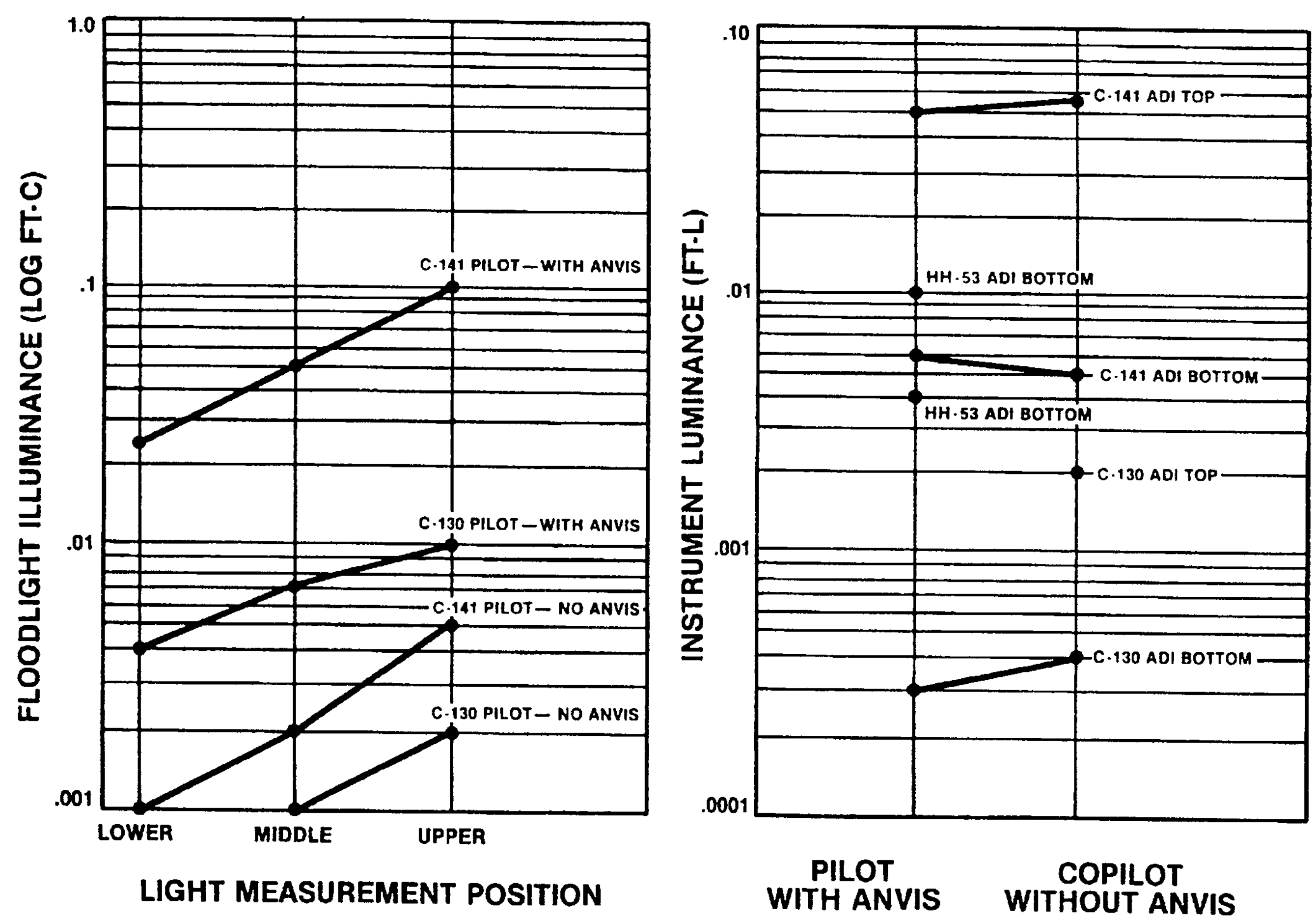

Figure 8. Effect of ANVIS on Instrument Lighting Levels

DISCUSSION

As indicated previously, one of the objectives of this work is to determine luminance levels required for instrument legibility when the visual system is adapted to ANVIS display luminance. The data derived from these studies can then be used to define an accurate test luminance for acceptance procedures of ANVIS compatible lighting components.

In the currently proposed specification, various lighting characteristics (i.e. chromaticity and spectral emissions) are tested for acceptance at luminance levels that are estimated to be representative of a pilot's actual operational levels. For the spectral emission acceptance procedure (by ANVIS radiance units, paragraph 3.2.5.1), the test condition luminance is Ø.1 ft-L. For the color acceptance procedure (by C.I.E. chromaticity coordinates, paragraph 3.2.4.1) the test condition luminance is Ø.Ø5 ft-L. The currently-estimated operational luminance levels do not consider potential effects of the preadapting ANVIS display luminance.

The laboratory results show that preadaptation to light sources of higher luminance (1.Ø ft-L or Ø.2 ft-L ANVIS condition compared to the Ø.ØØØ65 ft-L ambient condition) result in a corresponding increase in the lighting levels needed for readability of instruments. A closer examination of the data reveals that actual increases in instrument lighting levels, although significant, were small when compared to the corresponding change in preadapting luminance conditon. Increasing the preadapting luminance by roughly a factor of 3ØØ (Ø.ØØØ65 ft-L to the Ø.2 ft-L condition in Table 2), resulted in an increase in the airspeed instrument lighting levels by a factor of 1.5 (Ø.ØØ4Ø ft-L to Ø.ØØ61 ft-L). Similarly, an increase in preadapting luminance by a factor of 15ØØ (Ø.ØØØ65 ft-L to 1.Ø ft-L condition in Table 2), resulted in an increase in the airspeed instrument lighting levels by a factor of 1.6 (Ø.ØØ4 ft-L to Ø.ØØØ65 ft-L). This result indicates that this broad range of preadapting luminance has very little affect on pilot adjusted instrument lighting levels. In fact the increase in instrument lighting level, resulting from the 1.Ø ft-L lighting condition, is less than the range of mean lighting levels set by individual subjects.

Laboratory results also show luminance levels of the three lighting groups to be lower than the Ø.1 ft-L test luminance condition described in the draft specification. For the 1.Ø ft-L ANVIS condition, the mean luminance levels for the three front instrument panel lighting groups were as follows: Ø.ØØ65 ft-L for primary instrument cluster, Ø.Ø193 ft-L for the edge-lit panel lights and Ø.Ø2Ø2 ft-L for the flood lights. Each of these luminance values represents a single measurement point on the front instrument panel. For each lighting group, a range of luminance is actually defined, for various locations on the front instrument panel. It is notable that these luminance values are very much dependent on lighting design (i.e. luminance distribution), the geometry of the front instrument panel, and the instructions provided to the subject. Instructions requiring the subject to "set instrument lighting to a minimum level" are believed to have resulted in these low luminance values.

The setting of the airspeed instrument lighting level was based on the subject's need to identify indicia on the instrument barrel readout. The character size of the barrel readout numbers is a significant factor in the luminance required for the subject to read the airspeed instrument. These are estimated to be 3.0 minute (20/60) targets (appendix E). This character size is therefore slightly larger than the 2.0 (20/40) to 2.5 (20/50) minute target size range, defined as typical for most aircraft indicia design. Direct comparison of the results of this experiment with threshold acuity studies found in the literature is not possible though due to the completely different methodologies employed in the experiments.

The most obvious finding of the field study was that instrument lighting levels were, in all cases, lower than the currently proposed 0.1 ft-L test condition. For the pilots' settings of instrument lighting levels when using ANVIS, luminance values ranged from 0.003 to 0.086 ft-L for the C-141, C-130, HH-53, and OH-6 aircraft. The data collected on board these aircraft seem to indicate that a test condition luminance less than 0.1 ft-L would more accurately describe a condition of operational usage. Using the mean luminance data of Table 16, the operational levels were in the 0.006 to 0.055 ft-L range. This range of values is probably more "typical" of the operational luminances used than the specified 0.1 ft-L test condition. These calculated mean values, however, are dependent upon the location of measurement on the front instrument panel. Interpretation of these values must be considered, with individual data points used in the calculations.

Luminance uniformity requirements of the currently proposed specification are expected, generally, to contribute to lower luminance level settings than are present with instrument panels of broader luminance distribution. The specification (paragraph 3.3.5.2) states that the luminance ratio between lighted instruments shall be no greater than 1.75 to 1. It is notable that the OH-6 aircraft instrument lighting does not meet this requirement. For the 0.030 ft-L and 0.086 ft-L (Table 12) measurements, the luminance ratio is 2.87 to 1. Similarly, the C-141, C-130, and HH-53 aircraft do not meet this requirement.

CONCLUSIONS

The effect of a preadapting ANVIS display luminance results in a significant increase in primary instrument lighting levels set by pilots; however, this increase is small when compared to the change in preadapting luminance. When preadapted to the ANVIS display luminance (1.0 ft-L) an increase in instrument lighting levels, by a factor of 1.6 may be expected when compared to instrument lighting levels set following a preadaption condition of moonlight (0.00065 ft-L ambient).

There seems to be reasonable evidence to indicate that the current luminance test condition of 0.1 ft-L is higher than instrument lighting levels that are typically encountered in the field. Luminance measurements made on board the C-141, C-130, HH-53, and OH-6 aircraft show lighting levels to be generally less than 0.06 ft-L and to contain luminances in the 0.003 to 0.086 ft-L range.

APPENDIX A
NIGHT VISION TEST

The current AAMRL Night Vision Test (NVT) determined luminances required for the threshold acuity of Snellen characters. The subject was required to identify the orientation (up, down, right, left) of characters presented after adjusting luminance to a required level.

The threshold luminance required for the recognition of a target of 2.5 minute visual angle (2Ø/5Ø) is shown in Table A.1 for each of the eight subjects. The luminance level, as set for the legibility of the airspeed instrument is also included in this table. The calculated mean is Ø.Ø16 ft-L with a standard deviation of Ø.ØØ5 for the eight subject values. All individual subject data is within two standard deviations of the subject population mean.

No statistical correlation between the AAMRL Night Vision Test data and the laboratory study data was found (r=Ø.Ø7, p=Ø.8631).

TABLE A.1 NIGHT VISION TEST DATA FOR TARGET OF 2.5 MINUTE VISUAL ANGLE AND LABORATORY LUMINANCE DATA FOR SUBJECT'S SETTING OF THE AIRSPEED INDICATOR LIGHT ALONE.

SUBJECT NUMBER	NVT LUMINANCE (ft-L)	AIRSPEED LUMINANCE ALONE NUMBER FOR Ø.ØØØ65 ft-L AMBIENT (ft-L)
1	Ø.Ø19	Ø.ØØ75
2	Ø.Ø21	Ø.ØØ11
3	Ø.Ø13	Ø.ØØ11
4	Ø.ØØ6	Ø.ØØ24
5	Ø.Ø13	Ø.ØØ52
6	Ø.Ø16	Ø.ØØ45
7	Ø.Ø15	Ø.ØØ91
8	Ø.Ø21	Ø.ØØ3

APPENDIX B
SUBJECT STATION INSTRUMENT PANEL LIGHTING

All of the front instrument panel utilized electroluminescent lighting. Individual components used to illuminate the simulator instruments are described in Table B.1.

Luminance measurements of edge-lit panel lights were made at rated component voltage. These data, listed in Table B.2, describe the luminance uniformity of various edge-lit panels. The Weapons Panel knob was used to describe the luminance of the edge-lit panel lighting group for subject data listed in the laboratory results section. Luminance measurements at other locations are also shown in this table. Each table entry is the average of 3 measurements.

Luminance measurements of the 12 engine instrument gauges (photographic pictures) were made with flood lighting at rated voltage. Each value listed in Table B.3 represents a luminance measurement of a single instrument pointer in the engine instrument cluster. The Fuel Flow engine instrument pointer (row 2, column 3 in the table below) was used to describe the flood lighting luminance for subject data given in the results section of this report.

Luminance measurements of the individual primary instruments are shown in Table B.4. The index marker of the barrel readout was used as the measurement point for the airpeed instrument. All other primary instrument lighting levels may be expressed relative to this measurement location. Contrast was calculated by the formula provided in MIL-L-27160C (USAF): $C=(B2-B1)/B1$, where: B2 is the luminance of the white or gray area and B1 is the luminance of the black area. A loss of contrast, seen as cloudiness on the instrument face, is measured for instruments using the Lumicon Wedge lighting component. The contrast of the Attitude Direction Indicator Instrument indicia is notably poor.

The chromaticity coordinates of all individual lighting components were modified to comply with the proposed AN/AVS-6 lighting compatibility specification. Color coordinates of the modified lighting components are shown in Table B.5. A graph of the modified C.I.E. chromaticity coordinates is shown in Figure B.1.

All luminance data described in the laboratory results section of this report were calculated from voltages, using the digital voltage readout located at the experimenter's station. Figure B.2 shows the relationship between voltage and luminance for various lighting groups. These curves show that measurement of voltage input to a lighting circuit does accurately and precisely track luminance. The luminance range containing the least accuracy is the region of the curve with the largest slope. For Figure B.2, showing the voltage to luminance relationship for measurement of the Airspeed Instrument barrel readout, the largest slope is in the 80.0 to 115.0 volt range. The corresponding luminance is in the 0.006 to 0.012 ft-L range. For a change of .1 volts (accuracy of voltage readout at the experimenters station) the change in luminance is 0.00002 ft-L. This accuracy is an order of magnitude better than needed for purposes of this experiment.

Photometric measurements were made to ensure that the lighting components and their corresponding power supplies were stable with time. It was also determined that power supply loading effects, created by the use of various lighting groups, were negligible.

Reflectance characteristics of the photographic pictures were measured. The reflectance of white indicia elements was 51%. The reflectance of black indicia elements was 16%. The resulting contrast was C=2.2.

TABLE B.1 LIGHTING COMPONENTS USED FOR ILLUMINATION OF THE PRIMARY INSTRUMENT CLUSTER.

Description	Manufacturer/Model	Instrument Illuminated
3 Inch Ring Bezel	Midland Ross/PN 20-0187-5	Airspeed Ind.
3 Inch Ring Bezel	Midland Ross/PN 2-00187-5	Altimeter Ind.
Lumicon Wedge	Control Products/ ----	Attitude Direction Ind.
Lumicon Wedge	Control Products/ ----	Horizontal Situation Ind.

TABLE B.2 LUMINANCE UNIFORMITY OF EDGE-LIT PANEL LIGHTING AT MEASUREMENT POINTS ON VARIOUS EDGE-LIT PANELS.

Panel#	Indicia/Location	Mean (ft-L)	S
1	"J" of "JET"	0.073	(0.006)*
2	"H" of "HUD"	0.072	(0.019)
3	"D" of "Down Lock Override"	0.106	(0.014)
4	"R" of "Release Mode"	0.141	(0.004)
4	"Weapons Panel Knob"	0.307	(0.027)
5	"S" of "Sys"	0.072	(0.007)

*STANDARD DEVIATION IN PARENTHESIS

TABLE B.3 LUMINANCE UNIFORMITY OF ENGINE INSTRUMENT ILLUSTRATIONS, IN ft-L

Row#/Column#	1	2	3	4
1	0.0075	0.0121	0.0112	0.0115
2	0.0144	0.0110	0.0088	0.0089
3	0.0075	0.0071	0.0034	0.0043

TABLE B.4 LUMINANCE UNIFORMITY AND CONTRAST CALCULATIONS FOR THE PRIMARY INSTRUMENT CLUSTER.

Instrument	Indicia/Location	Luminance (ft-L) white/gray	Luminance (ft-L) black	Contrast
Attitude Ind.	tick mark at 3 oclock	0.0064	0.0048	0.3
	"O" at bottom	0.0052 (gray)	0.0045	0.3
	"M" near top	0.0092 (gray)	0.0089	0.03
Hor. Sit. Ind.	upper portion	0.0155	0.0031	4.1
	upper portion	0.0122	0.0026	3.6
	lower portion	0.0545	0.0206	15.3
	lower portion	0.0329	0.0022	14.3
Airspeed Ind.	1 knot	0.00752	0.0004	19.9
	150 knots	0.0059	0.0004	15.5
	300 knots	0.0032	0.0004	6.8
	450 knots	0.0091	0.0006	15.3
	index mark	0.0142		

TABLE B.5 COLOR COORDINATES FOR INDIVIDUAL LIGHTING COMPONENTS AFTER MODIFICATIONS MADE TO COMPLY WITH THE AN/AVS-6 LIGHTING SPECIFICATION.

Lighting Component	CIE Coordinates x	CIE Coordinates y	Graph Symbol
Grimes Full Circular Bezels	0.251	0.544	□
Lumicon Bezel	0.213	0.532	○
Glare Shield Floods	0.277	0.529	⬡
Edge Lit Panel	0.275	0.651	△

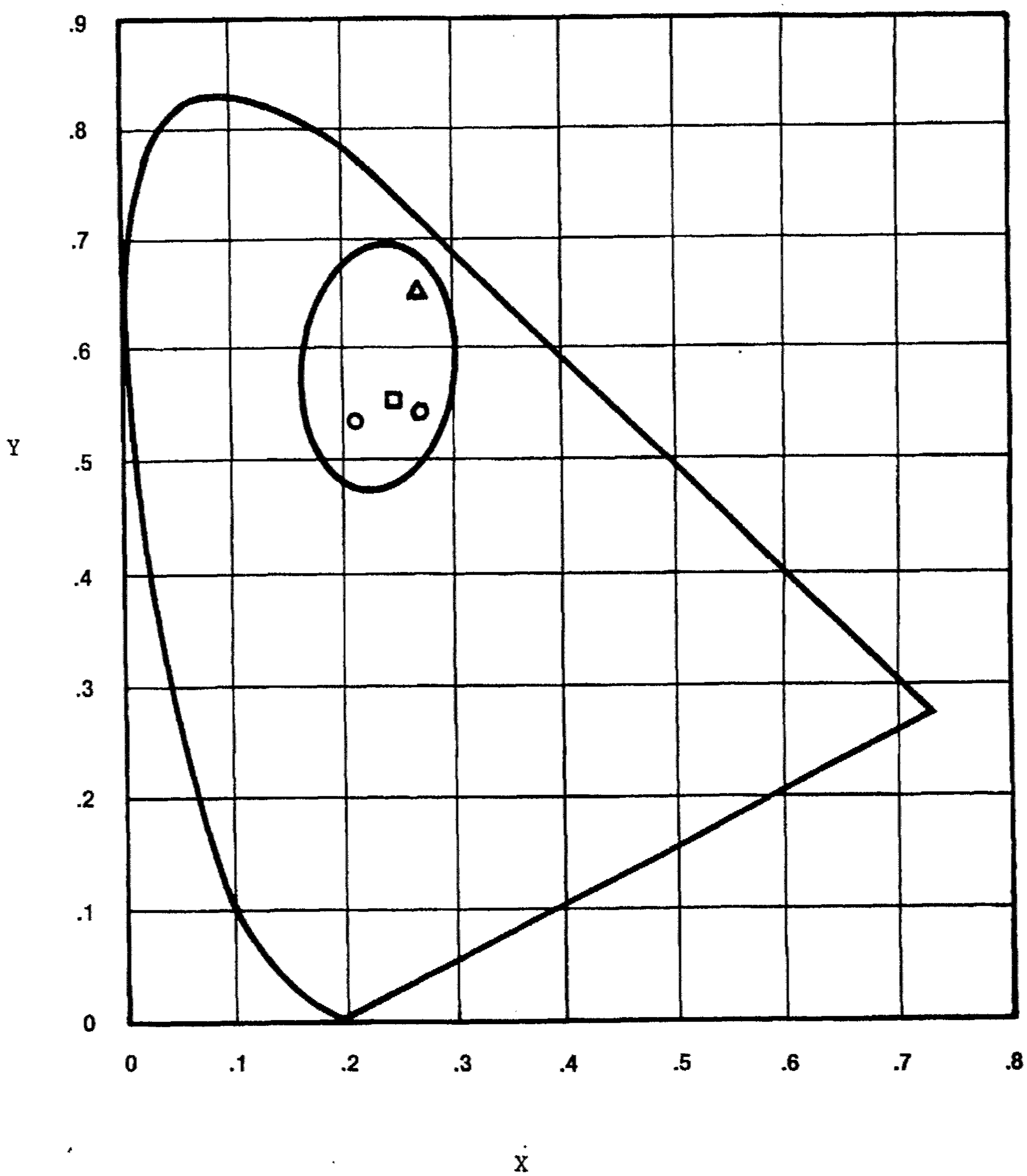

Figure B.1. Modified Color Coordinates of Individual Lighting and the Color Limits Defined by the Proposed AN/AVS-6 Lighting Compatibility Specification.

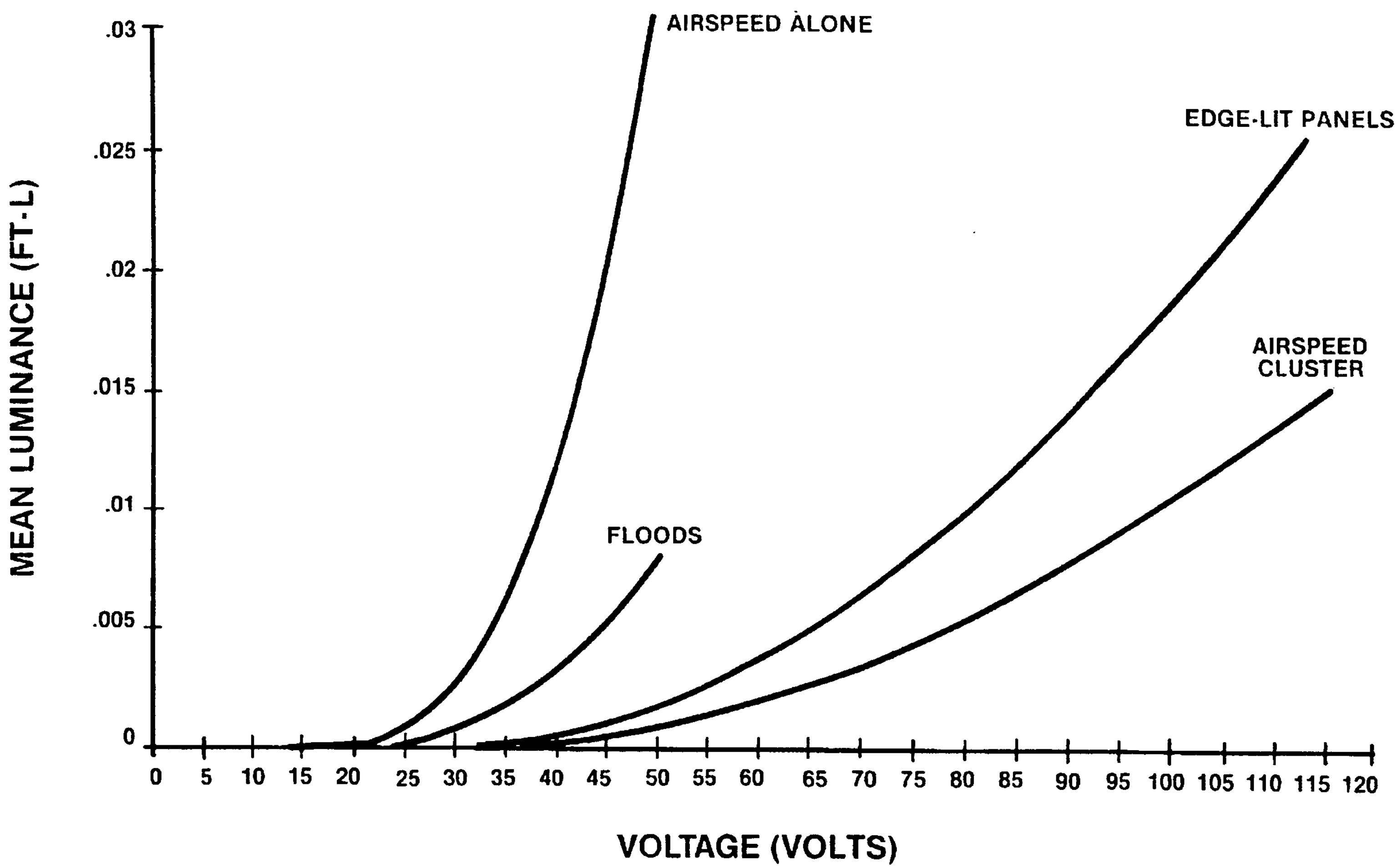

Figure B.2 Voltage Versus Luminance Relation for Various Light Groups Used in the Subject Station

APPENDIX C
INSTRUCTIONS TO SUBJECTS

The following instructions were read to each subject before the start of the experiment:

"The purpose of this experiment is to determine the lighting levels that you require for reading aircraft instruments when using Night Vision Goggles.

Consider the following mission scenario for the purpose of this experiment: You are flying at night, at low level, and you are using night vision goggles or unaided human vision to see ground terrain features outside of the aircraft. It is required that you read the airspeed instrument by glancing down from view of the hypothesized external scene. It is your intention to set instrument lighting to a minimum level in order to avoid detection by adversaries. It is also required that you read the airspeed instrument within 2 seconds of the time that you glance down.

Prior to testing, you will be dark adapted. To accomplish this, you will be required to remain in a darkened room for a period of 30 minutes. Following this period the data collection will begin.

Before each trial you will be required to view a simulated moonlight condition or a simulated ANVIS display for a period of 1.5 minutes. Look directly at this preadapting light source. Following exposure to the lighting condition, you will make adjustments of the front instrument panel lighting.

In the first trial you will be asked to adjust the airspeed instrument light to a level that you feel is necessary to read the pointer and barrel readout. After reading the airspeed in knots the luminance will be recorded and the instrument dimmed to the off position.

In the second trial you will adjust three groupings of front instrument panel lighting. Start by slowly increasing the primary instrument cluster lighting until you can read the airspeed instrument. Next, turn up the edge lit panel lighting until you can identify the location of switches, knobs and other controls on the front instrument panel. Next, adjust the instrument panel flood lighting until the pointer orientations of the engine instrument cluster are readable. Finally, make any adjustments to the primary instrument lights that you feel are necessary to compensate for effect of the other instrument lighting groups. You will then be asked to read airspeed in knots. The luminance of the lighting groups will be recorded and the lighting dimmed to the off position.

All subsequent trials will proceed in the same manner as the ones that I have just described. Take time now to memorize the location and function of the three lighting groups and their corresponding dimmer potentiometers."

After the subject became familiar with the lighting the experimenter asked: "Are there any questions before we begin the dark adaptation period?"

APPENDIX D
PHOTOMETRIC MEASUREMENT PROCEDURES

LUMINANCE MEASUREMENTS

The method used to measure photometric brightness (reference 15) of aircraft instruments is described as follows:

1- A 22 inch focal length achromat lens was placed over the standard objective lens to decrease the measurement field size.
2- A measurement field size was selected that was about 1/2 the stroke width of the indicia.
3- Luminance measurements were taken by orienting the optical head to place the measuring field within the instrument indicia.

ILLUMINANCE MEASUREMENTS

The method used to measure illuminance is based on the use of an external reflectance standard, which has a diffuse reflectance of nearly 100% (the RS-1 reflectance standard). The method is based on the fact that the luminance (in foot-Lamberts) of a perfectly Lambertian diffusing surface is numerically equal to the illuminance (in foot-candles) which falls on its surface. The procedure is as follows:

1- The reflectance standard plaque was placed over the front instrument panel in the same plane as the instruments.
2- The photometer optical head was oriented at approximately 45 degrees to the surface of the plaque.
3- The luminance of the plaque was measured.
4- The luminance reading (in foot-Lamberts) was converted to illuminance (in foot-candles) using the following formula:

   Illuminance (in foot-candles) = Luminance (in foot-Lamberts) /R
   where R=1 and is defined as the absolute reflectance factor of the plaque

APPENDIX E
AIRSPEED SIMULATOR INSTRUMENT CHARACTER SIZE

The visual acuity required for legibility of characters on the cylinder readout was calculated to be a 3.Ø (2Ø/6Ø) minute visual angle by using the stroke width of the character and a viewing distance of 27 inches.

Because the character stroke width is not equivalent to 1/5 the character height and because the character width is not equal to character height (the requirement of a true Snellen character), this calculated value is only a rough estimate.

The size of various indicia for the airspeed simulator instrument, in inches, was measured as follows:

dial characters h=9/32, w=6/32, stroke width=3/64
pointer (white portion) w=3/32, L=1 4/32
cylinder digital readout w=1/32, h=5/32, stroke width=3/128

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NIGHT LIGHTING AND NIGHT VISION GOGGLE COMPATIBILITY

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SUMMARY

Proper lighting of aircraft instruments, panels, controls, indicators, and displays is essential in high performance aircraft. The lighting must be useable over a large range of ambient conditions; especially during dawn or dusk transitions and at night. It must be uniform, have low glare, and be continuously dimmable to very low luminance levels, so the pilot can become partially dark adapted for good, out-of-the-cockpit vision. Various aspects of cockpit lighting such as intensity levels, contrast, luminance and color uniformity, red versus white versus blue-green general lighting, color coding, and other parameters are discussed. Daytime lighting requirements will be noted throughout the paper because they are an important part of the overall design of the lighting system.

A special area of interest is night vision goggle compatible cockpit lighting. As night missions evolve, night vision goggles (NVGs) are being used with greater frequency. The characteristics and usage of NVGs are overviewed. Methods of achieving night vision goggle compatibility in the cockpit using filtered incandescent lamps, external bezels, floodlighting, light-emitting diodes, electroluminescent lamps, microlouver material, and black flight suits are described.

COCKPIT LIGHTING

Instruments, panels, switches, controls, indicators, and displays must be visible over a very large range of ambient lighting conditions. Ambient illumination ranges from 10^5 lux (10^4 foot candles) unobscured sunlight at altitude to a moonless, overcast night sky which is approximately 10^{-4} lux (10^{-5} foot candles). In the daytime, instruments and panels utilize the natural ambient light to be visible, whereas multifunction displays and annunciator signals must have high luminous output and good contrast to compete with the sun. Another demanding ambient condition occurs during dawn and dusk transitions. The cockpit can be in very dark shadows while the pilot is still viewing a very bright outside scene. The human eye can adapt to scenes that have about a 100 to 1 luminance range, while a dawn/dusk situation easily exceeds 1000 to 1. Depending on the sun angle, the pilot will turn the cockpit lighting to maximum, which is only 1 to 2 foot Lamberts (ft-L) for instruments and panels. Fortunately, this condition is of short duration. As the ambient illumination lowers, the pilot dims the cockpit lighting levels to reduce internal windscreen glare and increase his out-of-the-cockpit vision.

Dimming circuits are required to compensate for variations in the ambient illumination, different missions, individual pilot differences and preferences. Old style dimming circuits used discrete position switches that usually resulted in poor controllability. Continuously variable dimming is now used in most modern aircraft. Since the eye perceives logarithmic changes in luminance as near linear-like changes in subjective brightness, the dimming circuits should vary luminance logarithmically. To be effective throughout the entire ambient range, good controllability must be maintained from the 1 ft-L maximum through about 0.001 ft-L minimum before extinguishing (MIL-L-87240). Associated with dimming is tracking. As instrument and panel lighting is varied by the master control, individual units should appear close in brightness to each other. This is especially critical in the very low luminance range. For example, if an important instrument is dimmer than the others, a pilot will often turn up the master dimmer control until it is readable, but the rest of the instrument suite would then be brighter. Not only will this increase glare and internal reflections, but the entire cockpit also acts as an adaptive field to the eyes. The higher the adaptive field, the less sensitive the eyes will be to faint (near threshold) out-of-the-cockpit lights. It is for these reasons that the lower a cockpit can be uniformly dimmed, the better the external vision. To this end, some aircraft have individual dimmers, accessible by maintenance personnel, to balance out the lighting. When a new instrument or panel is installed, rebalancing may be required. Unfortunately, this balancing procedure is time consuming and has to be done at night by at least two people. Also, balancing requirements can reflect individual pilot visual differences or preferences in lighting, and aircraft are flown by different pilots on any given mission. Ideally, the individual trimmers would be accessible to the pilot, but the additional controls contribute to the complexity of the cockpit.

In an effort to verify cockpit lighting requirements, a field study was conducted by this laboratory at Eglin AFB, Florida. The study measured several qualities that related to night vision and lighting. Seven pilots served as subjects. Each pilot was dark adapted for at least 30 minutes. He then put on red goggles and was taken to either an F-15 or F-16 aircraft that was located at a dark, remote section of the field, away from lights. The pilot was seated in the aircraft, then instructed to remove his goggles and adjust the cockpit lighting to his normal nighttime settings. The windscreen was in the lowered position. The pilot then replaced his goggles and moved to a waiting area. Photometric equipment was then installed and luminance measurements of the pointers were taken on the airspeed, angle-of-attack, attitude direction indicator, horizontal situation indicator (HSI), altimeter, vertical velocity indicator, revolutions per minute (RPM), and temperature gauges. Mean instrument luminance readings (both aircraft) ranged from 0.04 to 0.023 ft-L. The lowest reading was 0.003 ft-L and the highest was 0.089 ft-L.

The tests were followed up by a questionnaire on cockpit lighting. All of the pilots felt the dimmers for these two aircraft had good controllability in the low end and the instruments could be dimmed as low as needed. Most pilots adjusted the main instruments to slightly higher levels than the side consoles. They preferred to read important main instruments, but with other instruments (such as RPM), they looked at pointer position only and these were often set at lower levels. Variations in luminance among instruments (balance) caused higher than desired setting. For example, the HSI had a poorly illuminated tumbler readout. Due to its importance, the pilots turned up the master dimmer so they could read the numbers, which in turn caused higher luminances and increased windscreen reflections. Maximum obtainable luminance settings were judged adequate. They were used for pre- and post-flight checks and dawn/dusk transitions. The side console panels created the most glare and reflections. Pilots often used small amounts of floodlighting to even out the cockpit illumination. As indicated by the data, dark adapted pilots set their instruments very low, thus verifying the minimum luminance, uniformity, and controllability requirements set forth in MIL-L-87240.

Contrast is as important a requirement as luminance and dimming. Except for color coding, instrument and panel surfaces are matte black with white markings, which yields the highest contrast over a large range of viewing conditions. Contrast is usually defined in military specifications as the difference between the scale and background luminances, divided by the background luminance. A contrast of 12 is typical for white markings and pointers on black backgrounds. A contrast of five is recommended for white on gray. Higher contrasts can be obtained by varying paints or using filters. However, very high contrast at night is not recommended since it can induce a visual illusion termed the autokinetic effect. Bright light sources (especially point sources) that have very dark surrounds may appear to be floating or moving when in fact they are stationary. Early lighting systems had luminescent paint markings on a black background and were floodlighted with ultraviolet light. Besides causing eye strain and increasing the risk of cataracts, the instruments had extremely high contrast, which had the undesirable result of inducing the autokinetic effect.

Over the past 20 years, cockpit lighting colors have changed from red, to white, and now most recently, blue-green for night vision goggle compatibility. Red was used to help maintain the pilot's partial dark adaptation because, at that time, out-of-the-cockpit vision was very important. There were several disadvantages which included eye strain and focusing problems that caused fatigue over time. Color coding of maps and instruments was also limited. As the pilots' eyes began to be supplemented by radar and other sensors, white lighting began to be employed. The main advantages of using white-lighted instrumentation were lower eye fatigue, higher visual resolution, and more effective use of color coding. For modern fighter aircraft, the US Air Force uses white lighting. Night vision goggle compatible lighting is blue-green because the red and infrared components have been eliminated due to their interference with the goggles.

When the pilot is looking out of the cockpit at night, the instrument and panel luminances act as an adapting field. Different average adapting luminances cause corresponding threshold changes, or levels of partial dark adaptation, for detecting a faint stimulus like a distant aircraft light. The color of any given field luminance also affects the eye's level of dark adaptation. Smith and Goddard (1967) measured the effect of cockpit lighting color on dark adaptation. The 50 percent probability of detection thresholds and 90 percent confidence limits were calculated. For a given adaptive luminance field, the probabilities of detecting the presence of a 200 micro ft-L stimulus were approximately 0.935 for red, 0.54 for white, and 0.3 for green lighting. The difference between thresholds after exposure to a green adaptive field versus the red field was statistically significant. Green versus white and white versus red comparisons showed no statistically significant differences between detection thresholds. It should be noted that the experimental setup used a floodlighted instrumentation panel which resulted in a large illuminance of the retina that would not be found in an edge-lighted suite. Also, the difference between the pure red and green conditions are a worst-case condition not usually found in a regular, color-coded (mixed colors) cockpit. Both of these factors caused larger threshold differences,than would be expected in a real cockpit. From an operational standpoint, it is unlikely that different colors cause a significant decrement in the pilot's ability to detect faint lights outside of the cockpit, especially when considering the variability among crew members' vision and the large amounts of light emitted from populated areas. Also, the broadband nature of white and blue-green lighting seems to contribute to the reduction of visual fatigue over long periods of use.

Another important factor to consider is the effect color has on visual resolution, which relates directly to the visibility of small details within the cockpit. Figure 1 shows the smallest resolvable grating (half cycle in arc minutes) as 0.55 for red, 0.476 for white, and 0.466 for green, which is an operationally non-significant difference. The crew members' ability to resolve the relatively large lettering, pointers, scales, etc., is not effected, though the appearance of color coded markings, flags, or maps may be changed when viewed under various colors. Fine detail in maps would be more visible under white and green illumination.

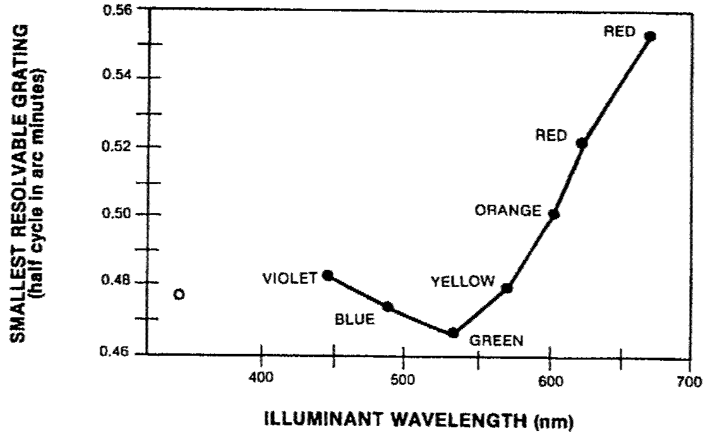

Figure 1. Visual acuity and illuminant wavelength.

The specification of color has undergone numerous changes. An early color matching scheme was devised by Munsell, which is still in use today. It consists of a large set of standardized color chips. Matching of a test sample to the chips was performed under the same illuminant. The drawbacks of this system were that matching varied from observer to observer and that it was a slow process to be performed routinely.

In 1931, the International Commission on Illumination, or Commission Internationale de l'Eclairage (CIE), devised a method to specify color matching that used the actual physical measurement of the spectral energy distribution (SED) curve instead of through subjective visual methods such as that used by the Munsell system. The SED curve is the relative energy output of a filtered or unfiltered light source plotted as a function of wavelength. The CIE system is based on the trivariance of vision, which is the physiological fact that any monochromatic light, is equivalent to the algebraic sum of suitable amounts of three reference lights or primaries. The actual chromaticity is determined by calculating the amounts of the three primaries required by a standard observer to obtain a visual match.

Figure 2 shows the spectral tristimulus values for the 1931 standard observer. Note that the $\bar{y}$ curve is the photopic curve, which is the subjective human visual response to light as a function of wavelength, or color. The $\bar{x}$ and $\bar{z}$ primaries do not physically exist, but were formulated to avoid negative colors.

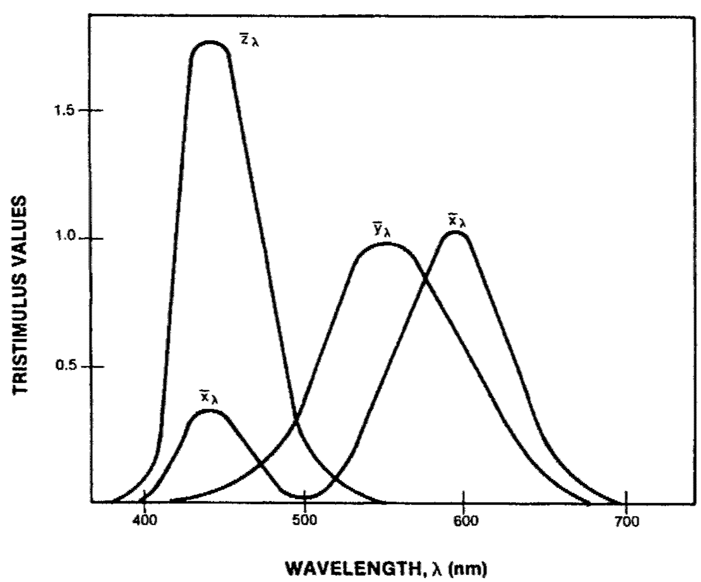

Figure 2. Spectral tristimulus values for the 1931 standard observer.

To calculate the CIE color coordinates, each tristimulus curve (Figure 2) is individually multiplied by the measured SED curve of the sample under consideration, and then integrated over wavelength, the resultant values of which are denoted by X, Y, and Z. Using these values, Equation 1 shows how the chromaticity coordinates x, y, and z are calculated. This procedure normalizes the chromaticity values so that x + y + z = 1.

$$x = \frac{X}{X + Y + Z}; \quad y = \frac{Y}{X + Y + Z}; \quad z = \frac{Z}{X + Y + Z} \qquad (1)$$

Figure 3 shows the 1931 CIE chromaticity diagram. There are several features that should be noted. Since the coordinates sum to one, typically, only the x and y values are plotted, the z value being determined by the others (two degrees of freedom). The upside down u-shaped part of the curve represents the 100% saturated, pure spectral colors, which are defined by a single wavelength, as labeled. This curved line is derived by taking the $\bar{x}$, $\bar{y}$, and $\bar{z}$ tristimulus values for each separate wavelength of the standard observer (Figure 2), and calculating the x, y, and z chromaticity coordinates using Equation 1, where $\bar{x}$, $\bar{y}$, and $\bar{z}$ are substituted for X, Y, and Z respectively. Another feature of the diagram is that the colors become pastel, or desaturate, toward the center until they are white. The 1931 CIE color space can only show if two colors match. Differences between two points are nonuniform with respect to human vision. Tolerances found about a point (e.g., the square box shown is x = 0.25 ± 0.05, y = 0.55 ± 0.05), such as those found in some military specifications, are misleading due to the nonuniformity of the 1931 color space.

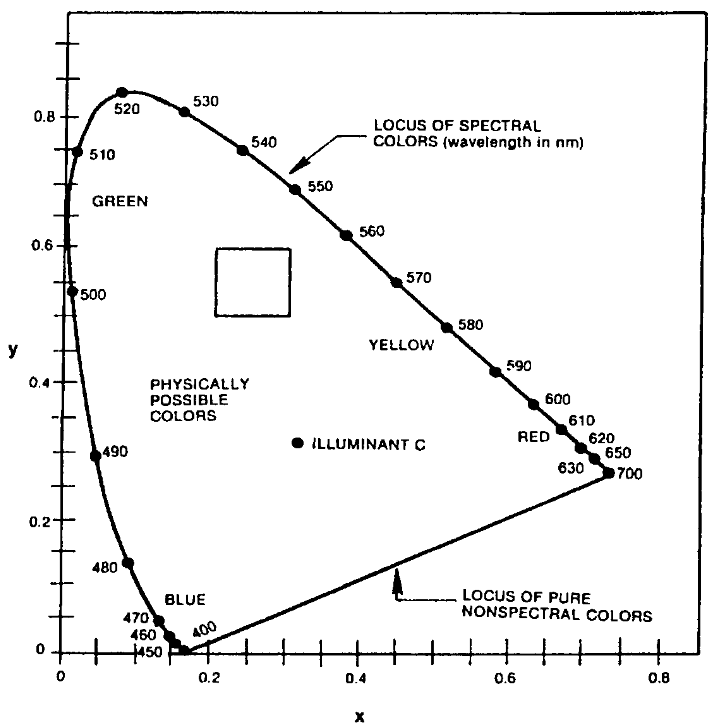

Figure 3. 1931 CIE chromaticity diagram.

The nonuniformity of the 1931 color space was investigated by MacAdam (1942). He measured the adjustment precision for color matching (made by one observer) at relatively high luminances. Figure 4 shows the results, the best fit of the data being ellipses. A common error when interpreting the data from this figure is that the axes of the ellipses are typically drawn ten times the size of the standard deviation of the actual data. MacAdam estimated that the minimum detectable chromaticity difference is three times the standard deviation. Note the nonuniformity among t.e different color regions.

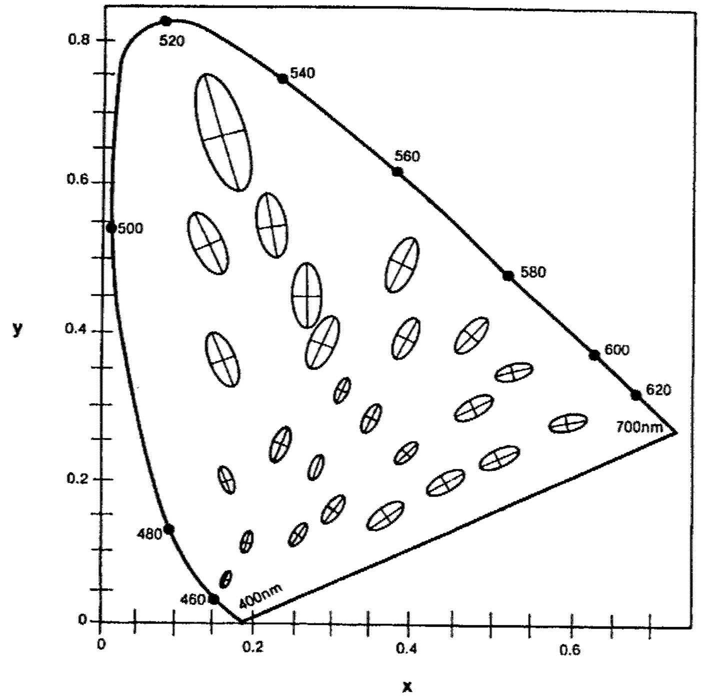

Figure 4. MacAdam's ellipses on 1931 CIE diagram.

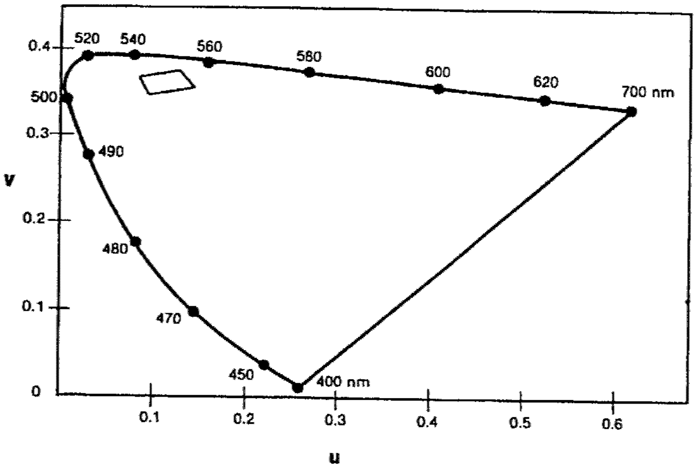

Figure 5. 1960 UCS diagram.

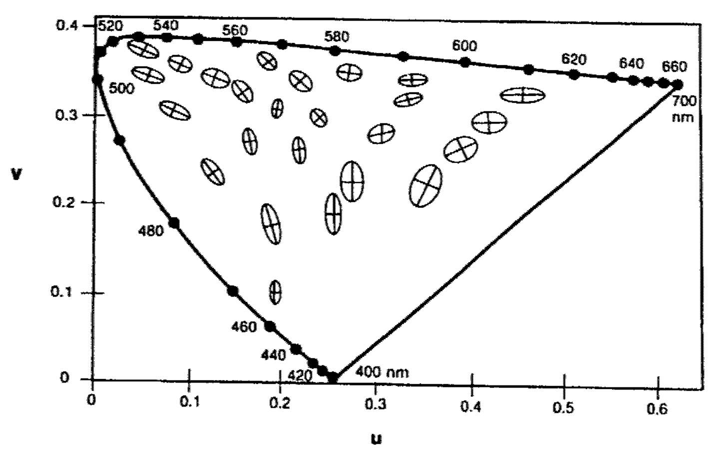

Figure 6. MacAdam's ellipses plotted on 1960 UCS diagram.

In 1960, the Uniform Chromaticity Spacing (UCS), as shown in Figure 5, was adopted in an attempt to make the color space more homogeneous with respect to human visual perception. The chromaticity coordinates were designated u and v. Note the square box from Figure 3 has been plotted on the UCS diagram and it now appears quite different. Figure 6 shows MacAdam's ellipses plotted on the UCS diagram, where again the ellipses are ten times the standard deviation of the actual data. It can be seen that, although it is nonuniform in some regions, it is very good in view of color sensitivity variations among individuals and is a good compromise between accuracy and simplicity. Tolerances about a point would be specified as either a circle or an amorphous area that would be empirically derived.

The mathematical relationship between the CIE and UCS color spaces is defined by Equation 2. The x and y CIE coordinates can be directly converted to u and v UCS coordinates. Modern color measurement equipment already performs these computations. Equation 3 shows how to convert u and v to x and y coordinates, respectively.

$$u = \frac{4x}{-2x + 12y + 3}; \quad v = \frac{6y}{-2x + 12y + 3} \qquad (2)$$

$$x = \frac{3u}{2(u + 2 - 4v)}; \quad y = \frac{v}{u + 2 - 4v} \qquad (3)$$

In 1976, the UCS diagram was further refined and designated CIE 1976 (u',v') UCS diagram, using u' and v' coordinates. It is shown in Figure 7 with the accompanying equations to convert from 1960 to 1976 space. The mathematical relationship between the 1976 and the 1960 spaces is u' = u and v' = 1.5v. Again, note the change of the tolerance box shape as replotted in the 1976 space.

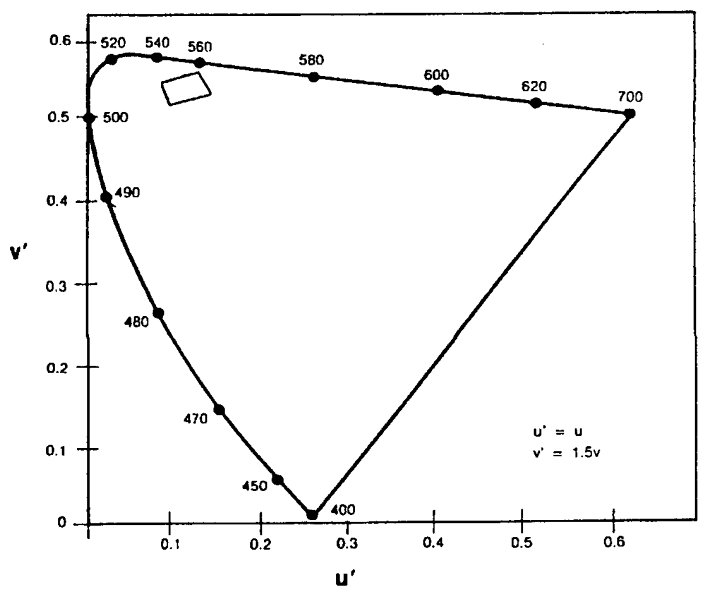

Figure 7. CIE 1976 (u',v') UCS diagram.

Given this background, practical applications using the CIE 1976 (u',v') UCS diagram can now be discussed in some detail. Figure 8 shows the 1931 CIE space with points of blue-green, green, and yellow-green light sources that represent candidates for night vision goggle compatible lighting applications. The distances among the points have little meaning due to the nonuniformity of the space and may be erroneously interpreted as having large perceived color differences. Figure 9 shows the same points plotted in 1976 space. Distances among points are now meaningful with respect to visual perception. The perceived color differences can be predicted to be small.

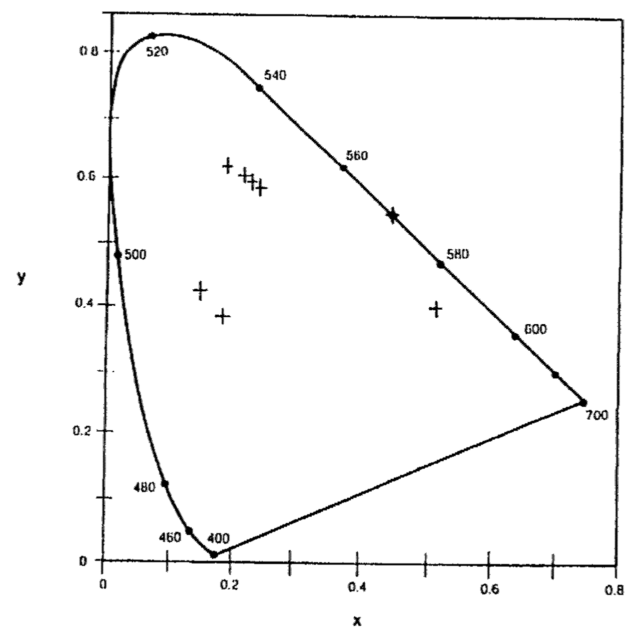

Figure 8. Various greenish colors plotted in CIE space.

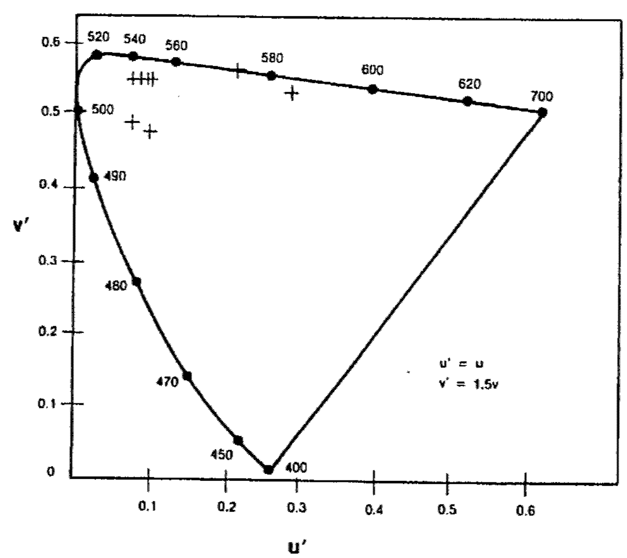

Figure 9. Same colors of Figure 8 replotted on the CIE 1976 (u',v') UCS diagram.

Color specification for aircraft should be defined in the 1976 space, not the 1931 space. The defined chromaticity areas should be based on performance criteria, not arbitrary tolerances or wholly aesthetic qualities. The limits should be empirically derived, if possible. For example, many specifications require one ft-L maximum luminance with chromaticity tolerances in 1931 CIE space. However, as was shown earlier, operational instrument luminances typically range from 0.1 to 0.001 ft-L. Figure 10 shows the perceived desaturation of hue (color) as a function of luminance (Hunt, 1953) in 1976 space. The outermost points (#1) are the actual measured chromaticity of variously colored lights at 314 ft-L. As the luminances of the lights were reduced (points #2 through #5 were 19, 2.4, 0.8 and 0.09 ft-L, respectively), their perceived hue desaturated. While these colors appeared very different at the higher luminances, at operational levels they desaturated and appeared more similar. An additional factor is that many basic color experiments, such as the one constructed to derive the data in Figure 10, use standard and test color patches that are visually adjacent. Very small color differences are easily detected using this method. Lights in aircraft are usually separated by some small distance, which also makes the detection of the (perceived) desaturated light's color differences even more difficult. Given the low operational luminances and physically separated signals found in cockpits, some specified color tolerences may be too restrictive.

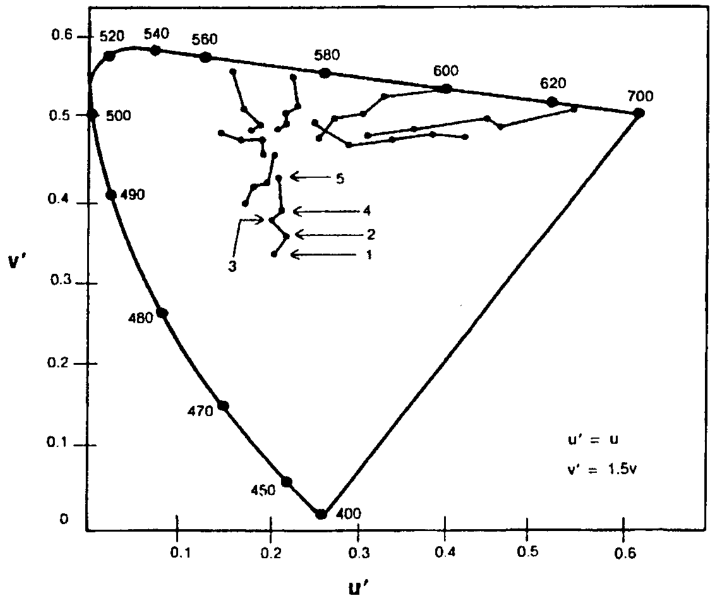

Figure 10. Perceived desaturation of hue as a function of luminance.

There are other performance criteria to be considered when specifying color tolerances. Variables that affect performance include: operational luminances, proximity of light signals, ambient lighting, chromaticity, and color coding. For empirical investigations, error rates, response times, fatigue, and workload may be used as evaluation criteria.

It has been shown that the 1931 CIE space is for matching colors only. The CIE 1976 (u',v') UCS diagram is more appropriate when specifying color tolerances. Color specifications and tolerances should be based on performance criteria, whenever possible.

Returning to other subsystem lighting requirements, illuminated pushbuttons have to be visible in high ambient illumination, as do warning, caution, and advisory signals. Several years ago, one hundred ft-L was common. Two to three hundred ft-L are required to be clearly visible. These signal lights are typically dimmed to 15±5 ft-L, which is still quite bright in a darkened cockpit. At night, the F-15 maintains the master warning and master caution lights at about 10 ft-L but employs continuous dimming for all other annunciator lights, down to an absolute minimum of 0.05 ft-L. The annunciator lights cannot be dimmed to extinction. Pilots report that this system works very well at night, especially when some of the signals (e.g., landing gear down) remain lit for relatively long periods of time.

Floodlights are used for pre- and post-flight checks, as an emergency backup system in case of a primary lighting system failure, as supplemental or fill lighting to the primary lighting, and during lightning storms to diminish the deleterious visual effects of the bright flashes of light. Aircraft that may be exposed to nuclear flashes have the floodlight system coupled to the automatic thermal protective closure systems for anti-dazzle. The highest floodlight illumination on the main instrument panel should be at least 100 ft candles and 150 ft candles for nuclear flashblindness protected pilots. The higher illumination is needed because, even though the protective closure system (PLZT) has been activated, it is not instantaneous and the pilot may still be exposed to a very bright flash. The higher cockpit illumination is needed to maintain instrument readability. Floodlighting must be continuously dimmable to very low levels before extinguishing. They must also have good, uniform coverage of the entire suite with a minimization of direct or reflected windscreen glare and few shadows on or within the instruments.

Head-up displays (HUDs) are specialized pieces of equipment, designed for specific aircraft and missions. To that extent, only the F-16 A/B and C/D HUDs will be overviewed. The F-16 A/B HUD has a total field of view (FOV) of 20 degrees. The strokewritten images must be visible against a background illumination of 10,000 ft candles and have an average luminance of the symbol lines of 1,600 ft-L minimum. Contrast ratio is a minimum of 1.2:1 which is a 0.2 contrast. Note that achievable contrast for this display is much lower than that of painted instruments. Dimming is controlled by the cathode-ray tube (CRT) brightness control which is continuously variable. The control of the luminance is logarithmic so the subjective impression of the brightness changes is linear. A broad range of luminances is achieved by the insertion of a night filter into the optical path of the HUD. The CRT utilizes a green P-1 phosphor.

The F-16 C/D HUD differs from the A/B in that it has 25 degrees FOV, and it can display a raster generated image, like a television, with simultaneously displayed stroke-written symbology. The raster mode is used to display sensor imagery such as forward-looking infrared. The luminance and contrast for the stroke-written symbology is the same as the A/B HUD. In the raster mode, the HUD is capable of six shades of gray against a 30 ft-L background. Since this HUD has a raster capability, its night brightness mode is more difficult to achieve. It must be able to clearly and uniformly display information while not obscuring outside vision of a dimly lit scene such as a horizon lighted only by moonlight. The veiling, blank areas of the raster, cannot exceed 0.02 ft-L. This HUD also uses a green P-1 phosphor.

The F-16 C/D also utilizes a CRT multifunction display (MFD) that can display both 525 and 875 line vertical resolution. It is capable of 3,000 ft-L output, but is attenuated to 1,000 ft-L by the contrast enhancement filter. Brightness and contrast compensation are automatically changed as a function of ambient illumination down to 15 ft candles. The unit also has manual brightness and contrast controls that provide the pilot additional control over the display. Symbology brightness has a separate, continuous control. The F-16 A/B uses a radar/electro-optical CRT display that has a similar image display capability as the MFD described above, with the exception that its peak output luminance is 2,000 ft-L. Both displays utilize a P-43 phosphor.

NIGHT VISION GOGGLE COMPATIBLE LIGHTING

To this point, general and specific cockpit lighting characteristics and requirements for high performance aircraft have been described. A special area within this subject is night vision goggle compatible (NVGC) lighting. Night vision goggles (NVGs) are being used with greater frequency for night missions. NVGs amplify near infrared (IR) energy in order to enable the pilot to see at night. However, the standard lighting in aircraft emits large amounts of IR which interferes with the proper functioning of the goggles. The remainder of this paper will describe the basic NVG, light source characteristics, lighting specification, and the methods that are used to achieve NVG compatibility in the cockpit.

NVGs are electro-optical devices that detect, amplify, and display on a small green phosphor screen, visible and near infrared energy from dimly illuminated nighttime scenes. They look like small binoculars and can be worn on the aviator's helmet. NVGs utilize an image intensifier tube. As shown in Figure 11, the image intensifier tube has three basic elements: a photocathode for conversion of photons to electrons, a microchannel plate for electron multiplication, and a phosphor coating for conversion of electron energy back to photons for viewing. The output window is a bundle of fiber optics constructed with a 180 degree twist to yield a right-side-up image for viewing. The goggles have a FOV of 40 degrees and their resolution, in terms of human visual acuity, is about 2 arcminutes or 20/40. NVGs have an automatic gain feature that adjusts the sensitivity of the goggles to minimize bloom or wash out of the image.

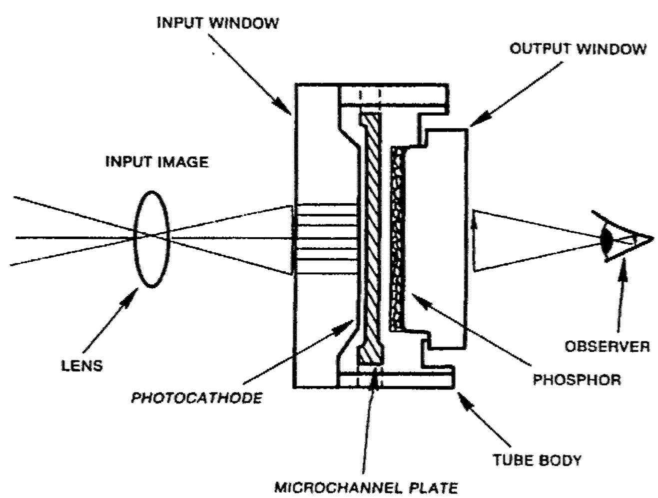

Figure 11. Image intensifier tube.

There are several types of NVGs currently in use (see Verona, AGARD-CP-379). They differ in their optics, spectral sensitivities, and packaging. The Army's original PVS-5 goggles were either strapped to the helmet or worn on the face, but peripheral vision was restricted. The PVS-5 goggles were then modified by cutting away the lower part for use in rotary and fixed-wing aircraft. It must be noted that aviators look through the goggles at outside scenes and underneath them, using direct, unaided vision (as represented by the photopic curve, Figure 12) to look at their instrumentation. The modified version is designated ANVIS-5 and both types used generation 2 image intensifier tubes, employing a multi-alkali photocathode. Another version with different optics and having greater sensitivity is designated generation 2-plus. Third generation intensifier tubes use a gallium arsenide photocathode, have even greater gain, and are more sensitive to IR energy as available from the night-sky spectral irradiance. Figure 12 shows the relative sensitivities of generation 2 and 3 NVGs, as a function of wavelength. Note the generation 3's greater sensitivity and shift toward the IR. The figure also shows the energy from the night-sky spectral irradiance, which is predominantly in the IR. Figure 12 also shows the spectral energy output of a standard white incandescent lamp. It can be seen that large amounts of energy are in the same region of the goggle's sensitivity. This IR pollution causes glare and reflects off the inside of the windscreen. The autogain adjusts to the higher input of the IR reflections, making it impossible to see the outside, lower energy scene.

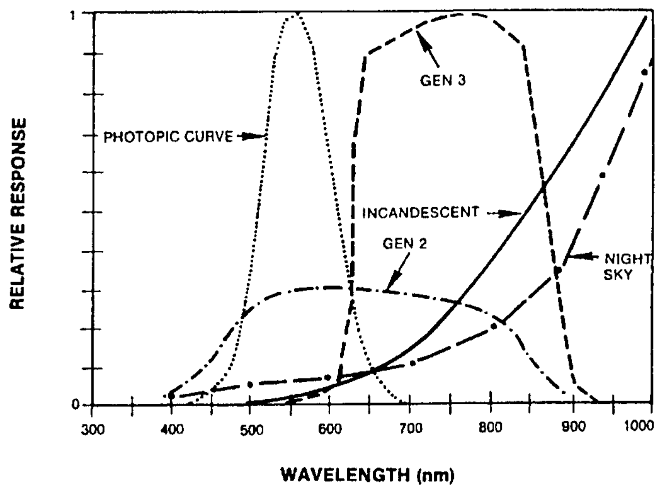

Figure 12. The photopic curve, generation 2 and 3 sensitivities, incandescent lamp curve, and night-sky spectral irradiance.

NVG compatibility is achieved by removing the IR energy from as many light sources as possible. It should be pointed out that, since generation 2 goggles use part of the visible spectrum as well as the IR, 100% NVG compatibility is difficult to achieve. However, filtering the IR energy from the lighting helps a great deal for generation 2 goggles. Filters are often placed on the goggles themselves, but performance is reduced. Generation 2 NVGs require extra filtering but generation 3 goggles have incorporated a minus-blue filter that blocks out visible light below 580 nanometers. Complete NVG compatibility is achieved with generation 3 goggles when the SED of the cockpit lighting does not overlap the goggle sensitivity. The cockpit lighting must still be visible to the unaided eye. The required luminance levels, as previously described, apply to a NVGC lighted cockpit. Removal of the red component of white light results in the characteristic blue-green colored NVGC cockpit. If the outside scene is bright, the NVGs will act as a relatively high (several ft-L) adaptive field, requiring slightly higher average instrument luminance settings by the pilot. A NVGC lighted cockpit, as seen through NVGs, has a greatly reduced IR signature from both inside and outside of the aircraft.

NVGC LIGHTING SPECIFICATION

The current military specification for NVGC lighting in aircraft is MIL-L-85762A. It is a comprehensive document that addresses lighting subsystems found within most aircraft. It has established the dimmed, nighttime luminance and illuminance levels at which an article is to be tested. Chromaticities for NVGC green, yellow, and red have been established in 1931 CIE color space. Measurement techniques and equations have been detailed to measure and calculate the luminances, illuminances, contrasts (with compensating multipliers), spectral energy distributions, and chromaticity coordinates of the lighting subsystems in question. The bottom line is that no cockpit light energy (for instrumentation at 0.1 ft-L) can exceed 1.7×10^{-10} watts/steradian-cm^2, which is the ANVIS-weighted radiance reflected by tree bark illuminated by starlight (see Breitmaier and Reetz, AGARD-CP-379). This value is believed to be the practical lower limit to conduct maneuvers and any cockpit lighting that exceeds this might cause interference with the goggles. It is a stringent criterion to meet and lights that are not in the goggle's FOV are penalized. Actual measurement of such low energy levels is also a practical problem, and requires specialized equipment.

Night vision goggle compatibility is defined as lighting that is sufficient for the unaided eye to read instruments and displays and, simultaneously, does not interfere with the operation of the NVGs in viewing scenes outside of the cockpit. Until recently, there were no NVGC light specifications to use as guidelines for the manufacture of the needed lighting equipment. To this end, a framework and approach were developed by this laboratory (see Genco, AGARD-CP-379) to establish a more quantitative description of NVGC lighting. There are two broad areas of NVGC lighting that must be considered. The effects on direct, unaided vision and the effects on NVG performance.

The lighting effects on vision can be divided into four desirable attributes. (1) There must be sufficient light to read the instrumentation and displays. (2) It is preferred that color and intensity be relatively (perceptively) uniform. (3) If possible, retain color coding and cueing. (4) The lighting must be suitable for non-NVG night flights.

Item 1 is a hard requirement, since proper use of NVGs involves looking through the goggles to see outside and underneath them to directly view the instruments and displays. However, one should not immediately dismiss the possibility of eliminating (turning off) all lights to achieve NVG compatibility.

Item 2 is not a hard requirement, but is highly desirable. The easiest approach to specifying this characteristic is to designate an acceptable area of CIE color space. However, as stated earlier, CIE space is nonuniform with respect to visual sensation and color perception is greatly reduced for the lighting levels of concern for night operations. The first fact implies that the allowed coordinates, if expressed in 1931 CIE space, will not correspond to some symmetric geometric shapes (i.e., square or circle). As discussed earlier, it is more appropriate to specify a circular area in the CIE 1976 space since it relates more closely to human visual color discrimination. The second fact implies that the area in 1976 or 1931 space can be relatively large because it's just not possible to easily perceive color differences at these low light levels. The exact area in color space that is allowable is subject to discussion.

Item 3 is highly preferable, but again, not required. If the location and light level of indicator lights are carefully established, it is possible to retain the use of red and yellow light (limited uses) without affecting NVG operation. The present (1931 CIE) specification of these colors for cockpit use is probably acceptable.

Item 4 should probably be regarded as a hard requirement. It may be accomplished by providing auxiliary lighting for normal night flight which can be totally turned off for NVG flight.

The NVGs can be adversely affected in several ways: a NVG shutdown due to light sources in the field of view, severe contrast loss due to reflections of light sources in the windscreens, and loss of contrast due to flare (light scattering within objective lens of NVGs due to cockpit lighting). As a result of these effects, it is proposed that the lighting be considered in three categories. These three categories are divided according to the effect of the lighting on the NVGs. Category 1 is for lights that appear directly in the FOV of the NVG when viewing outside the cockpit. Category 2 is for light sources that are located so as to directly reflect in the windscreen. Category 3 is for light sources that are in the cockpit, generally adding to the IR pollution (neither Category 1 nor Category 2). To assess the level of compatibility of each of these light sources, it is necessary to calculate (or measure) the relative vision sensitive light compared to NVG sensitive light. This is done by calculating the compatibility ratio (C_R). The C_R is measured by calculating the ratio between vision sensitive light and NVG sensitive light as shown in Equations 4,5,6. Category 1, as depicted in Figure 13, is probably the most severe and will require the highest compatibility ratio. Category 2 (Figure 14) is also of considerable concern, but since the windscreen only reflects 8-10% of the light incident on it, the compatibility ratio for Category 2 sources may be somewhat less than Category 1. Category 3 (Figure 15) is the least severe since it represents general IR pollution in the cockpit. Note the yellow and red indicator lights should be situated so they fall into Category 3 in order to be NVG compatible.

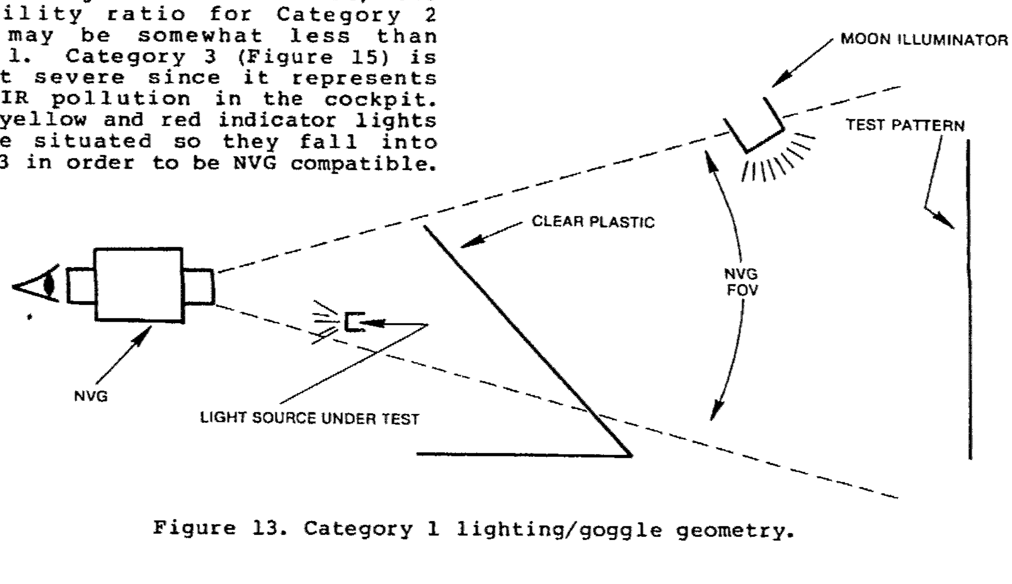

Figure 13. Category 1 lighting/goggle geometry.

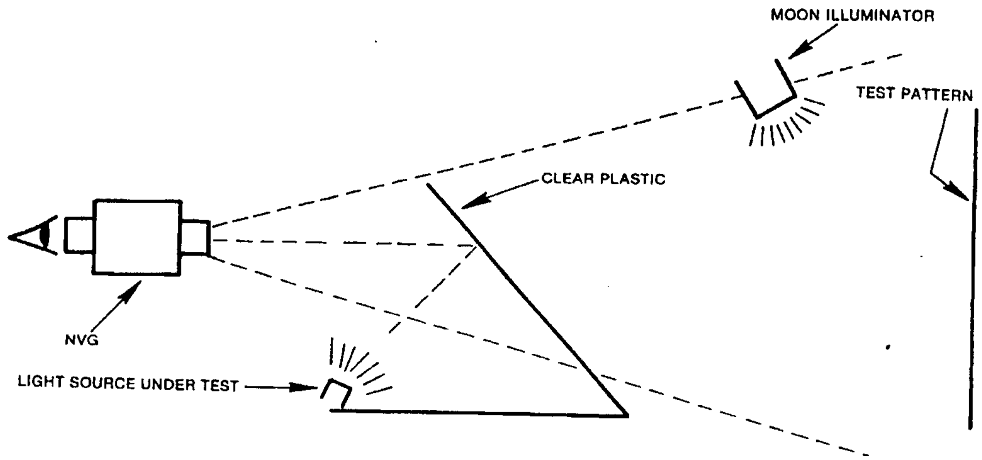

Figure 14. Category 2 lighting/goggle geometry.

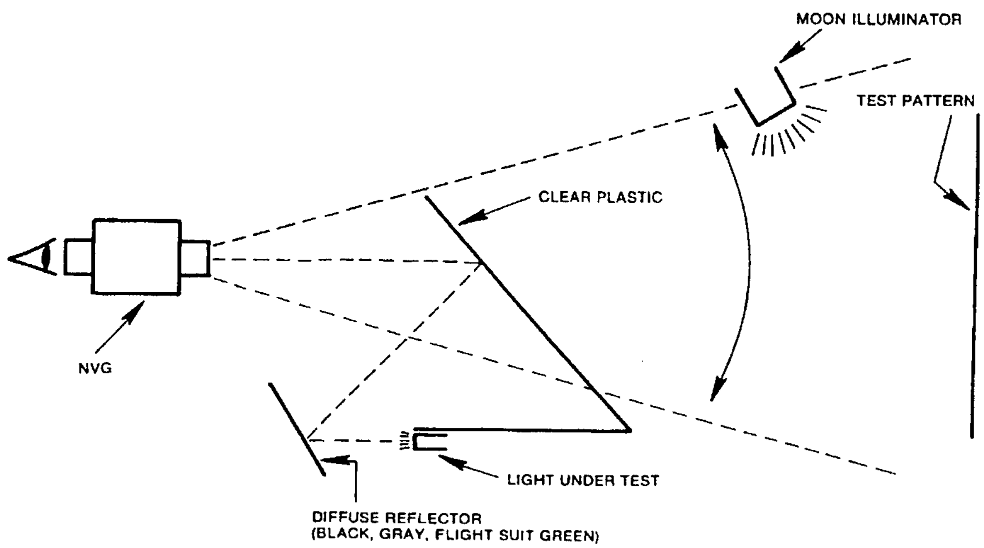

Figure 15. Category 3 lighting/goggle geometry.

Vision calculation:

$$\text{LUMINANCE} = L_V = 680\int_{\lambda=400\text{ nm}}^{\lambda=700\text{ nm}} S(\lambda)F(\lambda)V(\lambda)d\lambda \qquad (4)$$

where: $S(\lambda)$ = Spectral distribution of light source (Watts/cm^2-STR-μm)

$F(\lambda)$ = Filter spectral transmissivity (no units)

$V(\lambda)$ = Visual spectral sensitivity (no units)

λ = wavelength

NVG calculation:

$$\text{RADIANCE} = R_{NVG} = K\int_{\lambda=400\text{ nm}}^{\lambda=1000\text{ nm}} S(\lambda)F(\lambda)G(\lambda)d\lambda \qquad (5)$$

where: $G(\lambda)$ = NVG spectral sensitivity
K = Proportionality constant (TBD)

Compatibility Ratio (C_R) calculation:

$$C_R = \frac{L_V}{R_{NVG}} \qquad (6)$$

Equation 4 calculates the luminance the observer will see taking into consideration the spectral distribution of the light source, the filter's spectral transmissivity, the visual system's sensitivity, and integrating over the visible spectrum (400 to 700 nm). The calculated luminance value (L_V) forms the numerator in Equation 6. Equation 5 calculates the radiance amplified by the goggles by accounting for the spectral distribution of the light, the filter's spectral transmissivity, the goggle's sensitivity, and integrating over the visible and goggle spectrum (400 to 1000 nm). The calculated radiance (R_{NVG}) forms the denominator of Equation 6. The higher the compatibility ratio (C_R; Equation 6), the more stringent the requirement. Thus, Category 1 lights would have to meet or exceed a higher C_R than a Category 2 light. A Category 2, C_R would be higher than a Category 3, C_R.

The weighting of light sources according to their geometric relationship to the FOV of the NVGs and their subsequent effect on the compatibility, as calculated by the above equations, form a conceptual framework and predictive model for NVGC. Additional work is required to validate the model; however, the NVGC lighting specification (MIL-L-85762A) is currently undergoing revision that takes into account (through weighting) the geometric location of color CRTs.

NVGC LIGHTING TECHNIQUES

There are numerous methods that can be used to control the IR within the cockpit (see Task and Griffin, December 1982). Primary methods are light source selection and filtering techniques. Figure 16 shows the SED curves for unfiltered and filtered incandescent lamps, electroluminescent (EL) panels, and light-emitting diodes (LEDs) in relation to generation 3 NVG sensitivity. Incandescent lamps need to be filtered because of their high IR output. Incandescent lamps are blackbody radiators, thus their output varies as a function of temperature. EL is a cold light source that is essentially a capacitor with a CRT phosphor coating that glows when excited by an alternating electrical current. Figure 17 shows an exploded diagram of an EL lamp. As can be seen in Figure 16, green EL lamps emit very little, if any, IR energy. Certain LED colors also work well for these applications, as shown in the same figure.

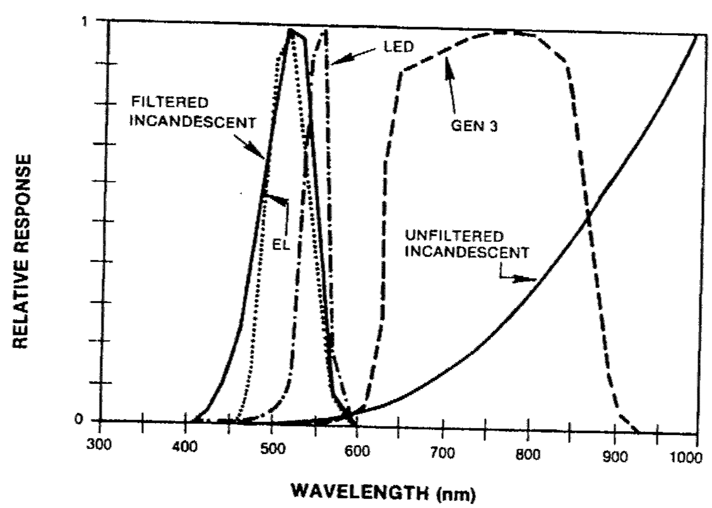

Figure 16. SED curves for unfiltered and filtered incandescent, EL, and LED light sources shown in relation to generation 3 NVG sensitivity.

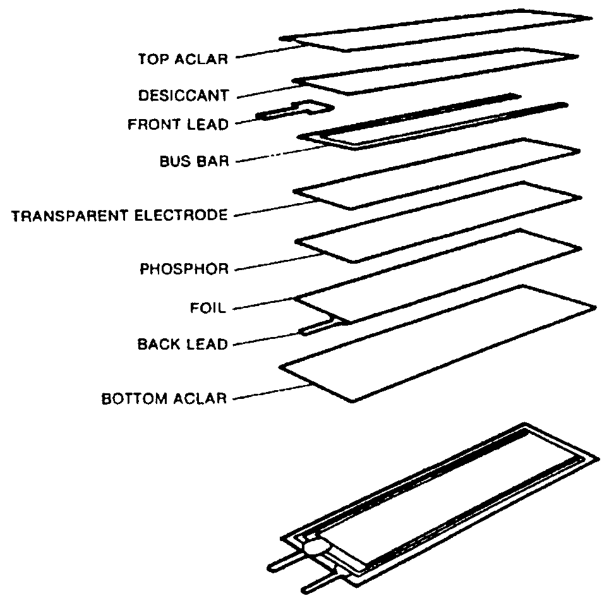

Figure 17. EL lamp construction.

In addition to source type and filtering, other methods are available to make a cockpit goggle compatible. Reflections on the inside of the windscreen can be controlled through the use of microlouver material, an extended glare shield, and black flight suits. Microlouver (ML) is a 1/16 inch plastic film developed by 3M Corporation that has numerous parallel baffles at a fixed angle, very similar to venetian blinds but very small and cast in plastic. By varying the baffle spacing and tilt, the fan of light that is allowed through the material can be controlled. ML comes in three fan widths of 48, 60, and 90 degrees and a specified tilt angle with respect to the vertical. Fan and tilt angles can be appropriately chosen to direct light from a display or light toward the pilot and away from the windscreen to reduce reflections. ML also reduces the amount of light, as well as resolution of detail, to the observer. While ML effectively controls visible light, it was found to be partially transparent to IR. An IR-blocking plastic film must be used over the display or light. With this modification, ML material can be successfully used in NVGC lighted cockpits.

Reflected glare can sometimes be controlled by extending the glare shield to reduce glow from the main instrument lights. The extension may also provide additional space to mount NVGC lights. A glare shield extension can be made adjustable, so different pilots can pull it in or out as needed. Care must be taken to not hamper the crew's escape pathways (through windows) or impinge on the ejection seat envelope of aircraft so equipped. Black, nomex flight suits are also desirable for use in NVGC cockpits to reduce reflections, as would a black helmet. Black suits appear to be more effective in partially modified cockpits where there is still some IR pollution being reflected. Fully modified cockpits have virtually no IR to be reflected, though external ambient energy could be reflected.

Aircraft can be modified to varying degrees of NVG compatibility, depending on the time and money available. A quick-fix modification is fast and low cost, but there is usually some reduction in visibility of the direct view instrumentation with some residual IR pollution. A full-up modification is costly and time consuming, however, it approximates state of the art NVGC lighting where there is essentially no IR and direct view visibility is excellent.

A quick-fix modification can be as simple as turning off the entire lighting system and illuminating the cockpit with filtered floodlights. Black tape can be used to cover indicator lights. Under the glare shield, incandescent lamps can be directly replaced with green LEDs. Various displays and lights can be fitted with Schott blue-green glass, Wamco glass, or Glendale green plastic filters that can be snapped on and off as needed. NVGC external light wedges, or bezels (see Figure 18), are sometimes mounted over the most important instruments.

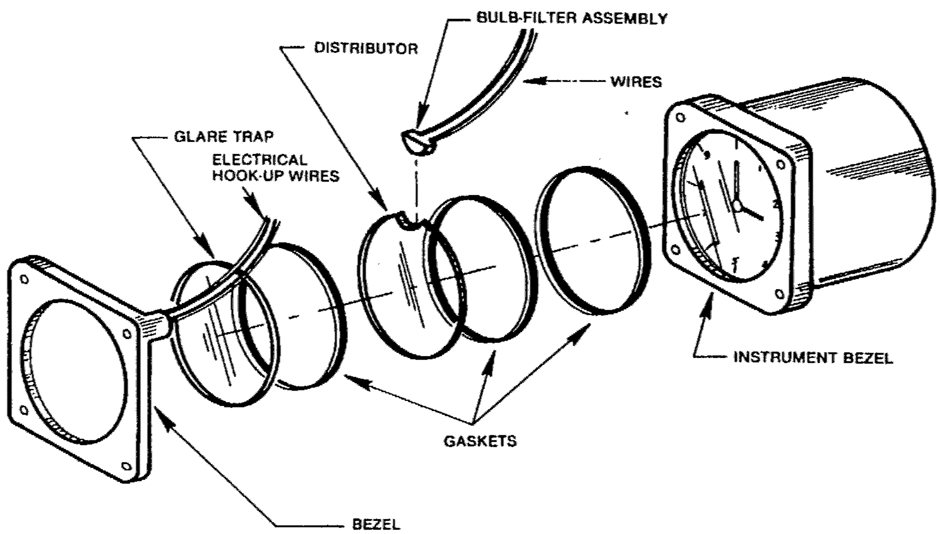

Figure 18. External light wedge (bezel) construction.

A full-up modification is very extensive. External light bezels (Figure 18) are placed over all instruments except the ones that are illuminated with small individual post (flood) lights. The post light caps are filtered. All floodlights and work lights are filtered. Green advisory and yellow caution annunciators are filtered to blue-green. Red warning lights are changed to NVGC yellow. All panels are replaced with NVGC green. Depending on the panel type, the light source is either filtered incandescent or electroluminescent. CRTs and moving map displays, if present, are covered with filters. Aircraft CRTs are often green P-43 phosphors that have a small red component that, if necessary, is easily filtered. Glass filters are best, due to their higher degree of stability under the extreme environmental conditions that are so often encountered.

CRTs used in radar, MFDs, and moving maps can be filtered to achieve NVG compatibility. HUDs usually have green, P-43 phosphor CRTs in order to obtain maximum brightness in the daytime. These types of HUDs can usually be turned down very low at night and directly viewed through the goggles. Focusing is no problem since the HUD is collimated, and the NVGs are focused at optical infinity to view the outside.

For aircraft that do not have HUDs, it is desirable to have flight information displayed while maintaining a head-up, out-of-the-cockpit position. This laboratory has developed a retrofit NVG/HUD system (see Genco, AGARD-CP-379) to perform this task. Figure 19 shows the NVG/HUD layout. The flight instrument raw signal information is collected by the aircraft's signal processing computer, converted into properly formatted data, and transmitted to the display unit. The display unit converts the data to symbols and displays them on a red CRT. Red is used so that the symbols are visible through the goggles. The symbology display is reflected from a front surface mirror to a relay lens which focuses the image onto a flexible fiber optic bundle. The bundle transmits the image to the NVG where a collimating lens projects the symbol image to optical infinity. This image is then reflected from a beam splitter into one ocular of the NVGs. The observer views the image of the HUD symbols superimposed over the outside view.

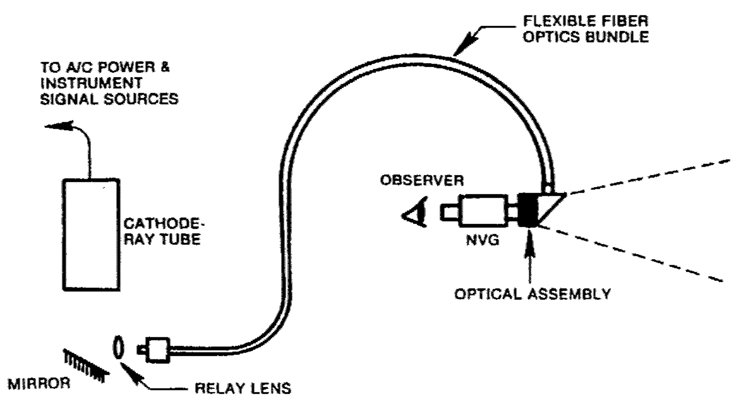

Figure 19. NVG/HUD Configuration.

This paper has described the night lighting requirements for high performance aircraft cockpits. It also overviewed NVG characteristics and defined NVG compatibility for cockpit lighting. Methods of achieving NVG compatibility were shown as represented by quick-fix and full-up modifications. These modifications greatly enhance the performance of NVGs that help the pilot to successfully complete his mission.

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AFAMRL-TR-84-036

BRIGHTNESS COMPARISON OF ELECTROLUMINESCENT VERSUS INCANDESCENT LIGHTING: A PHOTOMETRIC VALIDATION

MARY DONOHUE PERRY

AIR FORCE AEROSPACE MEDICAL RESEARCH LABORATORY

JUNE 1984

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Previous studies involving the brightness comparison of electroluminescent (EL) versus incandescent (INC) lighting indicated that observers saw the EL light as being "brighter" than the INC light even when both lights were photometrically identical. The intent of this experiment was to determine if a perceptual process was present that inhibited the direct photometric measurement of EL lighting. Twelve observers were asked to compare a variable EL light with a fixed INC light. Nine different brightness levels of the EL light were tested. Subjects were asked to rate if the test lamp (EL) was higher, lower, or the same as the reference lamp (INC). The results from this study showed no difference between the two types of lighting; this in turn validates the use of photometry to measure EL lighting directly.

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SUMMARY

Electroluminescent (EL) lighting has been proposed as an alternative lighting that would eliminate several problems associated with current incandescent (INC) lighting in aircraft (glare, infrared rays, "hot" spots, etc.). The use of photometry to measure EL lighting has been questioned since previous studies indicated that EL lighting appeared to be "brighter" than INC lighting, even when both light sources were photometrically identical. The following describes the experimental exposure:

* Observers were twelve naive subjects, both male and female, aged 19-29.

* Subjects were asked to compare a variable EL light with a fixed INC light.

* Nine different brightness levels of the EL light were tested six times each for a total of 54 trials. Brightness levels were determined as percentage differences of the fixed INC luminance of 4.90 fL.

* Brightness levels ranging from -20% to +20% in 5% increments were used in the experiment: 3.92, 4.17, 4.41, 4.66, 4.90, 5.15, 5.39, 5.64, and 5.88 foot lamberts, respectively.

* Observers were asked to rate if the test lamp (EL) was higher, lower, or the same as the reference lamp (INC).

The results from this experiment were the following:

* The group mean and standard deviation obtained were respectively, $x = 4.82$, $s = 0.534$.

* A Student's t-test which compared the obtained group data with the EL and INC lights matching luminance of 4.90 was not significant, $p < .05$.

* The relationship between percentage of "HIGH" responses and luminance of the test lamp was a linear increasing function with $r = 0.98$.

* A plot of percentage of "LOW" responses as a function of test lamp luminance was a linear decreasing function with $r = 0.97$.

The results show that direct photometric measurements using current photometric instrumentation and procedures are valid and may be used to thoroughly evaluate this type of lighting for future aircrew configurations.

PREFACE

The research described in this report was completed at the Air Force Aerospace Medical Research Laboratory, Human Engineering Division, Crew Systems Effectiveness Branch as a part of Project 7184 12 15. This study was funded by the PRAM SPO (ASD/RAOE) of Aeronautical Systems Division.

I am indebted to Dr. Harry L. Task for his guidance during this research. His knowledge and expertise were most appreciated.

INTRODUCTION

Lighting, both in and out of the crew station, has been a critical factor in the success of Air Force missions. Incandescent (INC) lighting has been the standard for many years, but as the technology has become more advanced, new types of lighting are now being considered as alternatives to incandescence. Before integrating them into Air Force applications, different types of lighting configurations should be evaluated thoroughly. The intent of this report is to describe one relatively new type of lighting, electroluminescent (EL) and to determine if standard photometric techniques may be used to measure it.

Basically, an EL lamp is a capacitor - it has a dielectric material sandwiched between two conducting surfaces. The luminescent phosphor is scattered within the insulator so that it may lie in the path of the electrostatic field. Electric bus bars are mounted to the top transparent conductor, and finally a mylar coating is added to retard moisture. The entire lamp is then laminated in plastic to complete the construction. When an alternating current is applied, the changing electric field causes current to flow within the phosphor particles embedded in the insulator. The induced current causes the electrons in the phosphor to jump energy levels, thereby giving rise to "luminescence" - the emission of light not due to temperature of the source.

The main advantage of EL lighting is the even distribution of luminance across the face of the lamp. This is unlike the INC lamp, whose intensity is brightest at the center and falls off as the distance from the center increases. EL lamps have been considered for Air Force lighting applications for other reasons as well:

1. Dependable - major catastrophic failures eliminated
2. Shapes and lamp design can be easily specified
3. Available in several colors: white, yellow, green, and red
4. Light intensity controlled over a wide range
5. No significant color change when dimmed
6. Readily withstand vibrations
7. Emit no ultraviolet and few infrared rays
8. Relatively narrow spectrum of emission
9. "Cold" source - heat loss is minimal

Recently, questions have been raised about using standard photometric techniques to measure EL lamps. Previous studies involving some comparison between EL and INC (Blouin, 1978) indicated that observers saw the EL lamp as being "brighter" in appearance than the INC even when the two sources were photometrically the same. This would seem to indicate that some perceptual process was present that invalidated direct photometric measurements of EL lighting.

This experiment was formulated to define any perceptual differences between EL and INC. If no difference existed, then photometry could be applied for measuring EL lighting. In theory, the photometer should have the same response as a human eye. An observed perceptual difference would result in a "scaling factor" that should be used for EL lighting measurements.

It was hypothesized that in previous experiments some parameters were not properly controlled, and a physical inequality was somehow present between the two lights. This resulted in observers judging the EL to be "brighter" than the INC, even when they were photometrically the same. For example, if the luminance of the INC lamp is not properly diffused, observers will always judge the light to be dimmer than an EL since the first part of any target examined is its edges, and an improperly diffused INC lamp will appear dim around the edges. It was the aim of this experiment to eliminate any previous confounding variables, and to determine if the lights were perceptually different to observers once they were made physically similar. The result would be a validation of standard photometric techniques for EL lighting.

METHOD

Subjects

Twelve naive subjects, males and females aged 19-29 participated in the experiment. All observers were required to have 20/20 or corrected visual acuity as measured by a projected standard Snellen wall chart prior to engaging in the study. Before participating in the experiment, all subjects were asked to sign a consent form provided by the experimenter. A copy of this form can be found in Appendix A.

Apparatus

The apparatus consisted of two light sources, one incandescent (INC) and the other electroluminescent (EL). The light sources were separately contained in metal boxes with black exteriors and flat white interiors having dimensions 8 X 6 X 3.5 inches. A circle of 1/2 inch diameter was drilled into the center of the front face of each metal box. This diameter was chosen so that a large surface area would not be a factor in the judgment of the two lamps. The boxes were placed together with their sides touching on a table covered with black cloth; the resulting distance between the centers of the two circles on the front face of the boxes was eight inches.

The EL light, a flat panel, thick film lamp manufactured by EL Products, Inc., was taped on the interior front face of one box across the circular cut-out area. The EL lamp operated at 400 Hz AC, and was connected to a California Instruments AC Power Source Model 251 T so that the luminance of the EL panel could be varied by the experimenter.

To determine the appropriate filters needed for the INC to match the EL in color, a trial and error method was used. The luminance of the INC lamp was measured by a Pritchard 1980B photometer, and then the luminance of the EL lamp was set to this value. Using a Pritchard 1980B Spectraradiometer, the spectral distribution of the EL lamp was determined. Several filters were added to the INC box; a spectral scan was completed, and the EL and INC scans were compared. Depending on the outcome of this process, either the luminance of the EL lamp was adjusted, more filters were added to the INC lamp, or a combination of both procedures was used. This process was continued until both lamps had an identical luminance of 4.90 fL, and the color difference betweent the two was negligible. As a result of this procedure, the following filters were placed in the same circular region on the INC light box as described above:

1. Two (2) Edmund Scientific No. 878 light yellow green filters

2. One (1) Edmund Scientific No. 858 light blue green filter

3. Two (2) Kodak No. 80D Wratten gelatin filters

4. Two (2) infrared blocking filters

Figure 2 illustrates the color coordinates of the two light sources plotted in CIE 1931 space; Figure 3 shows the same coordinates in UCS 1976 space, and Figure 4 plots the spectral distributions for both lamps.

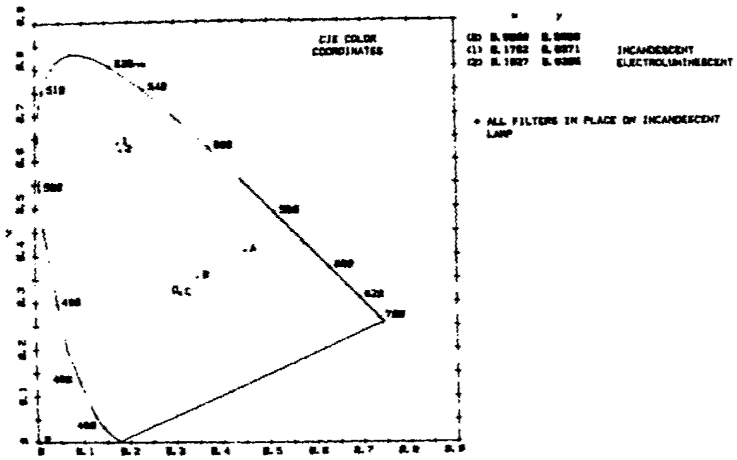


Figure 2. INC and EL Lights Plotted in CIE 1931 Space.

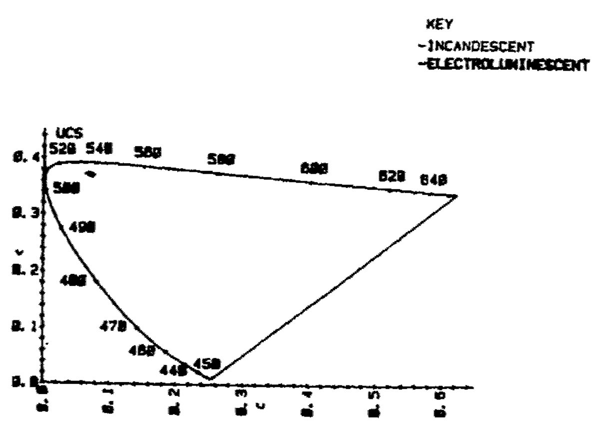


Figure 3. INC and EL Lights Plotted in UCS 1976 Space

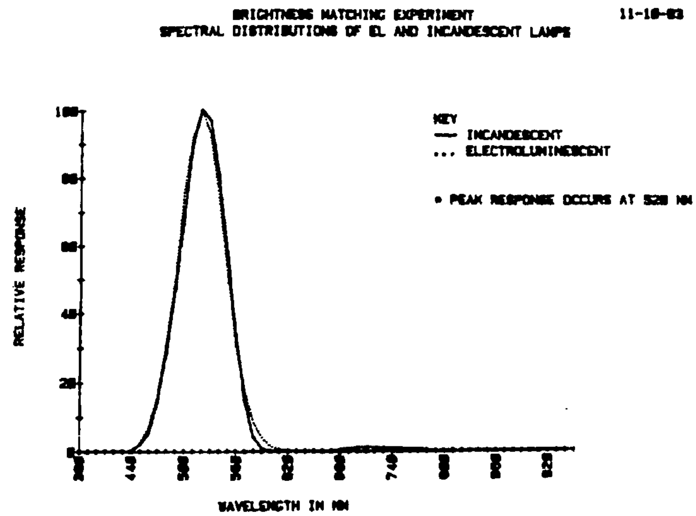


Figure 4. Spectral Distributions of EL and INC Lights

In order for an observer to make an accurate comparison of the intensities of the lamps, the luminance across the front viewing surfaces of the boxes must be uniform. The luminance across each front circular area was measured by a Pritchard 1980B photometer with a Spectar LF-19 microscopic lens, and output to a HP 7100B strip chart recorder. (All of the previously described filters were in place on the INC lamp.) Both lamps fulfilled the requirement of a uniform distribution, as indicated by Figures 5 (INC) and 6 (EL).

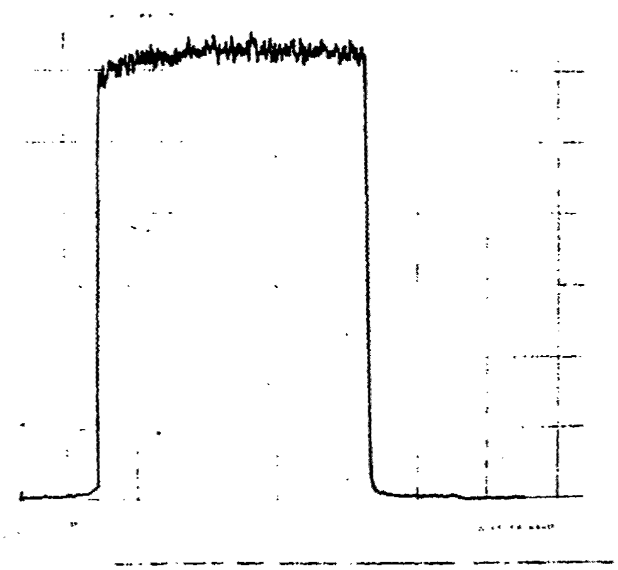
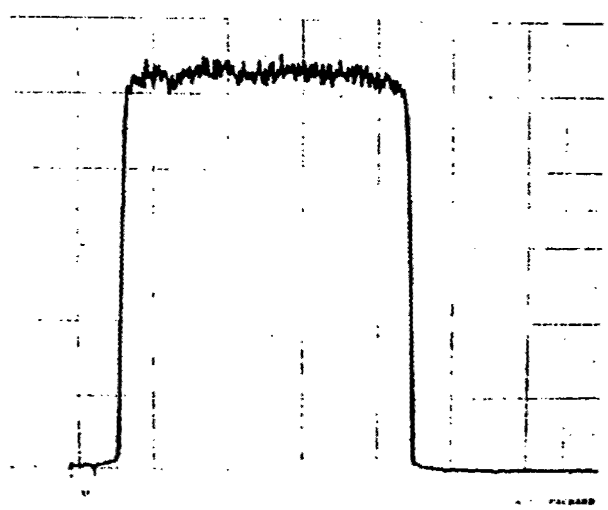


Chart speed = 0.2 in/sec
Range 5 volts/div
Slit Aperture

Figure 5. Incandescent Light Luminance Scan



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Slit Aperture

Figure 6. Electroluminescent Light Luminance Scan

The observer was seated 13 feet from the two lights in order that no texture cues from the EL lamp would be present to help him distinguish between the two different lamps. A partition was placed on either side of the cloth-covered table so that the subject was able to concentrate fully on the task at hand. Two 60 watt desk lamps were located within the testing room to add some ambient illumination to the test area. The average room luminance was recorded at 0.008 fL using a Pritchard 1980B photometer. This same photometer was aimed directly at the EL light to record luminance levels, and placed to the subject's left. The view from the observer's chair is shown in Figure 7.

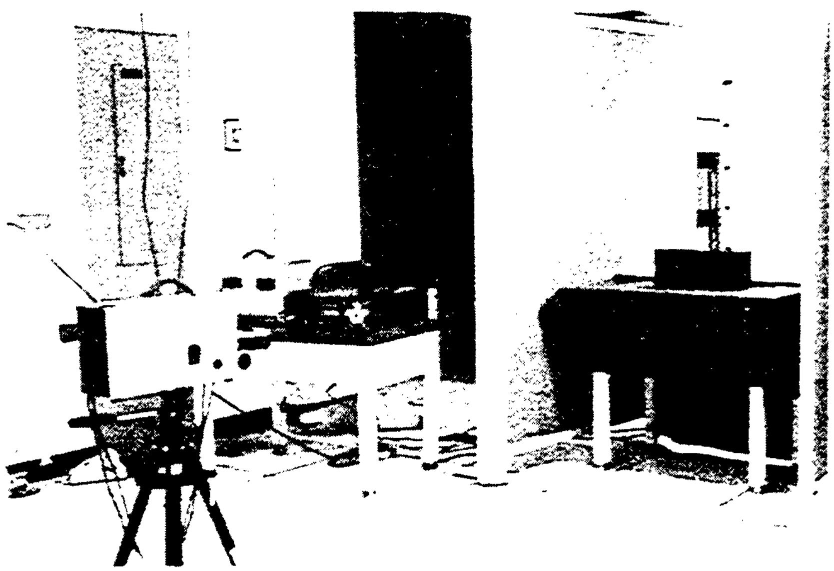

Figure 7. View from Observer's Position

The experimenter's station, located to the left front of the observer's position, consisted of the AC power source and the Pritchard 1980B control console situated on a table facing the experimenter. The subject was unable to see the direction of any luminance adjustments made by the experimenter, and also the corresponding output on the control console. Figure 8 is an illustration of the experimenter's station.

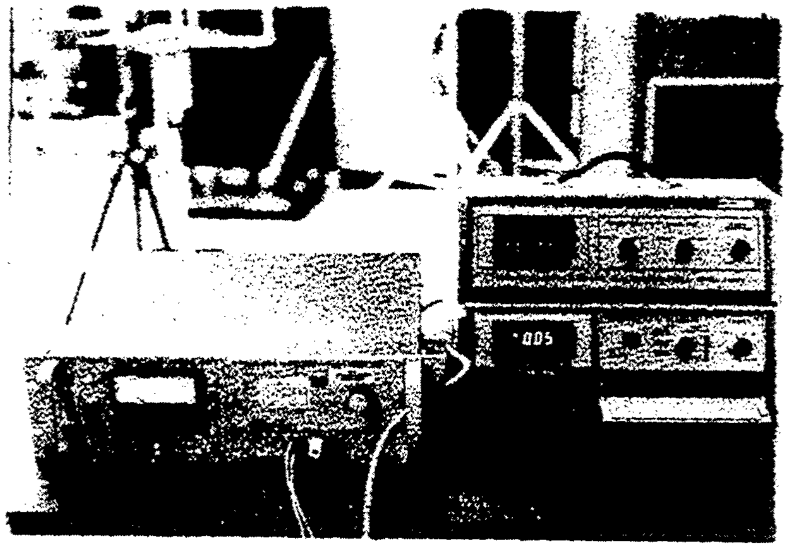

Figure 8. Illustration of Experimenter's Station

Procedure

After the instructions were read to the observer and the consent form was signed, a rest period of five minutes ensued wherein the subject was given the opportunity to adapt to the luminance in the testing room. When this period was over, the testing began. The consent form and instructions can be found in Appendices A and B, respectively.

The experimenter then proceeded to set the first brightness level on the EL lamp using the variable control knob on the AC power source after directing the subject to cover his eyes while the testing level was set. After the experimenter indicated that he was ready to begin, the observer opened his eyes and looked at the two lamps. The participant was asked to compare the intensity of the test light (EL), which was the lamp to the observer's left, with the intensity of the reference light (INC), which was the lamp on the observer's right. If the left light was brighter in intensity than the right light, the subject was told to respond, "HIGH". If the left light was dimmer in intensity than the right light the observer was asked to respond, "LOW". If there was no difference in the intensity of the lights, the observer was directed to reply, "SAME". Immediately after the subject responded, he was told to cover his eyes while the next brightness level was set. This entire procedure was repeated for a total of 54 trials.

Using the above procedure, nine different brightness levels were tested. Brightness levels were determined as percentage differences from the INC and EL matching luminance of 4.90 fL. The percentage differences tested varied in the range of -20% to +20% in +5% increments: -20%, -15%, -10%, -5%, 0%, 5%, 10%, 15%, and 20%. A repeated measures design was used to test each separate brightness level a total of six times. All levels of brightness were block randomized using a random number generator. Table 1 is a listing of the percentage difference from the matching luminance (4.90 fL) and the corresponding EL luminance used to set each brightness level during the experiment.

TABLE 1

EXPERIMENTAL BRIGHTNESS LEVELS

*REFERENCE LUMINANCE = 4.90 fL

% DIFFERENCE FROM REFERENCE	CORRESPONDING LUMINANCE (IN fL)
-20	3.92
-15	4.17
-10	4.41
- 5	4.66
0	4.90
+ 5	5.15
+10	5.39
+15	5.64
+20	5.88

RESULTS

In the past, subjects in other experiments involving some comparison between EL and INC light indicated that the EL always seemed "brighter" than the INC, even when the lamps were at the same luminance level. The purpose for this entire experiment was to determine if in fact a perceptual difference was seen between the two lamps. If a difference did exist, then direct photometric measurements aren't valid, and a "scaling factor" for EL lighting would have to be calculated to compensate for this difference.

To determine if a perceptual difference was present between the two lamps, the number of times the observer made a response of "SAME" was tabulated for each luminance level. These tabulations were converted into percentages and plotted as a function of the luminance of the EL lamp. The individual subject plots can be found in Figures 9-20, and the combined group data is seen in Figure 21. Theoretically, the responses should assume a normal distribution with a mean occurring at the matching luminance of 4.90 fL. Since a random sampling of the population was tested, any perceptual difference between the two types of lighting would result in the group data having a normal distribution with a mean that deviated significantly from the matching luminance of 4.90 fL. Individual subject means as well as the combined group data are shown in Table 2. By examining Table 2, it can be seen that the group observation yielded the following results: $x = 4.82$, $s = 0.53$. To test the significance of the obtained experimental group mean from the matching luminance, a Student's t-test was performed. The results of the test were not significant, $p < .05$.

TABLE 2

MEANS AND STANDARD DEVIATIONS FOR RESPONSES OF "SAME"

*MATCHING EL LUMINANCE = 4.90 fL

SUBJECT #	MEAN	STANDARD DEVIATION
1	5.20	0.56
2	4.90	0.50
3	4.74	0.25
4	4.90	0.56
5	4.68	0.44
6	4.66	0.46
7	5.02	0.64
8	4.72	0.40
9	4.93	0.62
10	4.74	0.66
11	4.47	0.50
12	4.60	0.60
*GROUP	4.82	0.53

If the individual subject plots are examined (Figures 9-20), it is apparent that some observers were quite adept at judging the intensities of the lights while others made their judgments with some difficulty. When questioned following the experiment, the subjects who made their judgments with ease indicated that they had set a certain criterion in the beginning trials, and had retained the same criterion throughout the entire experiment. It is obvious that subjects #5, #9, and #10 did not develop any criterion to help them with their judgments. Other observers actually required <u>more</u> luminance from the EL lamp to match the INC lamp. Subjects #1 and #10 illustrate this point.

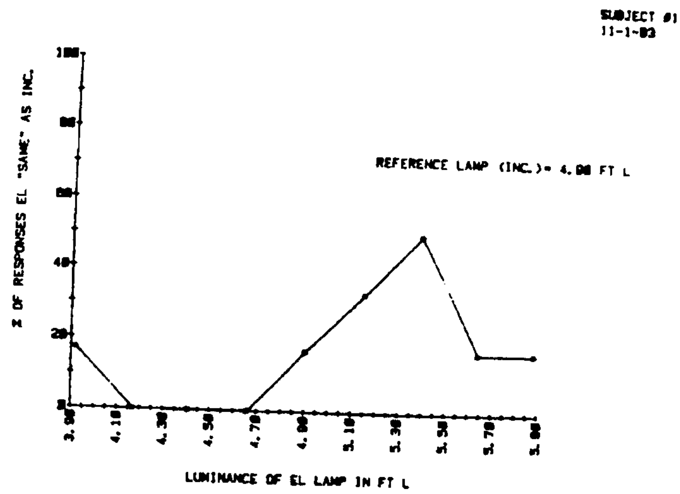

Figure 9. % of "SAME" Responses vs. Luminance of EL Lamp in fL for Subject #1

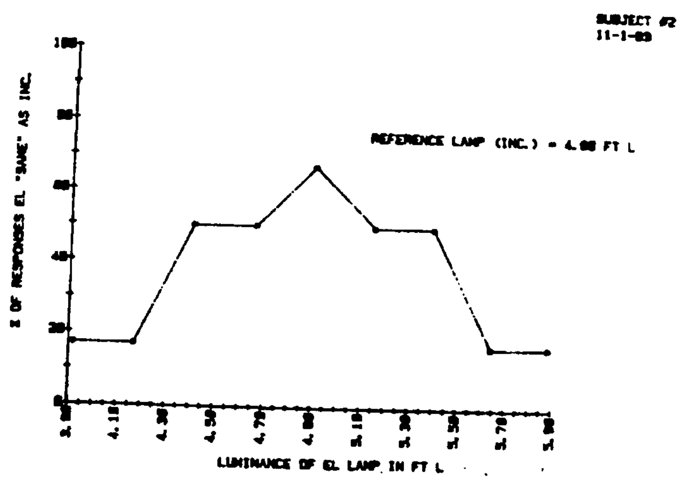

Figure 10. % "SAME" Responses vs. Luminance of EL Light in fL for Subject #2

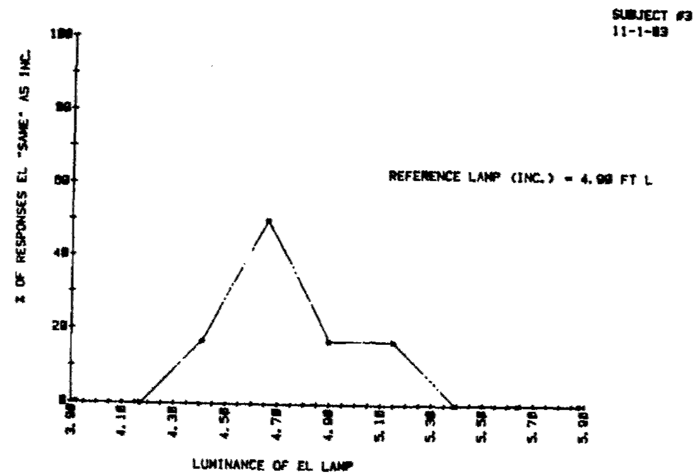

Figure 11. % "SAME" Responses vs. Luminance of EL Light in fL for Subject #3

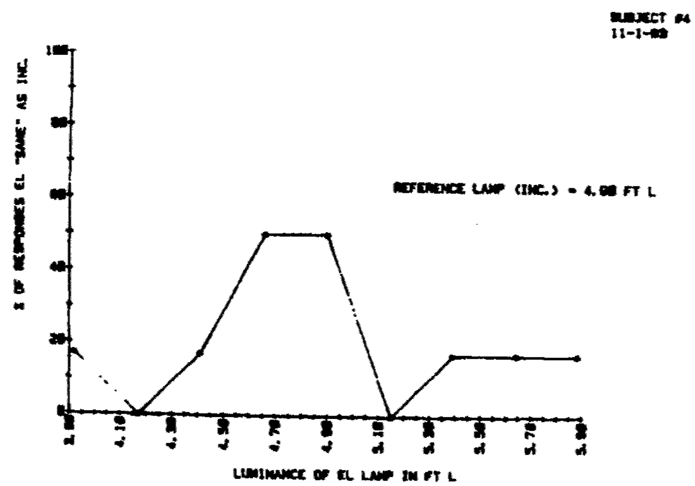

Figure 12. % "SAME" Responses vs. Luminance of EL Light in fL for Subject #4

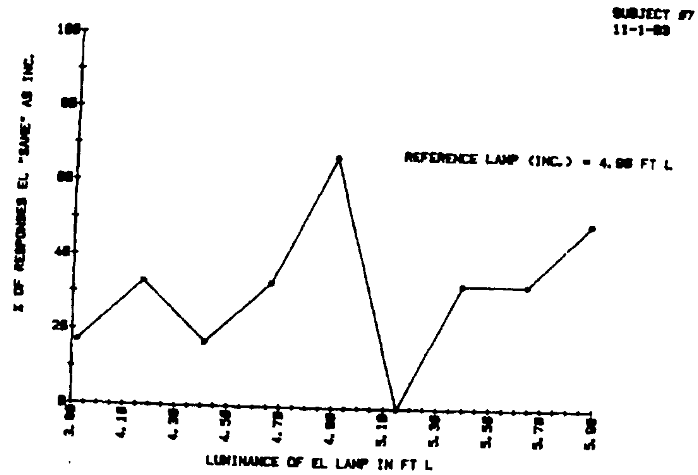

Figure 15. % "SAME" Responses vs. Luminance of EL Light in fL for Subject #7

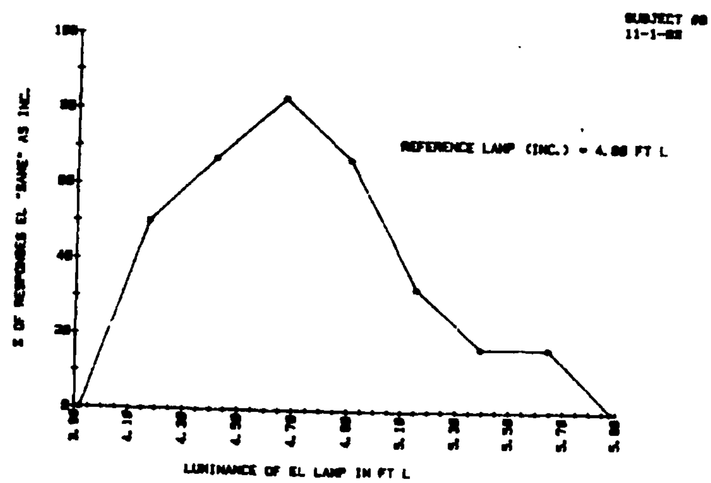

Figure 16. % "SAME" Responses vs. Luminance of EL Light in fL for Subject #8

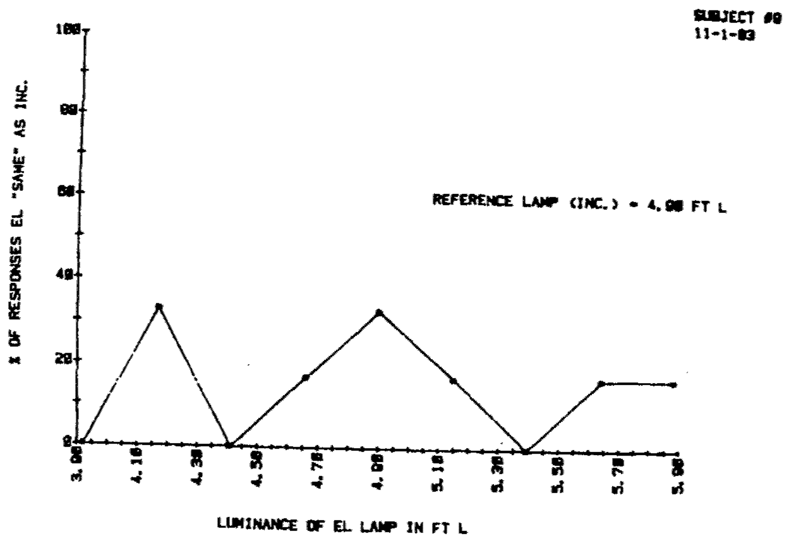

Figure 17. % "SAME" Responses vs. Luminance of EL Light in fL for Subject #9

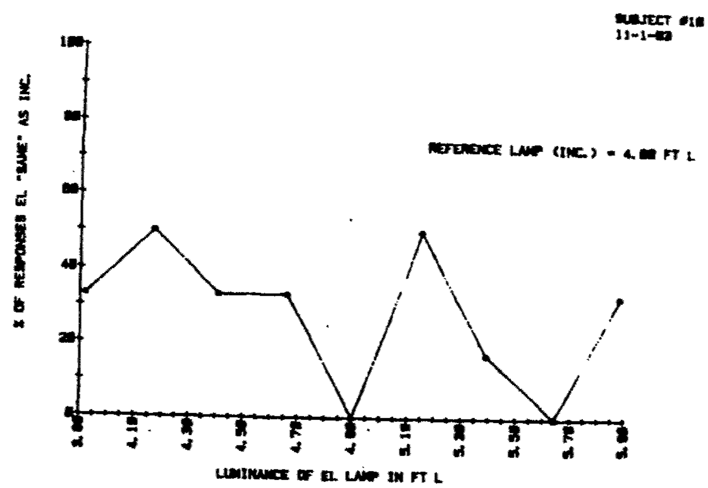

Figure 18. % "SAME" Responses vs. Luminance of EL Light in fL for Subject #10

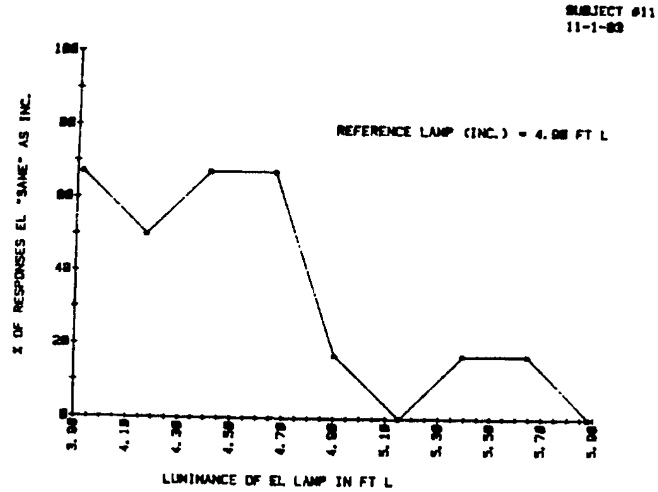

Figure 19. % "SAME" Responses vs. Luminance of EL Light in fL for Subject #11

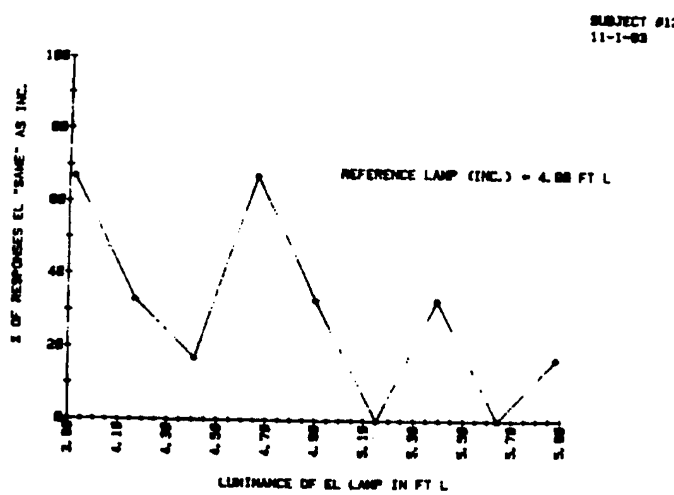

Figure 20. % "SAME" Responses vs. Luminance of EL Light in fL for Subject #12

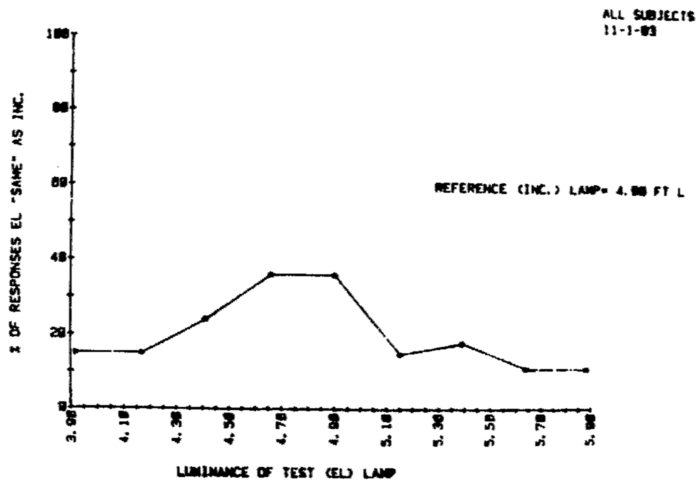

Figure 21. % "SAME" Responses vs. Luminance of EL Light in fL for ALL SUBJECTS

In a similar manner, the responses of "LOW" and "HIGH" were separately tabulated for each luminance level, and converted to percentages using the same technique described previously. Figure 22 plots the percentage of "LOW" responses for the combined data as a function of the luminance of the EL lamp, and Figure 23 plots the "HIGH" responses in a similar fashion. An examination of both of these curves also illustrates that no perceptual difference was evident between the two lamps; ie., the "LOW" response plot is a decreasing function of the luminance of the EL lamp with R = 0.97, and an increasing function is seen for the "HIGH" responses with R = 0.98.

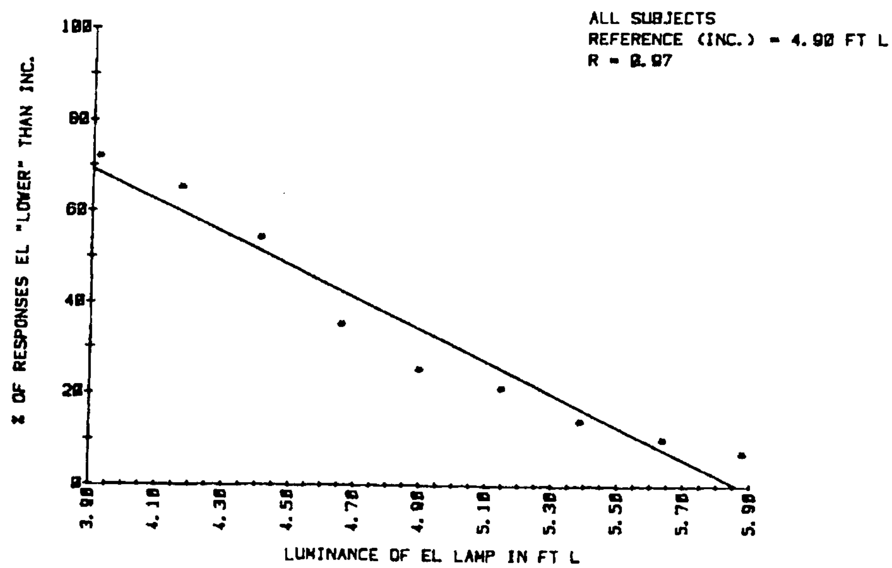

Figure 22. % "LOW" Response vs. Luminance of EL Lamp FOR ALL SUBJECTS

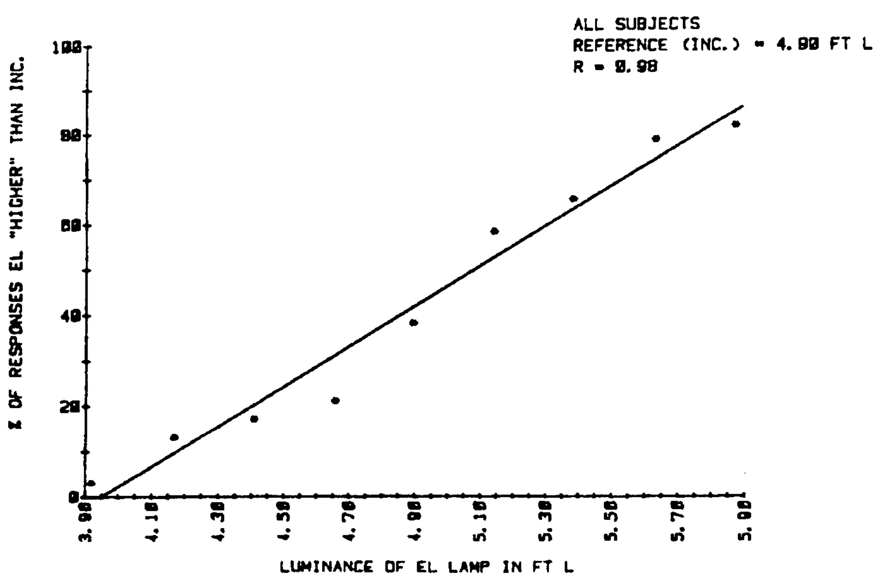

Figure 23. % "HIGH" Response vs. Luminance of EL Lamp FOR ALL SUBJECTS

CONCLUSIONS

The results indicated that once all physical parameters were equal, no perceptual difference was observed between EL and INC light. The outcome of this experiment is significant for Air Force lighting applications. No longer can EL lighting be considered a "magical" light source - one that can't be measured using photometric principles like other types of lighting. The argument that EL light is always "brighter" than INC light, and that a perceptual process is present that inhibits direct measurement of EL lighting is no longer valid. EL lighting must be evaluated on the same basis as other lighting configurations, and may be measured using currently available photometric instrumentation with no special procedures.

APPENDIX A

CONSENT FORM

BRIGHTNESS COMPARISON OF ELECTROLUMINESCENT VERSUS INCANDESCENT LIGHTING

I, ______________________________, having full capacity to consent, do hereby volunteer to participate in a research study entitled, "Brightness Comparison of Electroluminescent Versus Incandescent Lighting", under the direction of Dr. H. Lee Task, with principal investigator Mary Donohue Perry. The implications of my voluntary participation, the nature, duration, and purpose, the methods and means by which it is to be expected have been explained to me by Mary Donohue Perry. I have been given the opportunity to ask questions concerning this research project, and any such questions have been answered to full and complete satisfaction. I understand that I may at any time during the course of this project revoke my consent, and withdraw from the project without prejudice.

I FULLY UNDERSTAND THAT I AM MAKING A DECISION WHETHER OR NOT TO PARTICIPATE. MY SIGNATURE INDICATES THAT I HAVE DECIDED TO PARTICIPATE HAVING READ THE INFORMATION PROVIDED ABOVE.

AM
PM

____
Signature Date Time

I have briefed the volunteer and answered questions concerning the research project.

____
Signature Date

APPENDIX B

OBSERVER INSTRUCTIONS

BRIGHTNESS COMPARISON OF

ELECTROLUMINESCENT VERSUS INCANDESCENT LIGHTING

After five minutes of adaptation in a darkened room, you will be looking at two blue-green circular lights, approximately one foot apart. The light on the left will be brighter, dimmer, or the same as the light on the right. After the experimenter has set the light level, your task will be to respond "HIGH" if the left light is brighter than the right light, "LOW" if the left light is dimmer than the right light, or "SAME" if both lights are of the same intensity. This procedure will be repeated for a total of 54 times. Please cover your eyes in between trials as the experimenter sets the next light level. Do you have any questions? If not, then we will proceed with the experiment. Thank you for your participation.

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ASSESSMENT OF INTERIOR MODIFICATIONS IN C-130 AND C-141 AIRCRAFT FOR NIGHT VISION GOGGLE OPERATIONS (U)

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13. ABSTRACT *(Maximum 200 words)*
An evaluation was conducted to examine the effects of interior paint scheme modifications to C-130 and C-141 aircraft on night vision goggle (NVG) operations. The evaluation consisted of direct measurement of aircraft interior radiance levels, calculation of surface reflectivities, and a human factors assessment of effects on aircrew NVG performance.. The data were collected for both modified and original interior scheme C-130 and C-141 aircraft at Pope AFB and Charleston AFB, respectively. Reflectance values were determined for various flight deck and cargo bay surfaces. The reflectance values were calculated from the radiance levels within the sensitivity range of the NVGs. The results indicated that the reflectances were higher in modified aircraft for the majority of surfaces measured, but well within the specifications set by the relevant military standard. The human factors evaluation indicated that the vast majority of aircrew responding experienced no adverse effect on NVG performance attributable to the new interior scheme. In general, it was concluded that the modified interior scheme should not interfere with NVG operations.

14. SUBJECT TERMS
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SUMMARY

An evaluation was conducted to determine if modifications made to the interiors of the C-130H and C-141B aircraft interfere with night vision goggle (NVG) operations. These modifications were completed as part of the Military Airlift Command's (MAC) Equipment Excellence Interior Material Program. The purpose of the evaluation was to determine if modifications made to the cockpit and cargo areas of these aircraft had any substantial effects on the spectral reflectivity of the surfaces involved which could in turn interfere with NVG flight operations. A subjective assessment of the modifications was also conducted, in which questionnaire results were obtained from flight crew members who had flown NVG missions in both modified and unmodified aircraft.

The evaluation consisted of two components: 1) Measurements of interior radiance levels and calculation of surface reflectances; and 2) A human factors subjective assessment of effects on NVG operations. Data were collected from 13-16 April 1992 at Pope AFB, NC, and Charleston AFB, SC.

In general, the results indicated that the interior modifications that were completed as part of the Equipment Excellence Interior Material Program should not adversely affect NVG operations. The interior surface reflectances calculated from the measurements made were in most cases somewhat higher in the modified aircraft than the original configurations. The maximum allowable NVIS radiance levels specified in MIL-L-85762A were used to interpret the significance of actual surface NVIS radiances. Only one modified surface caused serious concern. The subjective assessment showed that the majority of aircrew who participated in the evaluation did not perceive a difference between the modified and original interiors, and that no adverse effects on NVG operations are anticipated.

PREFACE

At the request of the Military Airlift Center, Pope Air Force Base, North Carolina, this evaluation was completed under work unit 7184-18-07 by members of the Visual Display Systems Branch, Human Engineering Division, Crew Systems Directorate, Armstrong Laboratory, Wright-Patterson Air Force Base, Ohio and Logicon Technical Services, Inc., Dayton, Ohio. Funding for this study was supplied by the Military Airlift Center.

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I. INTRODUCTION

A new program has been initiated by Military Airlift Command (MAC) headquarters for enhancement of transport aircraft. The Equipment Excellence Material Program consists of a new paint scheme, major interior refurbishment, and upgraded maintenance of aircraft appearance. One modification is a new tri-color interior, which replaces the original five color layout, consisting of the following colors: dark blue, glossy beige, and light blue-green. Both the cockpit and cargo areas of the aircraft involved exhibit the new colors. In addition, changes were made to the texture of some flooring materials.

At the request of USAF Airlift Center at Pope AFB, personnel from the Visual Display Systems Branch of the Armstrong Laboratory at Wright-Patterson AFB evaluated the modified aircraft interior paint/material scheme for possible adverse effects on night vision goggle (NVG) operations. Evaluations were performed on C-130H and C-141B aircraft. Of specific concern was whether any increased surface reflectivities resulted from the interior modifications and what impact such increases might have had on NVG operations.

The evaluation was divided into two parts. The first consisted of measuring NVIS radiances of a variety of interior surfaces in both modified and unmodified aircraft and then calculating surface reflectances in the NVIS spectral region. NVIS radiance values were collected with a field portable instrument designed for cockpit lighting inspections. Surface reflectance was chosen as the primary evaluation metric to provide a consistent basis for comparison between aircraft versions. In addition, because the amount of windscreen glare is so important to aircrew members, attempts were also made to measure the NVIS radiance of several windscreen locations in each aircraft. This was followed by an aircrew subjective human factors assessment of possible influence on NVG operations. This assessment consisted of a questionnaire and interviews with NVG-qualified aircrews that had flown NVG missions in modified aircraft. The major findings of the evaluation are outlined in this report.

II. METHODS

Radiance Measures

Measurements of surface NVIS radiance values were made in modified and unmodified versions of the C-130H and C-141B aircraft under similar interior lighting conditions. NVIS radiance limits specified in MIL-L-85762A were used as thresholds to identify surface areas of particular concern. The radiance data were used to calculate surface reflectances in the NVIS spectral region. NVIS radiance values alone collected for any specific interior position were judged to be overly affected by variables beyond the control of the evaluators, most notably time varying levels of in-cockpit infrared energy due to exterior sources, to serve as a basis for accurate absolute comparisons between aircraft interior designs. However, given the availability of a reflectance standard, an accurate reflectance could be calculated for each type of surface. Based on these calculated surface reflectances, a comparison was made between the modified and unmodified versions of each respective aircraft to determine the potential for interference with NVG operations.

An NVG-103 Night Vision Imaging System (NVIS) Cockpit Inspection Scope manufactured by Hoffman Engineering Corporation was configured for AN/AVS-6 NVG emulation and used to collect quantitative radiometric data on the flight deck and in the cargo bay. The AN/AVS-6 (ANVIS) system is the type of NVG currently used by crews of the aircraft types involved and is based on a Generation III (Gen III) image intensifier tube. The NVG-103 design is based on matching the brightness of an adjustable reference provided within the instrument's field of view to the apparent brightness of the target. The uncertainty inherent in brightness matching was reduced by collecting twelve data at each location, six measures of the surface of interest and six of a barium sulfate tablet. Barium sulfate presents a greater than 95% reflective, Lambertian surface throughout the visible and near infrared portions of the electromagnetic spectrum. Further, half of all measures were initiated with the brightness reference set below that of the target and half with the initial reference setting brighter than the target. To further document the color and material modifications, 35mm color photographs and conventional super-VHS video were obtained. In addition, image intensified video in super-VHS format was collected for qualitative evaluation purposes.

All measurement sessions were conducted after local sunset in aircraft located in their normal parking ramp spot. The windscreens were covered with black cloth to minimize the effects of exterior lights to the greatest extent possible. Prior to each measurement set, cockpit lighting levels were established by qualified flight crews. Eight measurement locations were selected in each aircraft; four locations on the flight deck and four locations in the cargo area. In addition, because the amount of windscreen glare is so important to aircrew members, attempts were also made to measure the NVIS radiance of four windscreen locations in each aircraft. Windscreen areas exhibiting both low and relatively high levels of glare as seen by NVGs were evaluated. Reflectances were not calculated for these windscreen locations. These NVIS radiances were interpreted in terms of the guidelines in MIL-L-85762A. The measurement locations for the C-130H and C-141B flight decks are shown in Figures 1 and 2, respectively.

To establish the total NVIS irradiance from all sources incident on each cockpit surface being evaluated, a measurement was made of the NVIS radiance of a barium sulfate tablet placed upon that surface. Total NVIS irradiance at any interior location was comprised of energy emitted from the cockpit and from external sources such as moonlight and ramp lighting bleeding through the black tarps covering the windscreens. The NVIS radiance of the cockpit surface itself was then measured. The ratio of these two NVIS radiance values is effectively the broadband reflectance of the surface of interest in the NVIS spectral region.

Mathematically, this can be represented by:

$$R_{NVIS} = \frac{\int_{450}^{930} S(\lambda)*N(\lambda)\,d\lambda}{\int_{450}^{930} T(\lambda)*N(\lambda)\,d\lambda} \qquad (1)$$

where R_{NVIS} = NVIS broadband reflectance,
$S(\lambda)$ = Radiance of the surface under test,
$T(\lambda)$ = Radiance of barium sulfate, and.
$N(\lambda)$ = Gen III spectral response.

Measurements were made of one modified and one unmodified version of the C-130H and the C-141B aircraft (a total of four aircraft). Results from the unmodified aircraft were used as a baseline for comparison with the modified versions. To ensure consistent initial overall cockpit NVIS radiance levels between modified and unmodified versions of the same aircraft type for measurement repeatability, a black surface and a gray surface on the instrument panel were chosen as reference points and measured. These particular locations were chosen because the colors and finishes were the same in all four aircraft evaluated. Figure 3 shows the approximate location of the reference points for the C-130 and C-141 cockpits.

Four locations were evaluated in the cargo area of each aircraft, consisting of the paratroop doors, and several points on the ceilings. The same measurement procedures described for the flight deck were used in the cargo areas. Due to the extremely low light conditions prevailing in the cargo bays, it was necessary in most cases to use infrared chemical lights to provide sufficient irradiance for measurements. The blue and glossy beige paints used in the cargo areas of the modified aircraft are identical to those used in the cockpit.

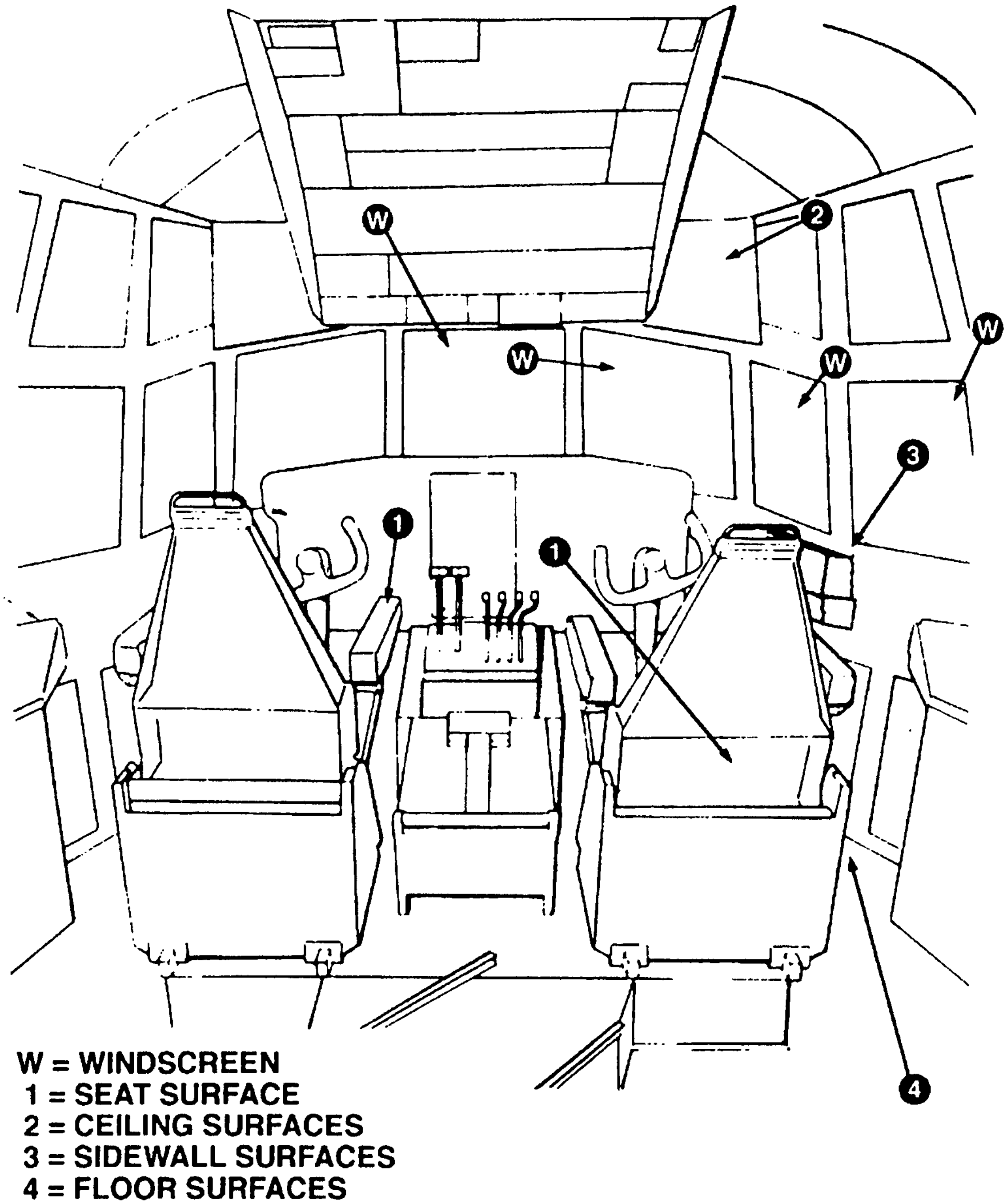

Figure 1: Radiance Measurement Locations on the C-130 Flight Deck.

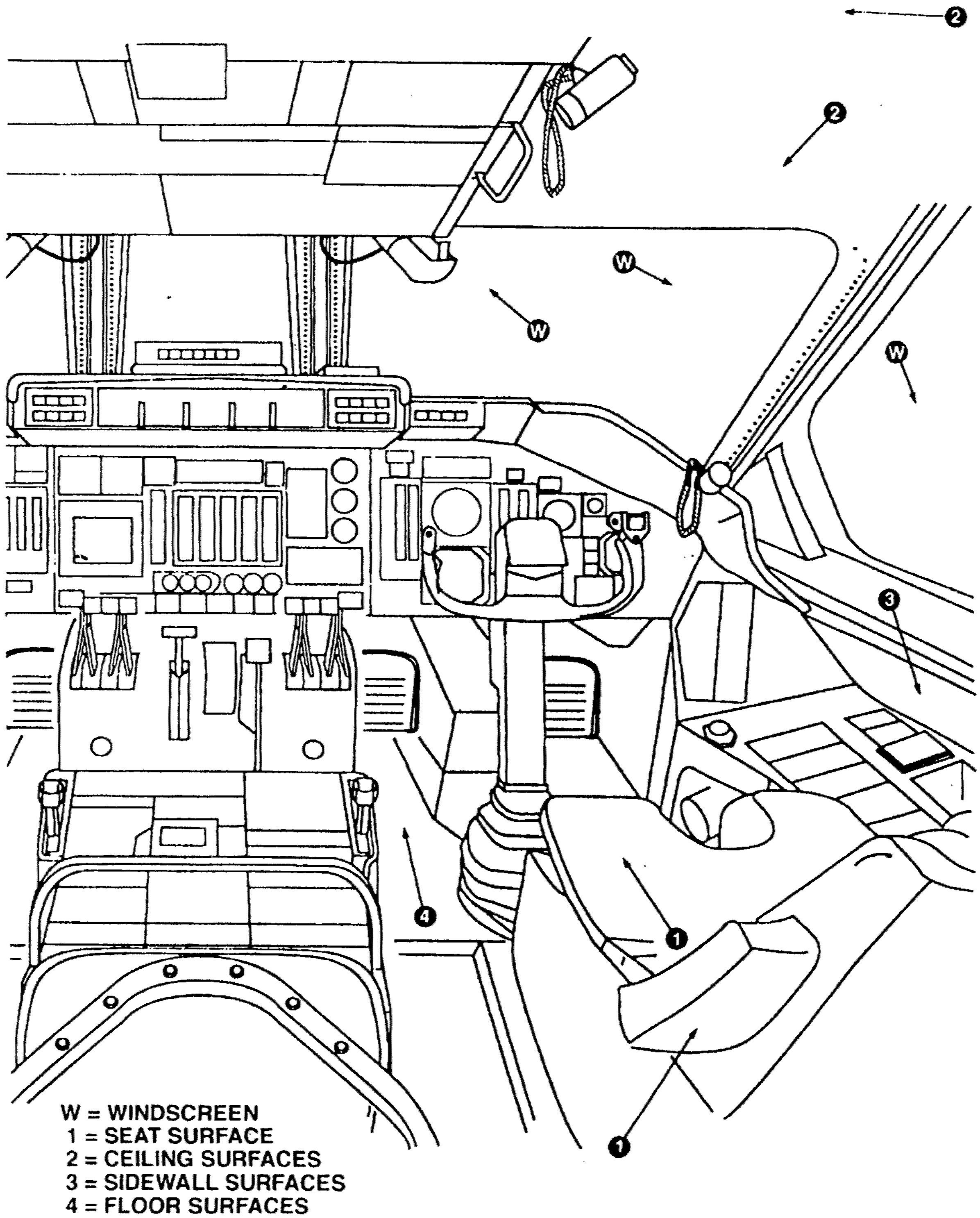

Figure 2: Radiance Measurement Locations on the C-141 Flight Deck

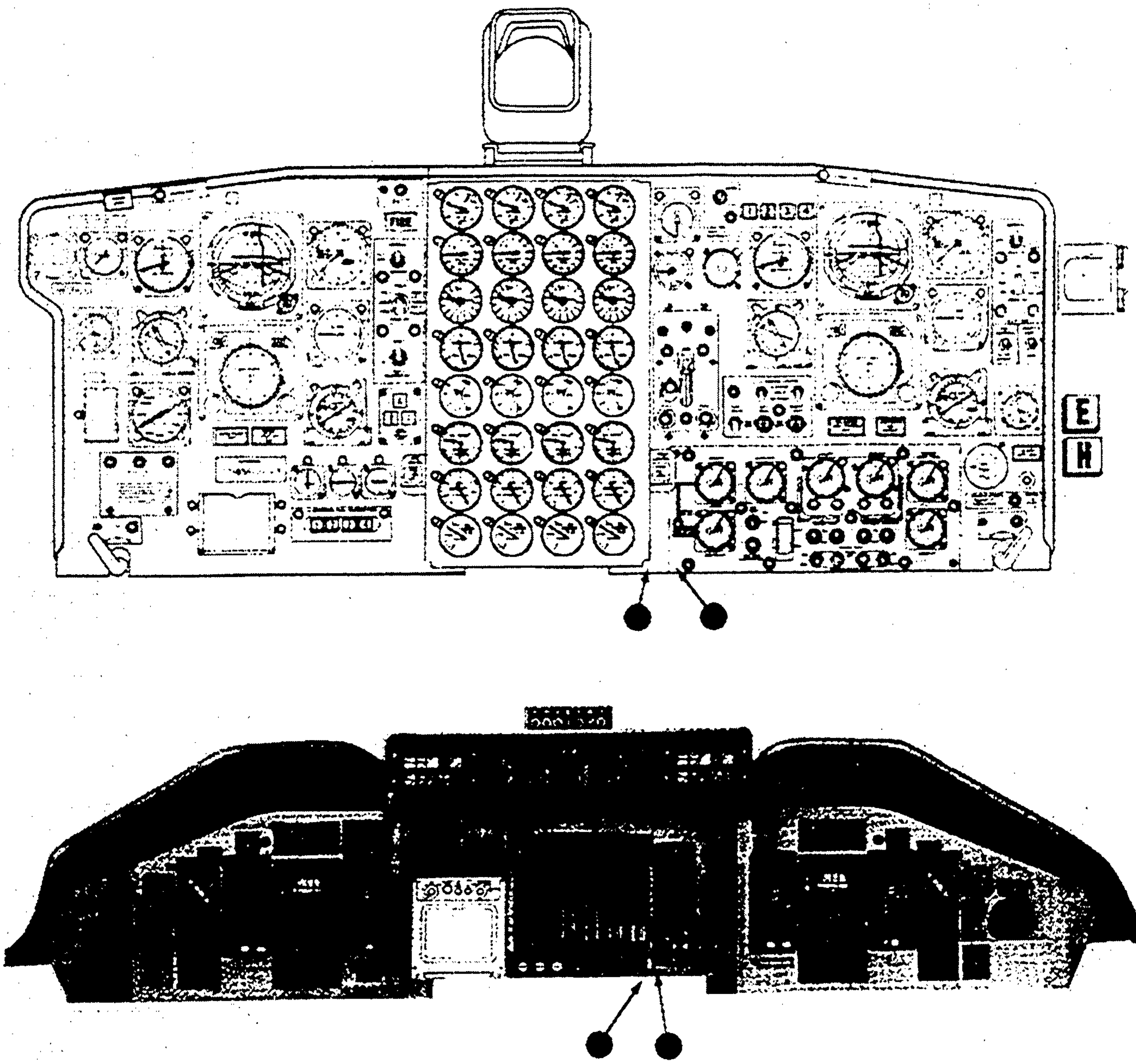

Figure 3: Reference Measurement Locations in the C-130 (top) and C-141 (bottom) Cockpit

Human Factors Evaluation

A brief questionnaire (shown in Appendix A) was administered to ten C-130 and eleven C-141 crewmembers. The questionnaire was designed to elicit opinions regarding the perception of differences for NVG performance for the modified and unmodified interiors, respectively. The questionnaire specifically addressed the effects of the modified interior on the performance of visual tasks and the presence of any noticeable reflections. Crewmembers completing the questionnaire had an average of 17.5 NVG hours experience in modified aircraft. The number of aircrew responding to the questionnaire is displayed in Table 1 as a function of aircraft type and crew position.

Table 1: Summary of Human Factors Questionnaire Participants

Aircraft Type	Crew Position	Number of Participants
C-130H	Pilot	4
	Co-Pilot	2
	Flight Eng.	2
	Navigator	2
C-141B	Pilot	3
	Co-Pilot	3
	Flight Eng.	2
	Navigator	3

III. RESULTS

Radiance Measures

Since the materials and paints used in the modification are consistent between the two types of aircraft, the results of the evaluation are presented here strictly in terms of the various types of surfaces found in the four possible cockpit configurations and cargo bays, with specific aircraft type annotated for clarity where necessary. Table 2 summarizes the calculated reflectances for all significant cockpit and cargo bay surfaces. Values listed in this table should be considered representative. For some surface types, measurements were made in multiple locations, and the value shown in the table is the mean calculated reflectance.

Data obtained during measurements of both aircraft types indicate that the reflectivity of several of the new colors and finishes is greater than that of the originals. However, even though reflectance in the NVIS spectral region generally increased, all measured NVIS radiance values were still within the limits specified by MIL-L-85762A with one notable exception which is discussed in the next paragraph. Perhaps the most notable overall finding from the radiance measures portion of the evaluation was the sharply increased reflectance, vis-a-vis that of the colors being replaced, of the new glossy beige color now used on both perforated vinyl and hard ceiling surfaces.

The shiny metal floor material found in the modified C-130 cockpit at the pilot and copilot stations is extremely reflective and produced very intense specular reflections which were too bright for the NVG-103 to measure. These specular reflections reach the windscreens, particularly in the swing window area. The shiny handgrips located above the forward windscreens also tend to produce reflections in the windscreen. The dark blue flooring which is now used in both aircraft types is significantly less reflective than the original floor materials.

Data collected at the various windscreen positions tended to indicate elevated levels of energy from the cockpit incident upon the windscreens in the modified aircraft, particularly in the area of the swing/sliding windows. The swing/sliding window glare is worse in the modified C-130. However, the glare shields in both aircraft protect the forward windscreen from excessive glare. Due to bleed through of varying levels of near infrared energy from external sources through the black cloth covering the windscreens, exact quantitative comparisons cannot be made of windscreen NVIS radiance values.

Measurements in the cargo bay indicate that NVIS radiance levels are so low that it is unlikely that the new paint scheme will have any noticeable effect on NVG operations performed there.

Table 2: Summary of Broadband Surface Reflectances

Paints	Reflectance
Original Green (Both Aircraft)	22%
New Blue, Color #25414 (Replaces Original Green)	29%
Original Beige (Both Aircraft)	24%
New Glossy Beige, Color #23531 (Replaces Original Beige)	60%
Materials	**Reflectance**
Ceilings - Perforated Vinyl:	
Original Green (C-130)	23%
Original Beige (C-141)	32%
New Glossy Beige	45%
Seat Covers:	
Original Orange (Both Aircraft)	28%
New Blue/Lamb's Cloth	44%
Seat Arms:	
Original Orange Vinyl (Both Aircraft)	17%
New Blue Vinyl (Both Aircraft)	7%
Floors:	
Original Green Linoleum (C-130)	38%
Original Tan (C-141)	34%
New Dark Blue (Both Aircraft)	5%
New Aluminum (C-130)	OFF SCALE*

*Too bright to measure with equipment

Human Factors

Crewmembers were asked to list the four most critical visual tasks they perform during a typical NVG mission, and to rate the impact of the modified interior on the performance of each task. Only one crewmember reported that the modified interior had any noticeable effect on his performance. All remaining crewmembers reported "no change" for each task listed. The one crewmember who reported a difference was a C-130 pilot who indicated that the modified interior scheme was slightly worse with respect to his four most critical tasks of take-off, landing, airdrop, and low level flight. He attributed this to glare or "window shadow" caused by increased reflections in the windscreen. A C-141 flight engineer reported that the modified interior scheme had resulted in improved visibility around the rear of the flight deck for non-NVG conditions. He attributed this improvement to the reductions in glare from the floor and seat coverings at the rear of the flight deck in the modified aircraft.

Crewmembers were asked to indicate whether any reflections were noticeable within the NVG intensified field-of-view that they believe were due to the modified interior. No noticeable reflections were noted by C-141 crewmembers. Two C-130 crewmembers reported slight reflections on the windscreen. One of these crewmembers reported that the modified floor surface and beige ceiling at the pilot and co-pilot positions were very reflective. This crewmember reported that lights from the navigator station reflected off the ceiling of the flight deck. A C-130 flight engineer noted slight glare from reflections on the windscreen during ground operations.

Crewmembers were also asked if the modified interior scheme affected previously existing lighting compatibility problems. Only one C-130 pilot noted any change for the worse in lighting compatibility between the original and modified scheme. This individual noted that the instrument panel lighting compatibility was slightly worse because of the reflections from the shiny aluminum floor surface at the pilot station.

Finally, each crewmember was asked if he could safely and effectively perform the Special Operations, Low Level (SOLL II) mission with an aircraft refurbished with the new interior materials. All crewmembers surveyed indicated they believed they could safely undertake SOLL II missions in modified aircraft.

IV. CONCLUSIONS

The results of the current analyses indicate that reflected ambient light in the interiors of C-130 and C-141 aircraft modified as part of the Equipment Excellence Interior Material Program should not be expected to interfere with NVG operations. NVIS radiance measurements indicated that while the visible and near infrared reflectances of the new surfaces are in general increased vis-a-vis those of the original configurations, surface NVIS radiance levels were still well within the limits established in MIL-L-85762A. One notable exception is the polished aluminum floor at the pilot's and co-pilot's stations in the C-130 cockpit. The human factors analysis corroborated this finding in that the overwhelming majority of crewmembers reported that they did not notice any negative impact of the new design on NVG performance. Nevertheless, two aspects of the modified design do result in increased surface reflectance in the cockpit. These are:

1. The polished aluminum floor at the pilot's and co-pilot's positions in the C-130 cockpit. This represents a highly undesirable surface material due to the unavoidable bright specular reflections associated with such a finish.

2. The beige-colored surfaces in the cockpits of both aircraft.

There was no observed glare on the forward windscreens within one steradian of the pilot's design eye position, in conformance with the military standard. However, glare is present in the side windows of both aircraft, more noticeably in the C-130. It is important to note that if all cockpit lighting was NVG compatible, then the incidence of cockpit lighting energy upon the windscreens would not be a matter of concern.

Appendix A

C-130/141 INTERIOR PAINT SCHEME
NVG EVALUATION QUESTIONNAIRE

Name ________________ NVG Type ______________

Aircraft _____________ Position ______________

Approximate hours of NVG flight experience with:

Old paint scheme _____ hrs.
New paint scheme _____ hrs.

1. List the four most critical VISUAL tasks you perform with NVGs during a typical night mission and for each task use the scale provided to rate any differences between the old and new interior paint schemes you may have experienced in performing each task.

Task	No Change	Slight Improvement	Significant Improvement	Slightly Worse	Signif. Worse
__________________					
__________________					
__________________					
__________________					

2. For those tasks which you rated anything other than NO CHANGE, please describe the differences in performing them between the old and new interior paint scheme in the space below:

3. Please describe any REFLECTIONS within the NVG field of view that you believe were caused by the interior paint scheme for the:

Old scheme ____

New scheme ____

4. Please list the reflection and rate its effect on your performance while wearing NVGs below.

Reflection: ________________

___ No Effect on performance
___ Slight (NVG performance only slightly affected)
___ Moderate (reflections limited the ability to perform NVG operations)
___ Signifcant (reflections made it impossible to perform duties with NVGs)

Reflection: ____________________

___ No Effect on performance
___ Slight (NVG performance only slightly affected)

___ Moderate (reflections limited the ability to perform NVG operations)
___ Significant (reflections made it impossible to perform duties with NVGs)

5. Under the old interior paint scheme, what was the greatest lighting compatibility problem with NVGs at your crew position?

6. How was this problem affected by the new interior scheme?

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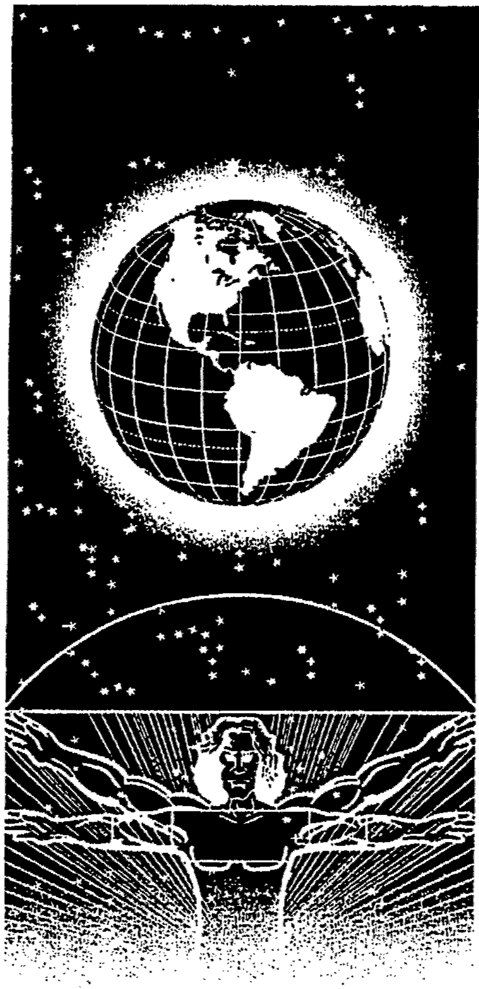

UNITED STATES AIR FORCE RESEARCH LABORATORY

NIGHT VISION IMAGING SYSTEM (NVIS) COMPATIBILITY AND VISIBILITY OF THE F-16 COMMON CONFIGURATION IMPLEMENTATION PROGRAM (CCIP) COMMON COLOR MULTI-FUNCTION DISPLAY (CCMFD)

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13. ABSTRACT *(Maximum 200 words)*

After preliminary operational testing of the Honeywell F-16 Common Configuration Implementation Program (CCIP) Common Color Multi-Function Display (CCMFD), a display intended to incorporate color into night vision imaging system (NVIS) compatible cockpits, some observers felt that the CCMFD did not present video with the same level of detail in NVIS mode as seen in daytime mode. It was also believed that the CCMFD might be interfering with vision through night vision goggles (NVGs), noticeably reducing visual acuity. In addition, pilots wearing NVGs felt that the display was too dim to easily read under certain conditions after prolonged NVG exposure. To address these concerns, the Air Force Research Laboratory, Human Effectiveness Directorate, AFRL/HECV, ran a series of tests with the assistance of the F-16 SPO, the Air Force Reserve and Air National Guard Test Center (AATC/DO), Honeywell, and Lockheed-Martin, to assess the NVIS compatibility and legibility of the CCMFD in its NVIS mode. This paper documents both the results of this testing and an analysis of subjective comments made by observers during a demonstration of the display under the suspect conditions noted by AATC/DO.

14. SUBJECT TERMS
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SUMMARY

In an effort to incorporate color into night vision imaging system (NVIS) compatible cockpits, the F-16 System Program Office (SPO) contracted with Lockheed Martin for the F-16 Common Configuration Implementation Program (CCIP). Lockheed contracted with Honeywell's Aerospace Electronic Systems division for the design and development of a Color Multifunction Display (CMFD). After preliminary operational testing, some observers felt that the CCIP Common Color Multi-Function Display (CCMFD) did not present video with the same level of detail in NVIS mode as seen in daytime mode. The CCMFD might also be interfering with vision through night vision goggles (NVGs), noticeably reducing visual acuity, suggesting that the display might not be truly NVIS compatible. In addition, pilots wearing NVGs, which can provide up to 5 footLamberts (fL) of light to the observer's eyes, felt that the display was too dim to easily read under certain conditions after prolonged exposure to bright NVGs.

To address these concerns, the Air Force Research Laboratory, Human Effectiveness Directorate, AFRL/HECV, ran a series of tests with the assistance of the F-16 SPO, the Air Force Reserve and Air National Guard Test Center (AATC/DO), Honeywell, and Lockheed-Martin, to assess the NVIS compatibility and legibility of the CCMFD in its NVIS mode. These tests showed that CCMFD met all existing NVIS B compatibility criteria. The color coordinates chosen by Honeywell allowed for good color discrimination and for an appealing, full-color display. Certain colors were displayed at lower luminance than desired by many observers, but the display met the luminance requirements stated in MIL-L-85762A.

Even though the display met the requirements of MIL-L-85762A, interactions with F-16 pilots with NVG experience during the tests yielded a number of interesting observations. According to one observer, the CCMFD displaying the target pod FLIR video in NVIS mode was too dark to distinguish the level of detail needed for targeting. When information is displayed at high densities, such as the FLIR image, more light is required to discern details. During the demonstration, the Honeywell representative set the display in day mode and adjusted the illumination until the observer said it was bright enough for targeting. At the observer's preferred setting, the luminance of the display measured 90 fL. This much light in the cockpit may degrade the pilot's visual capability looking out of the cockpit and may negatively impact NVG performance. It was discovered that pilots flying Block 30 aircraft in the NVIS mode are forced to set their lighting to a very bright level, nearly to the maximum luminance of which the NVIS lighting is capable, to see features of the horizontal situation indicator (HSI) and fuel totalizer. Again, the additional light may degrade the pilot's visual performance and may negatively impact vision through NVGs.

There appears to be a system-wide compatibility issue with the NVGs. However, initial flight programs have found the displays to be acceptable. The CCMFD's have passed qualification testing and bench testing for NVIS compatibility. Increasing the luminance of the CCMFD will require a design change. The desired luminance level remains unclear at this time. What is needed is an examination of the cockpit as a system to determine what could benefit from change. Areas other than display luminance that may require attention include reexamining the visibility requirements for NVIS displays, tightening the requirements for NVIS compatibility specifically for liquid crystal displays (LCDs), minimizing the windscreen reflectivity, or even improving cockpit display luminance balance.

INTRODUCTION

The F-16 is a single-engine, single or two-seat, multi-role tactical fighter with full air-to-air and air-to-ground combat capabilities. The F-16 System Program Office (SPO), ASC/YP located at Wright-Patterson AFB, OH, is responsible for the development of F-16 systems' capable of meeting the warfighter's operational requirements. F-16 avionics support all-weather air-to-ground attack and air-to-air missions. In support of these missions, the F-16 uses two Common Color Multi-Function Displays (CCMFDs) compatible with a Night Vision Imaging System (NVIS) or Night Vision Goggles (NVGs).

In an effort to incorporate color into night vision imaging system (NVIS) compatible cockpits, the F-16 System Program Office (SPO) contracted with Lockheed Martin for the F-16 Common Configuration Implementation Program (CCIP). Lockheed contracted with Honeywell's Aerospace Electronic Systems division for the design and development of a Color Multifunction Display (CMFD). Honeywell Electronic Systems, Albuquerque NM, developed the CMFD's in the late 1990's. The F-16 CCMFD is intended to be a replacement for the F-16 CFMD, which suffers from serious diminishing material source (DMS) issues. As a result, the F-16 CCMFD was developed using common, industrial grade components. The CCMFD is a 4-inch by 4-inch display and provides the pilot with high-resolution, full color video in different ambient conditions (e.g., full sunlight to low starlight levels). This display was intended to replace the standard cathode ray tube based MFD with which the Block 40 and newer F-16's are currently equipped. The CCMFD's specification required Honeywell to meet MIL-L-85762A, Military Specification, Lighting, Aircraft, Interior, Night Vision Imaging System Compatible requirements.

To determine if the new color multifunction display could be integrated into older aircraft flown by the Air National Guard and Air Force Reserves, the Air National Guard and Air Force Reserve Test Center (AATC/DO) in Tucson, AZ, asked for Honeywell to demonstrate their display on an NVIS compatible aircraft at AATC/DO. A number of researchers from AFRL/HEA, Mesa, AZ, assisted this effort by performing a series of tests intended to assess the NVIS compatibility of prototype cockpit displays and lighting.

After preliminary testing in Tucson, some observers felt that the CCMFD suffered from a few noteworthy problems. First, it did not present video with the same level of detail in NVIS mode as seen in daytime mode. The image quality of the display when set in NVIS mode was not as good as one would prefer for many of the F-16's missions. It was also noted that the CCMFD might also be interfering with or degrading visual performance through night vision goggles (NVGs). A measurable reduction in visual acuity through NVGs was attributed to the CCMFD, suggesting that the display might not be truly NVIS compatible. In addition, pilots felt that the display was too dim to easily read small symbols and characters on the CCMFD under certain conditions after prolonged exposure to bright NVGs. Initially, this was attributed to possible loss of dark adaptation due to prolonged exposure to NVGs, some of which are capable of presenting a 5 fL image to the observer, under the proper conditions.

As a result of these tests, the F-16 SPO asked the Air Force Research Laboratory, Human Effectiveness Directorate, AFRL/HECV, Wright-Patterson AFB to examine the issues noted by AATC/DO and demonstrate the visual phenomena in the laboratory. Before the displays could be made available for laboratory testing, initial studies were restricted to examining the visibility of small characters whose luminance was in the range displayed by the CCMFD. An experiment was assembled to test the hypothesis that observers adapting to a bright NVG image could have more difficulty reading small, dim display characters. The visual acuity of several observers was measured after prolonged exposure to bright NVGs. After dark-adapting for 10 minutes, the observer's baseline acuity was measured using a self-luminous array of Landolt C's (Figure 1). Then the observer was exposed to a 4 fL NVG output. Visual acuity was measured every 15 minutes for one hour. The experiment was repeated twice, once with the display luminance set to 1.0 fL and again with a display luminance of 0.1 fL. Studies showed acuity to be the same at the end of the hour of exposure as the baseline measurement, indicating that acuity was independent of NVG exposure time.

This result is supported by research conducted independently at AFRL/HEA, Mesa, AZ and documented in a paper soon to be released in the Journal of Aviation, Space, and Environmental Medicine (ASEM) [Howard, Reigler, and Martin, in press]. This paper described an experiment that measured the response time of a number of subjects reading a simulated NVIS compatible altitude direction indicator (ADI) as a function of the log luminance ratio of a bright NVG and a dim display. Howard, Reigler, and Martin noted measurable increases in response time at log luminance ratios of two or greater (Figure 2). The log of the luminance ratios experienced by observers in the AFRL/HECV experiment viewing Landolt C's never exceeded 1.6, minimizing the impact of this phenomenon.

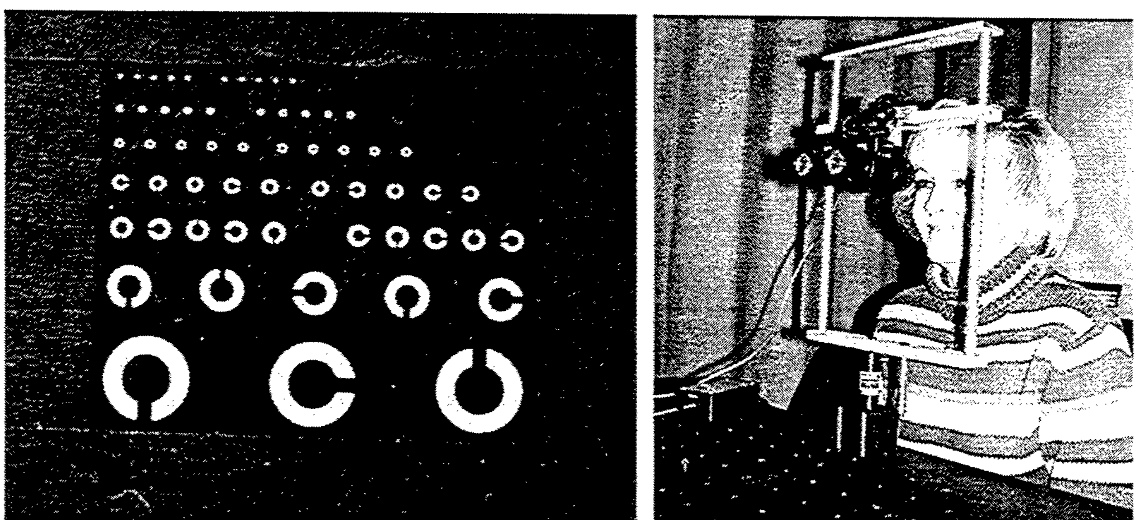

Figure 1. Landolt C's (left) and goggle mount (right) used in preliminary study to assess the visibility of small, dimly lit characters.

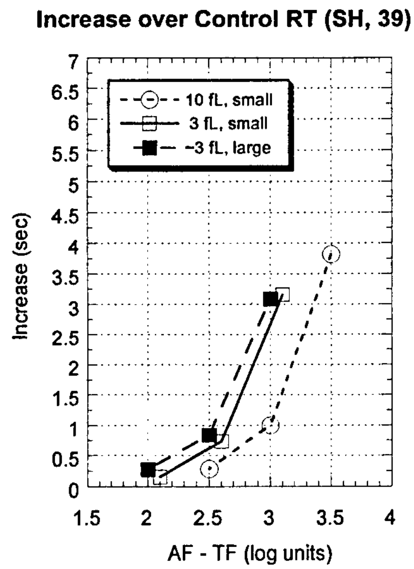

Figure 2. Increase in reaction time as function of luminance ratio in log units for three different targets (10 fL small, 3 fL small, and ~3 fL large) for one observer. [Howard, Reigler, and Martin, in press]

In light of this result, the F-16 SPO, AATC/DO, and Honeywell agreed that the visual interactions between the CCMFD and state-of-the-art night vision systems should be studied in greater detail. At the end of January 2001, Honeywell provided two CCMFD's for examination by AFRL/HECV at Wright-Patterson AFB, OH. This report documents the procedures applied in the analysis of the displays, the data acquired, and the results of demonstrations of the visual phenomena noted at AATC/DO.

MEASUREMENTS AND DATA

To examine the displays, a number of quantitative laboratory tests and demonstrations were held 29 Jan – 2 Feb 2001 at AFRL/HECV. Measurements made to characterize the displays included spectral, NVIS radiance, luminance, luminance uniformity, and character size. In addition, a low-fidelity cockpit simulation was assembled to recreate a number of visual phenomena under controlled conditions that were reported from initial operational testing. The test plan as compiled in January 2001 appears in Appendix A as additional information.

Spectral Measurements

A considerable amount of data could be obtained simply by making spectral measurements of the light emitted from the display. Display radiance, NVIS radiance, luminance, and color coordinates can all be calculated once the spectral content of the emitted light is known. Measurements were made using an Instrument Systems IS 320 radiometer (Figure 3) capable of measuring NVIS radiance. To start the measurements, the display was placed on a stage 24 inches from the radiometer's measurement head. A four-segmented image made up of quadrants of color: red, green, blue, and either black or white, was placed on the display (Figure 4). The radiometer's head was then aligned to each of the four colors and measured in sequence.

Measurements were made at three luminance levels: full NVIS bright, half full bright, and one increment above off. Once all three measurements were completed, the radiometer head was realigned on a different color quadrant of the display and the measurements repeated. To get the fifth color, either black or white, a second quadrant target was displayed and measured. To verify that the red, green, and blue color patches were the same on the two quadrant targets, one color was chosen, measured again from the second quadrant target, and compared to the previous measurements of that color. Data was saved to a computer file for extraction and analysis later. The data extracted on display NVIS A and B radiance, luminance and chromaticity are displayed in Table 1 through Table 6 of this document. Examples of the spectral data obtained in this effort are displayed in Figure 5 through Figure 9 below.

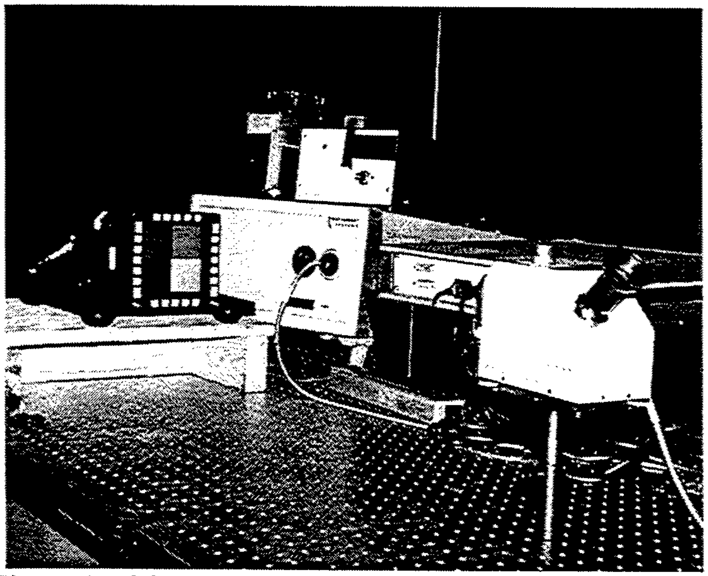

Figure 3. CCMFD in position for spectral measurements.

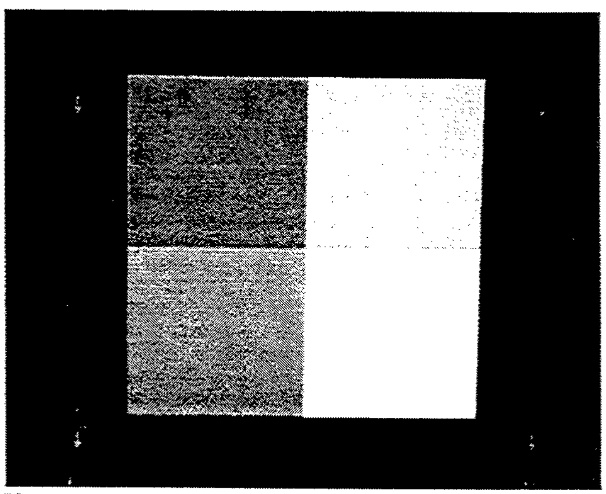

Figure 4. Target used for spectral measurements

Table 1. Display NVIS radiance, luminance, and UCS chromaticity for S/N 902002, display set to full bright.

	NVIS A	NVIS B	Luminance	u'	v'
red	5.35E-08	3.48E-09	0.226	0.4028	0.5306
green	4.47E-09	2.70E-10	0.559	0.1547	0.5497
blue	1.83E-09	2.83E-10	0.118	0.1060	0.4111
white	1.66E-08	1.20E-09	0.878	0.1996	0.5258
black	2.35E-08	1.33E-08	0.003	0.1846	0.5160

Table 2. Display NVIS radiance, luminance, and UCS chromaticity for S/N 902002, display set to half bright.

	NVIS A	NVIS B	Luminance	u'	v'
red	5.18E-08	3.13E-09	0.026	0.4000	0.5311
green	4.37E-09	2.49E-10	0.065	0.1363	0.5601
blue	1.08E-09	5.96E-11	0.014	0.1086	0.4086
white	1.72E-08	1.04E-09	0.103	0.2049	0.5245
black	1.53E-08	4.44E-09	0.003	0.1923	0.5119

Table 3. Display NVIS radiance, luminance, and UCS chromaticity for S/N 902002, display set to one increment above off.

	NVIS A	NVIS B	Luminance	u'	v'
red	5.01E-08	2.29E-09	0.006	0.4123	0.5341
green	2.50E-09	9.67E-11	0.015	0.1388	0.5603
blue	5.30E-10	5.06E-11	0.003	0.1028	0.3982
white	1.75E-08	8.83E-10	0.022	0.2037	0.5230

Table 4. Display NVIS radiance, luminance, and UCS chromaticity for S/N 901002, display set to full bright.

	NVIS A	NVIS B	Luminance	u'	v'
red	5.64E-08	5.03E-09	0.245	0.4067	0.5306
green	3.66E-09	3.02E-10	0.540	0.1409	0.5563
blue	2.43E-09	4.97E-10	0.108	0.1108	0.3887
white	1.80E-08	1.70E-09	0.833	0.2012	0.5213
black	1.75E-08	6.85E-09	0.003	0.1775	0.5036

Table 5. Display NVIS radiance, luminance, and UCS chromaticity for S/N 901002, display set to half bright.

	NVIS A	NVIS B	Luminance	u'	v'
red	5.58E-08	4.13E-09	0.029	0.4047	0.5299
green	3.39E-09	1.41E-10	0.066	0.1401	0.5565
blue	1.56E-09	9.12E-11	0.013	0.1088	0.3879
white	1.74E-08	1.44E-09	0.104	0.2007	0.5202
black	6.86E-08	5.51E-08	0.000	0.2260	0.5413

Table 6. Display NVIS radiance, luminance, and UCS chromaticity for S/N 901002, display set to one increment above off.

	NVIS A	NVIS B	Luminance	u'	v'
red	5.20E-08	3.55E-09	0.006	0.4110	0.5324
green	2.85E-09	1.34E-10	0.014	0.1392	0.5597
blue	7.69E-10	3.85E-11	0.003	0.1073	0.3755
white	1.95E-08	1.47E-09	0.020	0.2059	0.5171

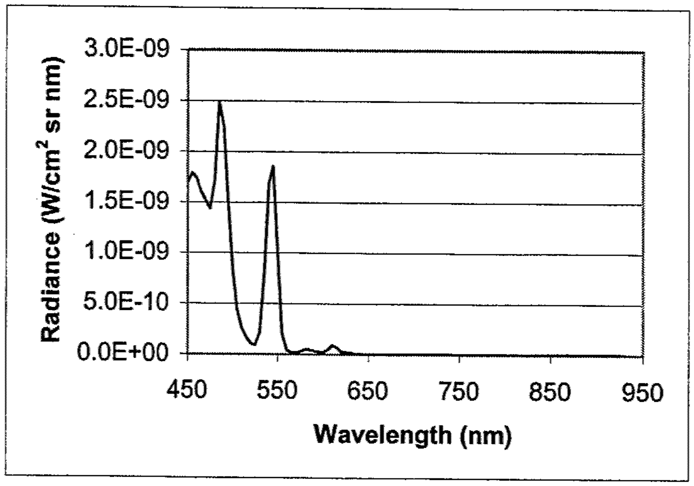

Figure 5. Radiance as a function of wavelength for CCMFD blue, display set for full brightness.

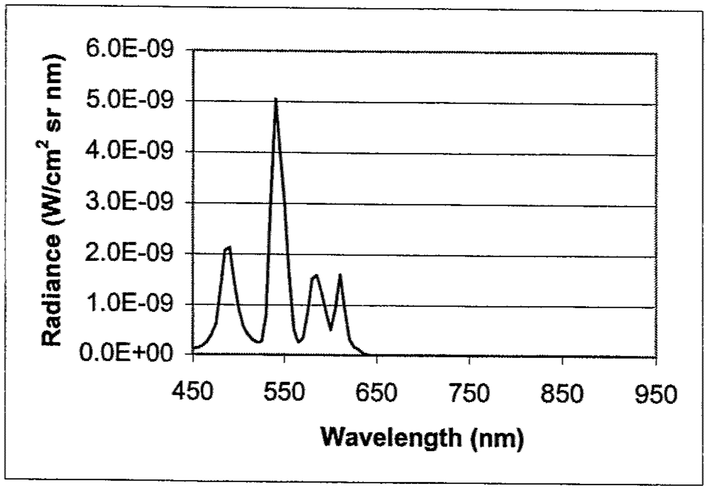

Figure 6. Radiance as a function of wavelength for CCMFD green, display set for full brightness.

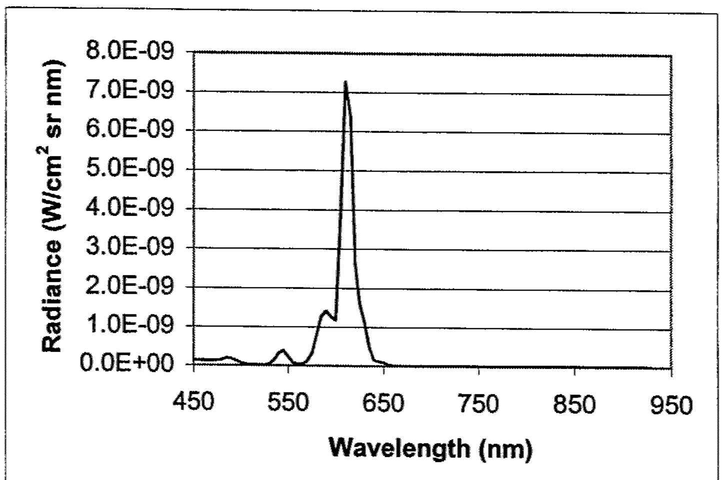

Figure 7. Radiance as a function of wavelength for CCMFD red, display set for full brightness.

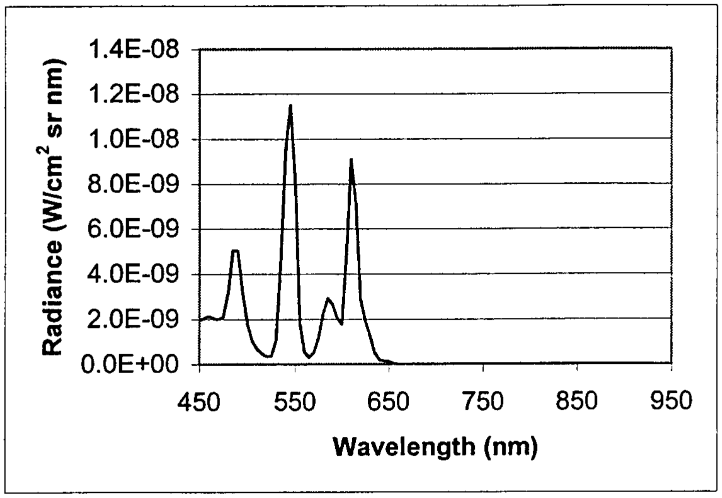

Figure 8. Radiance as a function of wavelength for CCMFD white, display set for full brightness.

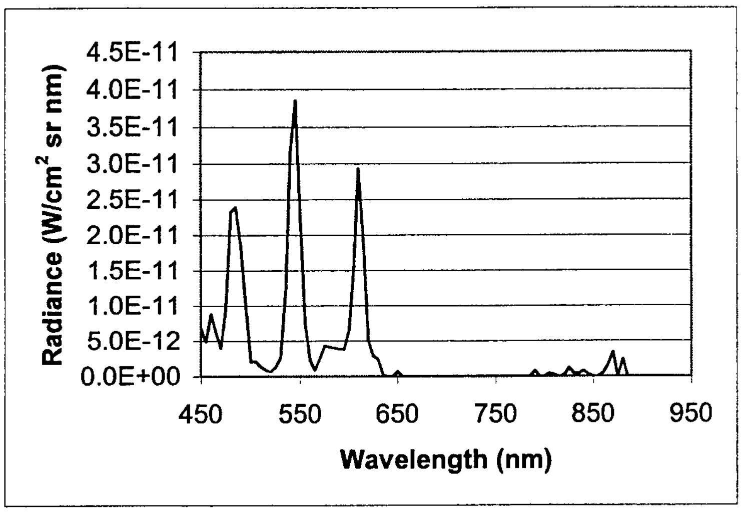

Figure 9. Radiance as a function of wavelength for CCMFD black, display set for full brightness.

Luminance Uniformity

In addition to the spectral measurements described in the previous section, the F-16 SPO asked for an evaluation of the luminance uniformity of the CCMFD to verify that the display met their uniformity requirement. To save time, only one display was measured. The test required the display to be illuminated all in one color. The display's luminance was measured for nine locations (Figure 10) using a Minolta hand-held photometer placed 43 inches from the face of the display. The photometer's one-degree field of view measured a 0.75-inch diameter circle at the display, insuring that there was no overlap between measurements. Display luminance uniformity was measured for red, green, blue, and white. The data collected are presented in this report in Table 7.

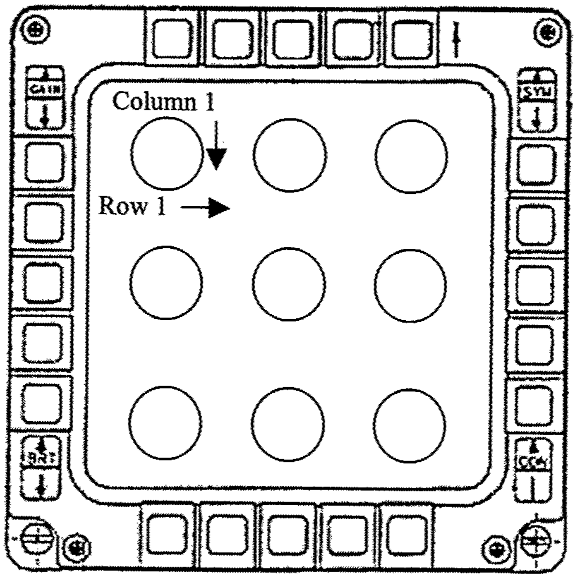

Figure 10. Relative locations on the CCMFD of the luminance uniformity measurements

Table 7. Luminance uniformity of CCMFD 902002.

White	Col 1	Col 2	Col 3		Red	Col 1	Col 2	Col 3
Row 1	1.082	1.034	1.091		**Row 1**	0.251	0.241	0.251
Row 2	1.024	1.005	1.023		**Row 2**	0.241	0.241	0.241
Row 3	0.956	0.947	0.956		**Row 3**	0.232	0.232	0.232
Green	**Col 1**	**Col 2**	**Col 3**		**Blue**	**Col 1**	**Col 2**	**Col 3**
Row 1	0.666	0.647	0.676		**Row 1**	0.145	0.135	0.145
Row 2	0.647	0.628	0.637		**Row 2**	0.135	0.135	0.135
Row 3	0.589	0.589	0.599		**Row 3**	0.126	0.126	0.126

The most noticeable trend found in luminance uniformity was a decrease in display luminance as the measurements moved farther from the top edge of the display. In addition, the upper corners tended to be brighter than the lower corners. The percent uniformity (*Uniformity*) was calculated for each tested color using the following equation:

$$Uniformity = \frac{Max - Min}{Max} \times 100\%$$

Here, *Max* and *Min* are the maximum and minimum luminance respectively, measured for a particular color from the display. The resulting calculated percentages are listed in Table 8.

Table 8. Luminance uniformity of the CCMFD (S/N 902002) for the four measured colors expressed as a percentage.

Color	% Uniformity
Red	7.7
Green	12.9
Blue	13.3
White	13.3

Character Size Measurement

One of the most pressing issues left unexamined by initial tests at AATC/DO in Tucson was the size of the characters that were considered difficult to read. The impact of the physical size of a target on its visibility is easy to understand. Larger targets are simply easier to see [Cobb and Moss 1928]. Due to the nature of the tests conducted at AATC/DO, researchers were unable to measure the size of the characters displayed on the CCMFD. The symbol sets used were not the symbology commonly used on the F-16 MFD, but rather were the result of the manufacturer's best guess at what the aircraft symbol generator might present on the display. To display this symbology, characters were generated on a personal computer and relayed to the displays through considerable electronics.

To measure the characters of interest, the individual files were first printed in the proper aspect ratio using a high quality laser printer (600 dpi). Symbols were then measured from the paper using a 20X loupe and reticule. To check these measurements, a number of characters were measured both off the paper printouts and directly from the displays themselves using the same loupe and compared. Comparison of the two sets of measurements showed both approaches to yield the same results to within the accuracy of the measurement loupe.

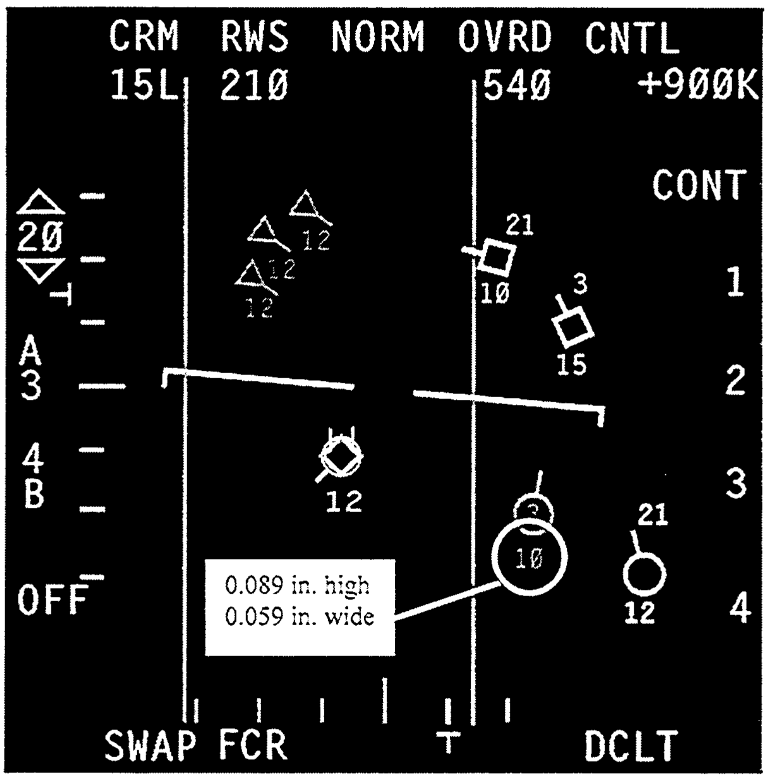

Figure 11. Conceptual image of tactical data displayed on the CCMFD. Figure reproduced to actual scale (4 inches X 4 inches).

The smallest, dimmest characters (the characters most difficult to see) were the blue letters and numbers, measuring 0.089 inches high and 0.059 inches wide. Observing these symbols at 28 inches, the nominal observation distance for this display in the F-16, the characters would be 10.9 arc minutes tall. This translated to a Snellen acuity of about 20/43.5. One should note that the displayed characters were not similar to those commonly used in acuity testing, and did not exhibit the defined length to width to stroke aspect ratio. Therefore, this analysis only yielded an estimate of Snellen acuity. The actual visual acuity of these characters was undoubtedly worse.

At the writing of this report, it was unclear if the symbols presented in the laboratory at AFRL/HECV were the same as those considered difficult to read at AATC/DO. Many believe that the characters used at AFRL/HECV had thicker line widths, making them easier to read. The usefulness of these measurements in explaining the objectionable conditions is, therefore, somewhat questionable for two reasons. First, the symbols might not be the ones found objectionable at AATC/DO in November. Secondly, they do not accurately represent the symbols that would be displayed in an operational aircraft. However, these measurements did establish the size of characters used in AFRL/HECV demonstration.

Gain and Spectral Sensitivity

The two night vision goggles loaned to AFRL/HECV by AATC/DO were both AN/AVS-9 (F4949) devices manufactured by ITT Night Vision Industries. One was an older C model AN/AVS-9, S/N 0568, having lower gain and a slightly different focus mechanism than state-of-the-art night vision devices currently flying in the US Air Force. The other was a new G model AN/AVS-9, S/N 5587, exhibiting high gain and high optical performance. Both were tested for gain and spectral sensitivity established procedures [Task, Hartman, Marasco, and Zobel 1993]. Brief descriptions of the procedures and the data acquired from the two goggles used in the demonstration are provided in Appendix B and C as additional information.

Vision Demonstration

To better examine the interaction between the display, the cockpit, and the night vision goggle, a demonstration was assembled in a laboratory at AFRL/HECV. This demonstration placed observers in a simulated cockpit with the CCMFDs and required them to assess their own visual performance under a number of conditions. Observer comments were noted and reviewed to determine the combinations of conditions under which visual performance was unacceptably degraded.

Conditions and Procedure

To assemble the cockpit simulation, the displays were placed in the correct geometry with respect to the observer's eye position using information provided by Lockheed-Martin (Figure 12, Table 9). The distances listed in Table 9 are in inches and are relative to the observer's correct eye position. In Table 9, the column labeled **Distance** lists the distance to the displays from the eye position. The column labeled **Horizontal** describes the separation between the displays. The column labeled **Vertical** describes the distance the displays were placed below the observer's line of sight.

Table 9. Coordinates of the four corners and the center of the two CCMFD's as positioned in the simulated cockpit. Distances are in inches and are relative to the observer's correct eye position.

	Distance	**Horizontal**	**Vertical**
Upper Outboard	28.6	±8.8	-12.5
Upper Inboard	28.6	±4.5	-12.5
Center	28	±6.7	-14.5
Lower Outboard	27.5	±8.8	-16.5
Lower Inboard	27.5	±4.5	-16.5

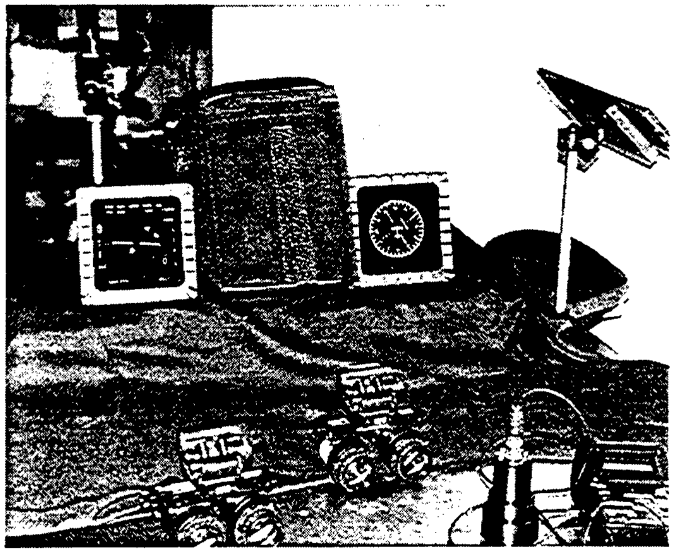

Figure 12. Low-fidelity cockpit simulation used to demonstrate visual interactions.

An electro-luminescent (EL) panel was mounted to a post near the displays to add additional NVIS "compatible" light, simulating the effect of other lights in the cockpit. The light from the EL panel was diffused by reflecting it off a large, flat, white surface. A 3X3 NVG resolution target (Figure 13) was placed in space 15 feet from the observer position. The target was provided as a visual performance reference to assist the observers in assessing the impact of the different display and lighting conditions. A sheet of Plexiglas was placed between the observer and the acuity target to reflect EL light back towards the observer. This created a veiling luminance that could interfere with visual performance (Figure 14) as a windscreen would in a real cockpit.

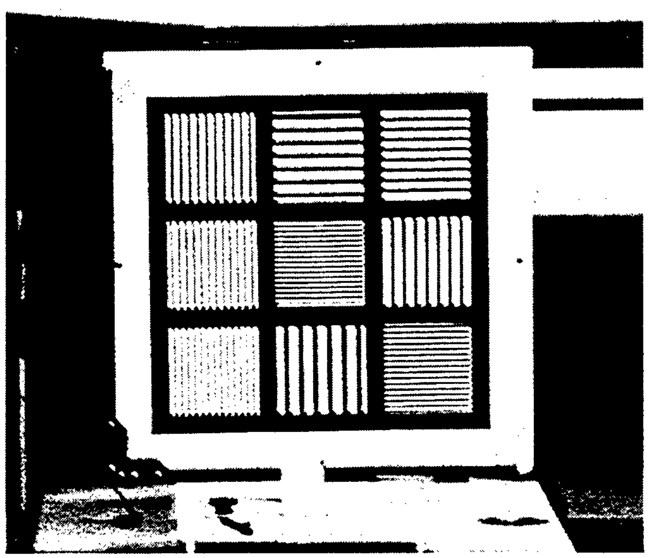

Figure 13. 3X3 NVG resolution target.

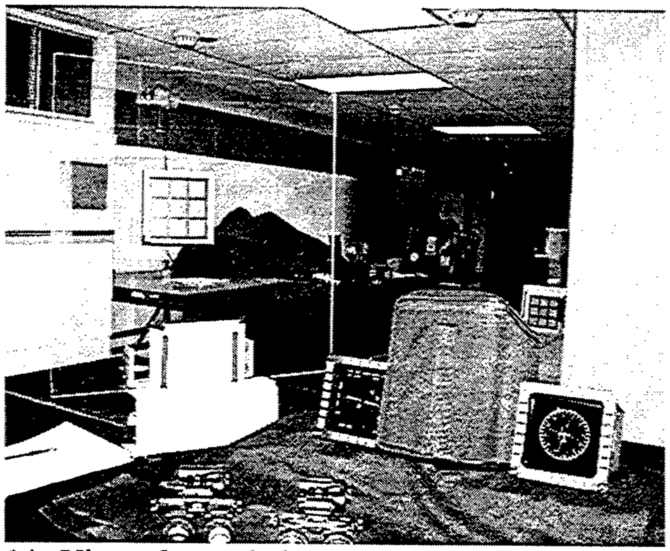

Figure 14. View of a resolution target from the simulated cockpit.

The experimental conditions examined were based on the observations made at AATC/DO. It was expected that exterior target luminance and CCMFD luminance would have the largest impact on visual performance. In addition, the amount of additional cockpit lighting was also expected to affect vision, making it a logical factor to include. Finally, the level of NVG performance was also suspected, not necessarily of being a factor affecting vision by itself, but of being part of an interaction involving the display luminance and cockpit lighting. A factor describing goggle performance was therefore included. One should note that newer NVGs tend to have improvements in a number of parameters, including higher gain, higher spectral sensitivity, and different minus-blue filters, making them perform differently than older goggles. Due to the limited number of NVGs available for this demonstration, it was impossible to differentiate the effects of the different NVG parameters on vision.

Figure 15. CCMFD compass demonstration. This image is not indicative of information currently displayed on the F-16 MFD.

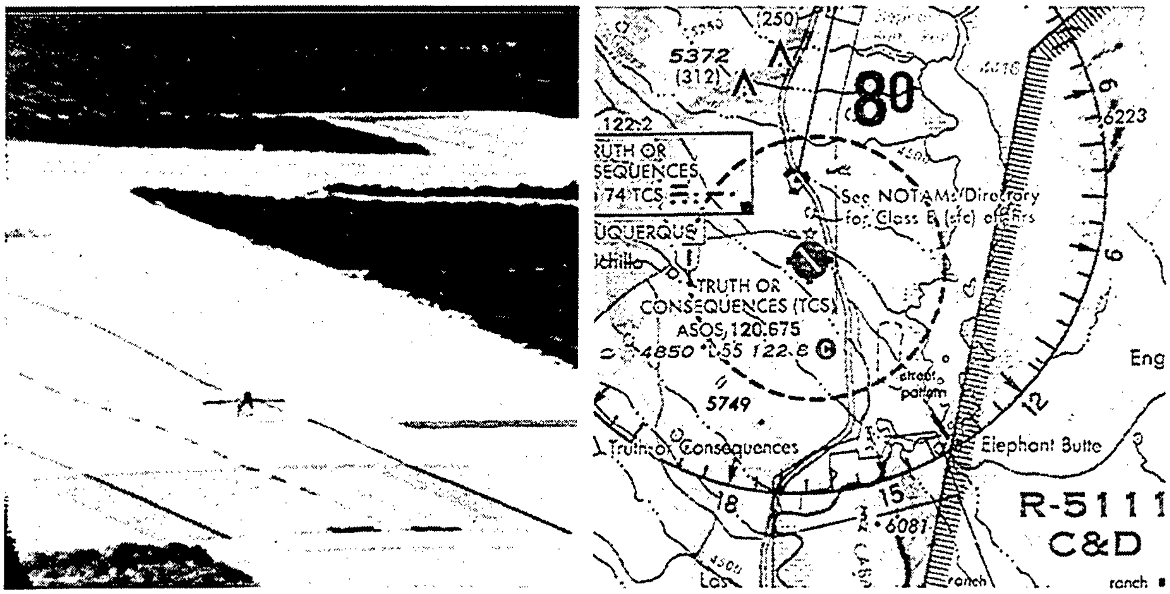

Figure 16. FLIR image (left) and full color map (right). Both images are not indicative of information currently displayed on the F-16 MFD.

Two levels of each factor examined were used in the demonstration. The target luminances presented to the observers were half moon ($1.18X10^{-2}$ fL) and half starlight ($2.94X10^{-4}$ fL) using a blackbody source having approximately a 2850 degree K color temperature. The bright and dim conditions for the CCMFD were established not by the luminance of the individual characters, but by the amount of the display illuminated. For the dim conditions, images having bright characters on a black background, such as the tactical display (Figure 11) and a compass (Figure 15), were displayed. The bright condition employed images where the whole display was illuminated to some degree, such as forward-looking infrared (FLIR) imagery and a full-color moving map (Figure 16). One should note that these images were intended for marketing demonstrations only and do not accurately reflect information normally displayed on the F-16 multi-function display. Two levels of additional extraneous NVIS "compatible" lighting were also examined in the demonstration. The two levels used were 1 fL to represent the luminance level commonly found in bright NVIS compatible cockpits ("on"), and no additional light ("off"). As noted earlier, the two NVGs examined were both AN/AVS-9's. One was a C model with a Class A minus-blue filter, the other a G model with a Class C minus-blue filter. Observers were presented all combinations of these four factors, creating 16 experimental conditions. The output luminances from the two NVGs for the deferent conditions were measured and recorded in Table 10. In addition, Table 10 includes the output luminances measured through the goggles with the displays turned off. These conditions were not presented to the observer, but were measured because they were considered important to the analysis of the displays.

Table 10. Goggle output luminances for the experimental conditions.

			C Mod		G Mod	
Target	**Display**	**Cockpit**	**Left**	**Right**	**Left**	**Right**
Half Moon	Dim		1.812	1.772	4.359	3.946
Half Moon	Dim	+	1.810	1.771	4.354	3.946
Half Star	Dim		0.399	0.312	0.871	1.000
Half Star	Dim	+	0.438	0.372	0.942	1.124
Half Moon	Bright		1.820	1.772	4.452	3.944
Half Moon	Bright	+	1.818	1.773	4.428	3.943
Half Star	Bright		0.429	0.312	0.951	0.980
Half Star	Bright	+	0.465	0.372	1.032	1.063
Half Moon	Off		1.610	1.775	4.408	3.915
Half Moon	Off	+	1.607	1.775	4.393	3.918
Half Star	Off		0.335	0.343	0.885	0.906
Half Star	Off	+	0.390	0.411	0.955	1.006

Before the start of a day of demonstrations, lab personnel focused both goggles and tested the target luminance levels. At the start of a demonstration session, personnel who wished to have their comments recorded provided certain demographic data including, but not limited to, name, age, eyewear, and NVG experience. Other pertinent information, such as the types of aircraft an observer flew, would also be recorded if necessary. Then observers were allowed to dark-adapt for 10 to 15 minutes. During this time, instructions regarding the task were given. Observers were also told that the goggles were pre-focused and that they were not to adjust them. The observer would first look through the C model NVG at the acuity target and call off the number of gratings that they could resolve. Then the observer was asked to continue looking through the goggles at the acuity target for approximately 5 minutes. This 5-minute adaptation was intended to readjust the observer to the bright goggle output and was only performed once at the beginning of the session. The observer was then instructed to look at the display and report what they could or could not see.

The experimenter running the demonstration asked several questions. For the dim CCMFD conditions, observers were asked if they could see all of the colors on the display. They were asked if they could see all of the displayed symbols and the numbers accompanying the symbols. Observers were asked about the appearance of the colors. They were asked if the colors looked like they should, such as, could they readily interpret red as red, blue as blue, white as white, and so forth. Observers were asked if any of the colors washed out when they looked at the display. In addition, observers who were also pilots were asked if they could see the display well enough to accomplish a mission. The observer then looked through the G model NVG at the acuity target and noted the number of gratings they could resolve. They then continued to look through the goggles at the acuity grating for approximately 1 minute and then looked back at the display. The same questions were asked as above. These procedures were repeated for all the conditions alternating between the C and G model NVGs.

Figure 17. Observer ready to assess visual performance.

Discussion

Observers largely felt that the symbols and imagery presented by the displays were visible. The colors displayed with greater luminance, such as white, green and yellow, were considered easily visible. Red and blue were more difficult to see but were still considered visible to a large percentage of the observers. The majority of the observers also considered FLIR imagery displayed on the CCMFD visible. However, pilots felt they needed more detail to accomplish a ground attack mission. One should note that the FLIR imagery used in the demonstration was originally target pod video that was transformed into an MPG file. This conversion degraded the video somewhat. This would have a negative impact on the visibility of details in the image. However, significant additional detail could be obtained from the FLIR video by simply increasing the display luminance, indicating that the visibility of the video was limited by the observer's eye during the demonstration, not the CCMFD. This was demonstrated in the laboratory when one pilot was allowed to adjust the display luminance and contrast to what he considered optimal using the display's daylight mode. Considerable additional detail became visible including ground crew near parked aircraft and aircraft features such as the refueling probe on an A6 Intruder. The display luminance of this "optimal" setting was measured to be approximately 90 fL using a handheld photometer. Unfortunately, using a display capable of that brightness at night is impractical for many reasons, such as increased cockpit reflections and veiling luminance. The probability of any manufacturer building a 90 fL display that is NVS compatible in the near future with existing technology is low.

One observer stated it most clearly by saying, "I didn't see a problem here… …but I would be hesitant to say the plane does not have a problem." The demonstration employed a subjective, simple task that did not duplicate the conditions under which the display is normally employed. To improve the demonstration and better quantify the display would have required more time and resources than were available at the time of the CCMFD evaluation. As noted earlier, observers were not all pilots. Most observers did not have a clear idea about how NVGs and NVIS lighting interact with the human visual system. Observers were also allowed to assess their own visual performance since time did not allow for a more objective assessment. In addition, observers were allowed to look at the display longer than what a pilot would, improving their visual performance since target duration often affects target visibility [Cobb and Moss 1928].

There were a number of concerns raised by the pilots who saw the cockpit simulation. The first issue was with the additional NVIS cockpit lighting. Pilots felt that the lighting present in the simulation was not bright enough and there were too few light sources placed around the cockpit. In addition, it was determined through questioning that pilots fly with their cockpits brighter than simulated in the demonstration. A number of small but critical displays, the Horizontal Situation Indicator and fuel totalizer in particular, must be bright enough for the pilot to read in flight. In order to increase the luminance of those displays, pilots are forced to increase the luminance of all of their cockpit instruments since the luminance of a particular instrument cannot be adjusted independently of the others in the cockpit.

Non-pilot observers tended to have their attention drawn to large, easy to see objects in the FLIR video, such as the airplane on the runway (Figure 16). Targets of interest to a pilot attacking a ground target will be relatively small and probably camouflaged. There was no easy alternative by which more realistic targets could be embedded in the marketing demonstration video, making this aspect of the demonstration more realistic. There were a number of small, low contrast details in the video. But only one observer noticed any of these. Therefore, it is difficult to conclude that the relevant details would always be visible when displayed at the luminance levels examined. Observers could not comment on the visibility of targets they simply could not see if they did not know they were there.

CONCLUSIONS AND COMMENTS

The data gathered in this effort showed that the Honeywell CCMFD passed MIL-L-85762A NVIS B specification, as required. The color balance between red, green, and blue allowed the display to achieve the full color sought for applications like moving maps. Also, the color coordinates selected by Honeywell for red, green, and blue were well chosen, allowing for easy color discrimination and identification. In general the Honeywell CCMFD is not NVIS A compatible as it was capable of emitting a significant amount of red light. However, this was not a program requirement.

The visibility of the display was found to be acceptable but marginal. This could be improved by increasing the luminance in the NVIS mode. However, increasing the luminance could negatively impact NVIS compatibility. Characters on displays like the compass and the tactical display (bright characters on a dark background) could be made larger to improve visibility. Unfortunately, it is unlikely that the display itself could be made larger since the F-16 MFD is currently limited in size due to cockpit constraints.

This effort found no evidence of reduced visual performance due to the observer adapting to a bright NVG at the display and goggle luminances examined. However, this evaluation only examined the display when set to full NVIS brightness. Research suggests that should the display be set to a dimmer luminance, bright adaptation to the NVG might become an issue. Since pilots tend to set the luminance of their NVIS compatible displays to nearly maximum, it is unlikely that the Honeywell CCMFD would be set to anything but full brightness.

In the future, a more controlled experiment should be conducted to accurately quantify visual performance under the luminances produced by the Honeywell CCMFD and study the interaction between the display and NVGs. This research should examine more realistic conditions. Additional and brighter cockpit lighting should be included to more accurately simulate the NVIS cockpit. Observers should be given a primary task that occupies most of their attention and be restricted to quick glances at the display symbology. Finally, a real F-16 canopy should be included in the simulated cockpit to induce the proper reflection intensities and geometries, which may play a larger role than initially suspected.

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APPENDIX A

F-16 Common Color Multi-Function Display (CCMFD) & Night Vision Goggles (NVG) Compatibility and Visual Acuity Test Plan 8 Jan 01

Objective: Determine and compare the F-16's CCMFD performance characteristics with the NVIS Military Standard (MIL-L-85762A) and assess the impact of the F-16 CCMFD operational performance on an observer's visual performance when using NVGs.

1. The compatibility test will be conducted by personnel from the Air Force Research Lab, Wright-Patterson AFB OH with support from Honeywell, Albuquerque NM, LM Aerospace, Fort Worth TX, ASC/ENAS, Wright-Patterson AFB OH, and F-16 System Program Office, Wright-Patterson AFB OH. The tests will, at a minimum:

   a. Measure spectral radiance of the CCMFD in day, night, and NVIS mode.
   b. Measure luminance (Display) and illuminance (Environment)
   c. Measure symbology/character size
   d. Demonstration of visual performance with Class B and Class C NVGs in a simulated cockpit environment

2. Required Assets/Data/Personnel:

   a. Two F-16 CCMD's and associated equipment required for CCMFD operation (Honeywell)
   b. Video Generator or PC with applicable TAD pattern (Honeywell/AFRL)
   c. Class B and Class C Night Vision Goggles and associated spectral curves (AFRL/ANG)
   d. Dark Room (AFRL)
   e. Photometer (AFRL)
   f. Spectroradiometer (AFRL)
   g. Visual acuity chart (AFRL)
   h. Apparatus for generating a veiling luminance visible to an NVG (AFRL)
   i. Barium sulfate target (AFRL)
   j. F-16 pilots from the F-16 SPO (F-16 SPO)
   k. Measured Spectral Radiance data of the MFD, CMFD, and CCMFD, along with the associated LCD curves for the OIS and APC LCD Glass (LMTAS/Honeywell)

3. CCMFD TESTING: The CCMFD's will display a video test pattern and a TAD test pattern. The CCMFD's luminance levels will be set at full brightness, mid-level brightness, and low-level brightness. Display spectral measurements content, NVIS radiance, and luminance will be measured at representative settings and conditions. The illuminance from the display will

be measured from a barium sulfate target placed in a position relative to the display that approximates the location of the pilot's chest and recorded. Symbology/character size for the displayed patterns will also be measured.

4. NVG LIGHTING DEMONSTRATION: A demonstration will be assembled and made available to volunteer observers who would like to experience conditions under which interactions between the CCMFD and an NVG may interfere with visual performance. The two CCMFD's will be positioned as they would be in an F-16 cockpit with respect to a chair for an observer. A target will be placed 20 feet from the observer's position. Observers will be allowed to dark adept for ten minutes. Then, observers will be asked to view the target through NVGs under simulated starlight illumination, once for each NVG of interest. Observers will then be presented with a series of visual conditions, simulating different operational situations, and asked to observe the target through NVGs. Visual conditions will be generated by changing NVG type, target illumination, the image displayed by the CCMFD and its luminance, and by introducing a controlled amount of veiling luminance. Observer comments will be recorded.

5. All data will be recorded and analyzed for NVIS Mil-Std and NVGs compatibility. A report will be written to summarize test data and provide conclusions and recommendations.

APPENDIX B

The spectral sensitivity of the two AN/AVS-9 goggles used in the demonstration was measured to confirm the type of minus-blue filters present in the goggles' objective lenses. The procedure used was designed to measure how sensitive an NVG is to different wavelengths of light. However, this is not a measurement of image intensifier tube photocathode responsivity as required by the image intensifier assembly specification, MIL-I-49428. In the procedure described here, measurements were made on the entire system, including the NVG minus-blue filter, objective and eyepiece lens transmissivity, and phosphor response, yielding a more realistic assessment of NVG performance.

A Tungsten-Halogen bulb, approximately a 3100K black body radiator, broadband, high intensity light source was activated and allowed to stabilize. One should note that any light source capable of emitting a measurable amount of light across the spectral range of NVG sensitivity could also be used. The light from the broadband source was injected into a monochromator. Narrow band, near monochromatic light from the monochromator was then dumped into one port of the integrating sphere to make it more uniform. The NVG under test was then focused to infinity and aligned into the integrating sphere so that the sphere output overfilled the NVG field of view. A photometer was then aligned so that it measured the center of the test NVGs field of view. The photometer field of view must be smaller than the field of view of the NVG under test. The field of view of the Hand-Held Night Vision Photometer normally used in this procedure was 20 degrees. NVG output luminance was then measured over the wavelength region of interest, 400 to 930 nm, in 10 nm increments. Measurements can be made at input wavelength increments finer than 10 nm if available equipment allows.

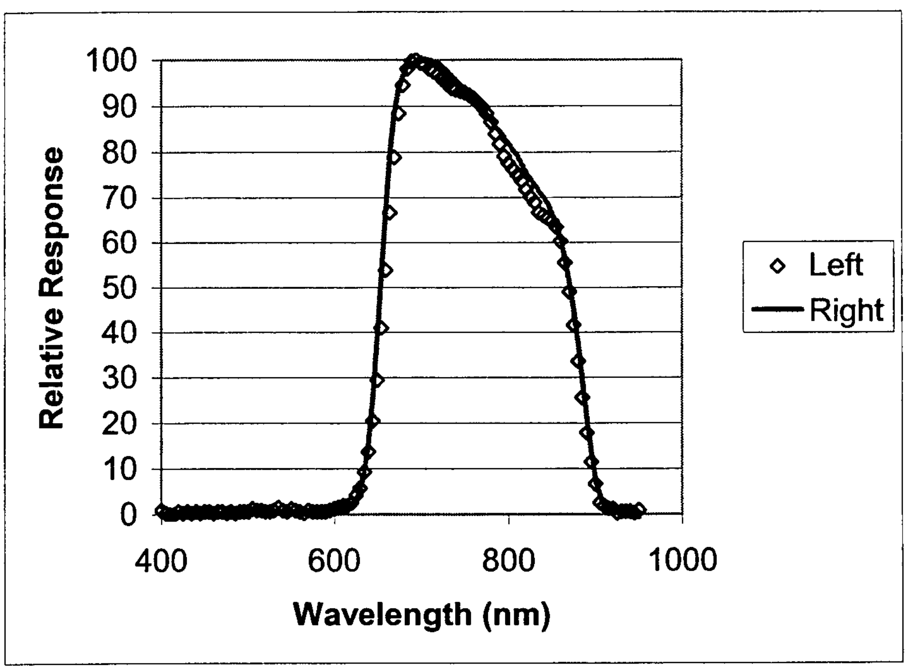

Figure 18. Spectral sensitivity for the left (diamonds) and right (line) oculars of the AN/AVS-9, G model, S/N 5572, used in the visual performance demonstration.

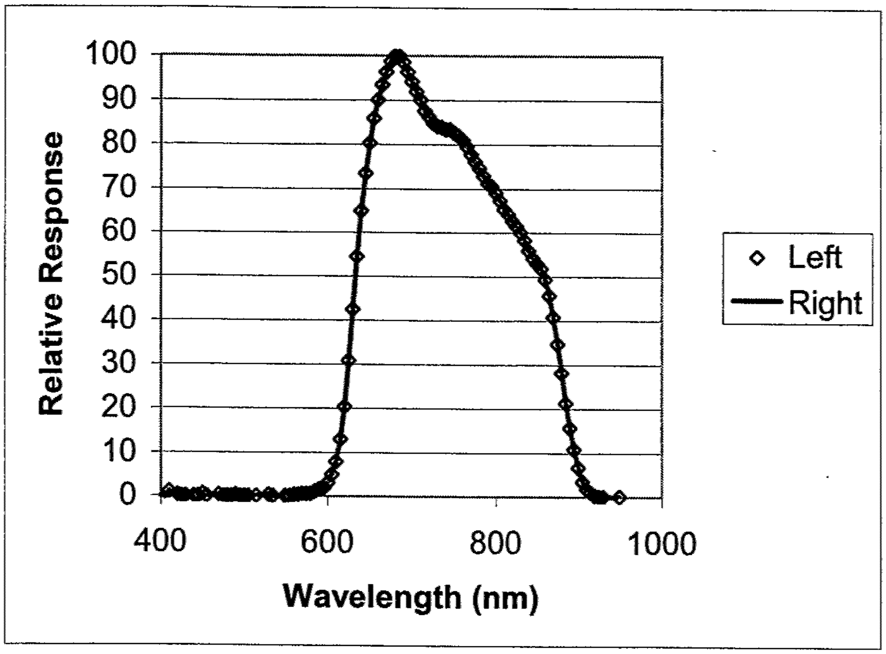

Figure 19. Spectral sensitivity for left (diamonds) and right (line) oculars of the AN/AVS-9, C model, S/N 0358, used in the visual performance demonstration.

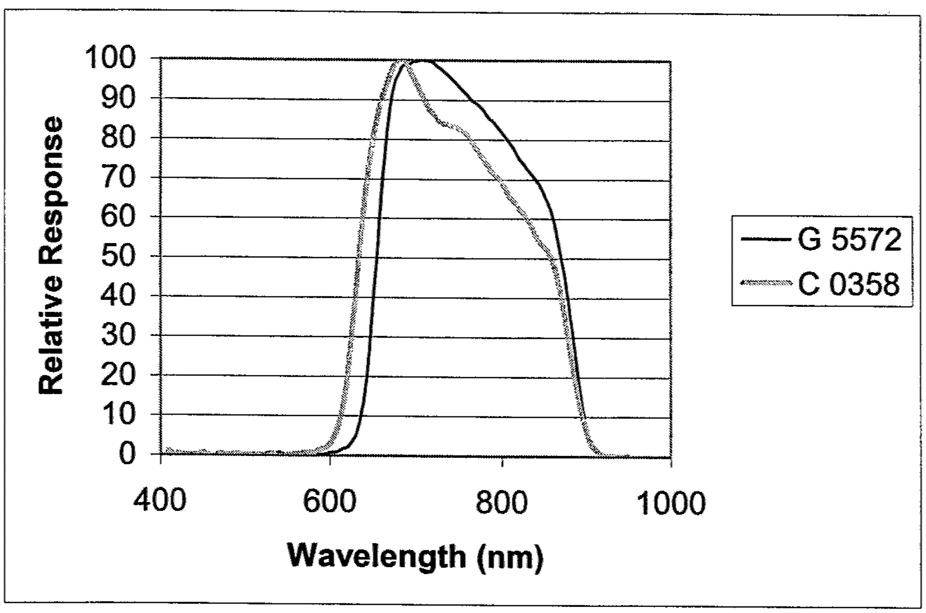

Figure 20. Spectral response, right channels, showing the difference in spectral sensitivity between the two goggles used in the demonstration.

Comparison of the spectral sensitivities of the two goggles yielded an unexpected result. Since the two minus-blue filters were supposed to be similar in nature (Class B and Class C filters), it was expected that the two spectral sensitivity curves should lie nearly on top of each other when plotted together. However, the distinct separation in the curves in the red region indicated that the AN/AVS-9 C model has a Class A minus-blue filter and transmitted more visible light, making it more sensitive to full color cockpit displays.

APPENDIX C

The system gain of the two NVGs used in the demonstration was measured to more thoroughly characterize them. A procedure documented in AL/CF-TR-93-0107 and a Hoffman Engineering ANV-120 gain test set was used to make the measurements that appear in the following plots. The AN/AVS-9, G model goggle was measured to exhibit higher system gain than the C model goggle, as expected.

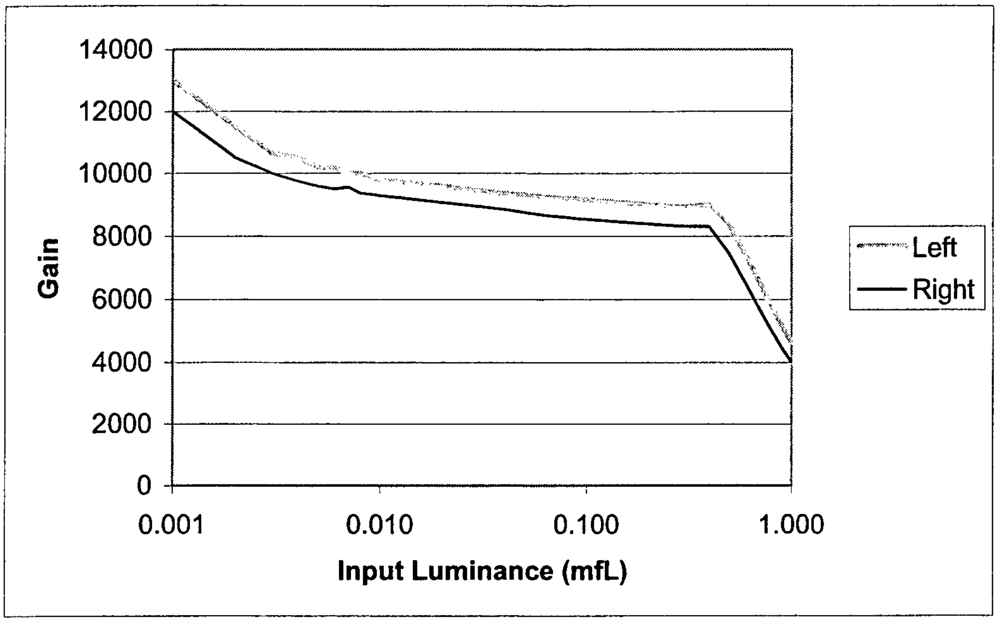

Figure 21. Gain vs. Input luminance for AN/AVS-9, G model, S/N 5572.

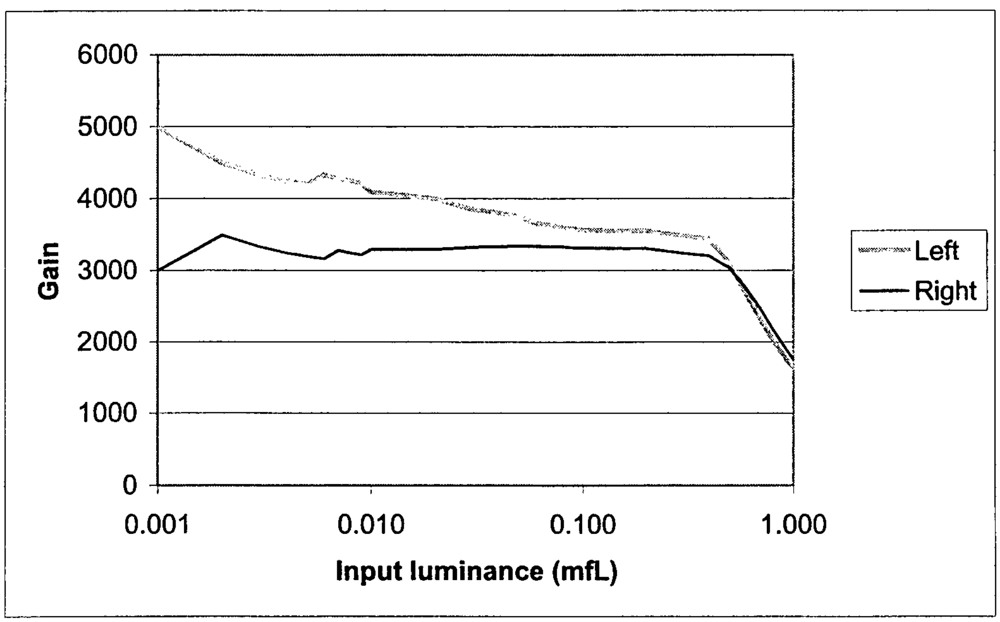

Figure 22. Gain vs. Luminance input for AN/AVS-9, C model, S/N 0358.

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THE VISIBILITY OF NIGHT VISION IMAGING SYSTEM COMPATIBLE DISPLAYS

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ABSTRACT

In an effort to incorporate color displays into night vision imaging system (NVIS) compatible cockpits, the F-16 System Program Office, through Lockheed Martin Tactical Aircraft Systems, requested Honeywell's Aerospace Electronic Systems division to design and construct a prototype color multifunction display. Observers indicated during preliminary operational testing that this display, when configured in NVIS mode, did not present video with the desired level of detail and was too dim to easily read under certain conditions. Testing showed that the Honeywell display met the existing MIL-L-85762A NVIS B radiance compatibility criteria required by contract. However, during a demonstration of the display, F-16 pilots with night vision goggle experience insisted that the display's visibility was marginal, reiterating their concerns on display legibility. This paper discusses the testing of the color multifunction display and potential factors that could be limiting the visibility of the display, in particular, the size of the characters displayed and the luminance levels specified in MIL-L-85762A.

INTRODUCTION

Full color displays are desirable in the cockpit because color-coding adds information in an easily understandable way. However, night vision imaging system (NVIS) compatible cockpits traditionally avoid employing red as the longer red and infrared wavelength light significantly interferes with vision through night vision goggles (NVGs). However, shorter wavelength red light can be employed to add a sufficient amount color to an NVIS compatible cockpit without greatly reducing visual performance through NVGs. Employing this concept, Honeywell's Aerospace Electronic Systems division developed a Color Multifunction Display (CMFD) to replace the existing monochrome cathode ray tube based multifunction display with which the Block 40 and newer F-16's are currently equipped. The CMFD is a 4-inch by 4-inch display that can provide the pilot with both symbology and video in different ambient conditions (e.g., full sunlight to low starlight levels) including an NVIS compatible lighting mode, for use with NVGs.

To determine if the new color multifunction display could be physically integrated into older aircraft flown by the Air National Guard and Air Force Reserves, the Air National Guard and Air Force Reserve Test Center (AATC/DO) in Tucson, AZ, asked for Honeywell to demonstrate their display on an NVIS compatible aircraft at AATC/DO. After preliminary testing in Tucson, some observers felt that the new CCIP CMFD (CCMFD) suffered from a few noteworthy problems. First, the image quality of the display when set in NVIS mode was not as good as pilots would prefer for many of the F-16's missions. In addition, pilots felt that the display was too dim to easily read small symbols and characters on the CCMFD under certain conditions after prolonged exposure to bright NVGs. Initially, this was attributed to possible loss of dark adaptation due to prolonged exposure to NVGs, some of which are capable of presenting a 5 fL image to the observer, under the proper conditions. Experimentation at the Air Force Research Laboratory, Human Effectiveness Directorate, AFRL/HECV, Wright-Patterson AFB showed bright adaptation to not be an influential factor.

As a result of these tests, the F-16 System Program Office (SPO) asked AFRL/HECV, Wright-Patterson AFB to examine the issues noted by AATC/DO and demonstrate the visual phenomena in the laboratory. At the end of January 2001, Honeywell provided two CCMFDs for examination at Wright-Patterson AFB.

MEASUREMENTS AND DATA

Factors influencing the visibility of a target include, but are not limited to: size, contrast, luminance, and duration. To examine the displays, a number of quantitative laboratory tests were used to examine the size and luminance of images displayed on the CCMFD. Target contrast was not explicitly examined since, at the luminance levels involved in this effort, visibility is a function of the image displayed (eye limited) than the display itself. Target duration was not examined either, as it is more closely related to the amount of time an observer has to study the display, or observer workload. In addition, display spectral radiance, NVIS radiance, and luminance uniformity were also measured. A low-fidelity cockpit simulation was also assembled to recreate a number of visual phenomena under controlled conditions that were reported from initial operational testing.

Spectral Measurements

A considerable amount of data could be obtained by measuring the spectral content of the light emitted from the display. Display radiance, NVIS radiance, luminance, and color coordinates can all be calculated once the spectral content of the emitted light is known. Measurements were made using a radiometer capable of measuring NVIS radiance. A four-segmented image made up of quadrants of color: red, green, blue, and white, was placed on the display (Figure 1 left). Measurements were made at three luminance levels: full NVIS bright, half full bright, and one increment above off. To get the fifth color, black, a second quadrant target was displayed and measured. The display NVIS A and B radiance, luminance and chromaticity data are displayed in Table 1.

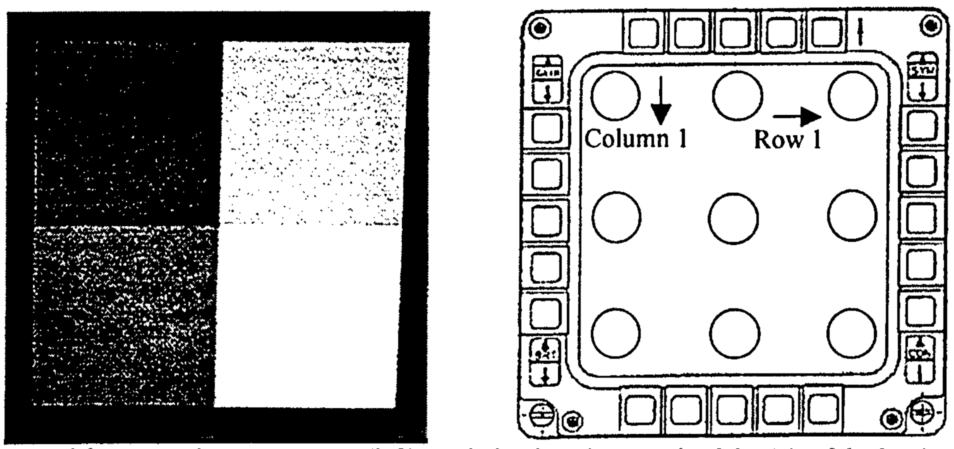

Figure 1. Target used for spectral measurements (left). Relative locations on the CCMFD of the luminance uniformity measurements (right).

Table 1. Display NVIS radiance, luminance, and UCS chromaticity for S/N 902002, display set to full bright.

	NVIS A	NVIS B	Luminance	u'	v'
Red	5.35E-08	3.48E-09	0.226	0.4028	0.5306
Green	4.47E-09	2.70E-10	0.559	0.1547	0.5497
Blue	1.83E-09	2.83E-10	0.118	0.1060	0.4111
White	1.66E-08	1.20E-09	0.878	0.1996	0.5258
Black	2.35E-08	1.33E-08	0.003	0.1846	0.5160

Character Size Measurement

The impact of the physical size of a target on its visibility is easy to understand. Larger targets are simply easier to see.[1] To measure the characters of interest, the individual files were first printed in the proper aspect ratio using a high quality laser printer (600 dpi). Symbols were then measured from the paper using a 20X loupe and reticule. To check these measurements, a number of characters were measured both off the paper printouts and directly from the displays themselves using the same loupe and compared. Comparison of the two sets of measurements showed both approaches to yield the same results to within the accuracy of the measurement loupe.

The smallest, dimmest characters (the characters most difficult to see) were the blue letters and numbers, measuring 2.25 mm high and 1.5 mm wide (Figure 2 left). Observing these symbols at 28 inches, the nominal observation distance for this display in the F-16, the characters would be 10.9 arc minutes tall. This converts to a Snellen acuity of about 20/44. One should note that the displayed characters were not similar to those commonly used in acuity testing, and did not exhibit the defined length to width to stroke aspect ratio. The actual visual acuity of these characters was undoubtedly worse. The symbol sets used were not the symbology commonly used on the F-16 MFD, but rather were the result of the manufacturer's best guess at what the aircraft symbol generator might present on the display.

Luminance Uniformity

In addition to the spectral measurements described in the previous section, the luminance uniformity can also impact the visibility of parts of the display. The test required the display to be illuminated all in one color. The display's luminance was measured for nine locations (Figure 1 right) using a Minolta hand-held photometer. Display uniformity was measured for red, green, blue, and white. The most noticeable trend found in luminance uniformity was a decrease in display luminance as the measurements moved farther from the top edge of the display. The percent uniformity (*Uniformity*) was calculated for each tested color using the following equation:

$$Uniformity = \frac{Max - Min}{Max} \times 100\%$$

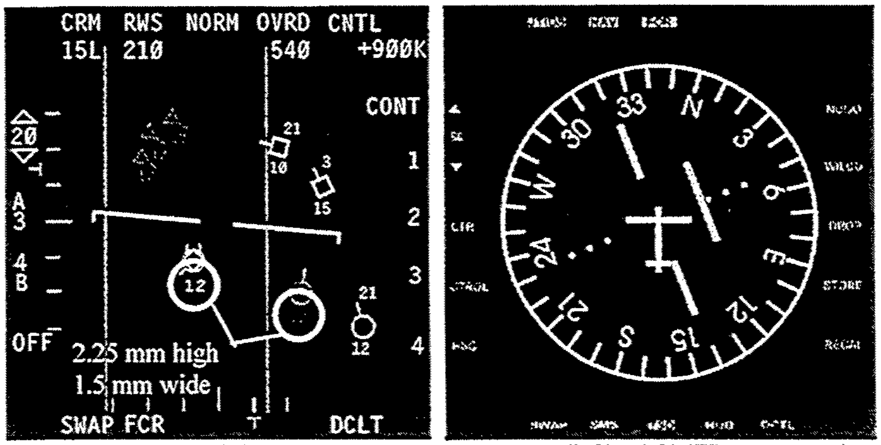

Figure 2. Conceptual image of tactical data displayed on the CCMFD (left). CCMFD compass demonstration (right).

Here, *Max* and *Min* are the maximum and minimum luminance respectively, measured for a particular color from the display. The resulting calculated percentages are listed in Table 2.

Table 2. Luminance uniformity of the CCMFD (S/N 902002) for the four measured colors expressed as a percentage.

Color	% Uniformity
Red	7.7
Green	12.9
Blue	13.3
White	13.3

Vision Demonstration

To better examine the interaction between the display, the cockpit, and the night vision goggle, a demonstration was assembled in a laboratory at AFRL/HECV. This demonstration placed observers in a simulated cockpit with the CCMFDs and required them to assess their own visual performance under a number of conditions. Observer comments were noted and reviewed to determine the combinations of conditions under which visual performance was unacceptably degraded.

Conditions and Procedure

To assemble the cockpit simulation, the displays were placed in the correct geometry with respect to the observer's eye position using information provided by Lockheed-Martin. An electro-luminescent (EL) panel was mounted to a post near the displays to add additional NVIS "compatible" light, simulating the effect of other lights in the cockpit. The light from the EL panel was diffused by reflecting it off a large, flat, white surface. A 3X3 NVG resolution target (Figure 3 left) was placed in space 15 feet from the observer position. The target was provided as a visual performance reference to assist the observers in assessing the impact of the different display and lighting conditions. A sheet of Plexiglas was placed between the observer and the acuity target to reflect EL light back towards the observer. This created a veiling luminance that could interfere with visual performance under the proper conditions (Figure 3 right) as a windscreen would in a real cockpit.

The experimental conditions examined were based on the observations made at AATC/DO. It was expected that exterior target luminance and CCMFD luminance would have the largest impact on visual performance. In addition, the amount of additional cockpit lighting was also expected to affect vision, making it a logical factor to include. Finally, the level of NVG performance was also suspected, not necessarily of being a factor affecting vision by itself, but of being part of an interaction involving the display luminance and cockpit lighting. Goggle performance was therefore included as a factor. One should note that newer NVGs tend to have improvements in a number of parameters, including higher gain, higher spectral sensitivity, and different minus-blue filters, making them perform differently than older goggles. Due to the limited number of NVGs available for this demonstration, it was impossible to differentiate the effects of the different NVG parameters on vision.

Figure 3. 3X3 NVG resolution target (left). View of a resolution target from the simulated cockpit (right).

Two levels of each factor examined were used in the demonstration. The target luminances presented to the observers were half moon ($1.18X10^{-2}$ fL) and half starlight ($2.94X10^{-4}$ fL). The bright and dim conditions for the CCMFD were established by the amount of the display illuminated. For the dim conditions, images having bright characters on a black background (Figure 2), were displayed. The bright condition employed images where the whole display was illuminated to some degree, such as forward-looking infrared (FLIR) imagery and a full-color moving map (Figure 4). One should note that these images were intended for marketing demonstrations only and do not accurately reflect information normally displayed on the F-16 multi-function display. Two levels of additional extraneous NVIS "compatible" lighting were also examined in the demonstration. The two levels used were 1 fL to represent the luminance level commonly found in bright NVIS compatible cockpits ("on"), and no additional light ("off"). As noted earlier, the two NVGs examined were both AN/AVS-9's. Observers were presented all combinations of these four factors, creating 16 experimental conditions.

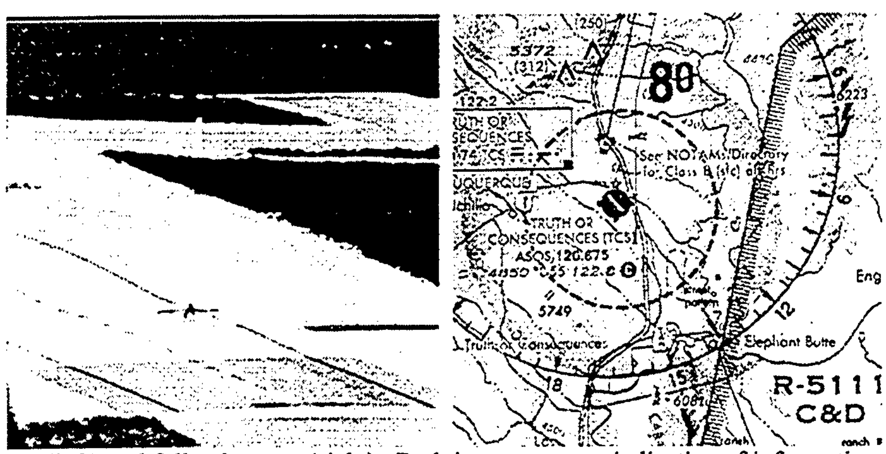

Figure 4. FLIR image (left) and full color map (right). Both images are not indicative of information currently displayed on the F-16 MFD.

At the start of a demonstration session, observers were allowed to dark-adapt for 10 to 15 minutes. During this time, instructions regarding the task were given. Observers were also told that the goggles were pre-focused and that they were not to adjust them. The observer would first look through the C model NVG at the acuity target and call off the number of gratings that they could resolve. Then the observer was asked to continue looking through the goggles at the acuity target for approximately 5 minutes. This 5-minute adaptation was intended to readjust the observer to the bright goggle output and was only performed once at the beginning of the session. The observer was then instructed to look at the display and report what they could or could not see.

The experimenter running the demonstration asked several questions. For the dim CCMFD conditions, observers were asked if they could see all of the colors on the display. They were asked if they could see all of the displayed symbols and the accompanying numbers. Observers were asked about the appearance of the colors. They were asked if the colors looked like they should, such as, could they readily interpret red as red, blue as blue, and so forth. In addition, observers who were also pilots were asked if they could see the display well enough to accomplish a mission. The observer then looked through the G model NVG at the acuity target and noted the number of gratings they could resolve. They then continued to look through the goggles at the acuity grating for approximately 1 minute and then looked back at the display and the questions repeated. These procedures were repeated for all the conditions alternating between the C and G model NVGs.

Discussion

Observers largely felt that the symbols and imagery presented by the displays were visible. The colors displayed with greater luminance, such as white, green and yellow, were considered easily visible. Red and blue were more difficult to see but were still considered visible to a large percentage of the observers. The majority of the observers also considered FLIR imagery displayed on the CCMFD visible. However, pilots felt they needed more detail to accomplish a ground attack mission.

Significant additional detail could be obtained from the FLIR video by simply increasing the display luminance, indicating that the visibility of the video was limited by the observer's eye during the demonstration, not the CCMFD. This was demonstrated in the laboratory when one pilot was allowed to adjust the display luminance and contrast to what he considered optimal using the display's daylight mode. Considerable additional detail became visible including ground crew near parked aircraft and aircraft features such as the refueling probe on an A-6 Intruder. The display luminance of this "optimal" setting was measured to be approximately 90 fL using a handheld photometer. Unfortunately, using a display capable of that brightness at night is impractical for many reasons, such as increased cockpit reflections and veiling luminance. The probability of any manufacturer building a 90 fL display that is NVS compatible in the near future with existing technology is low.

One observer stated it most clearly by saying, "I didn't see a problem here... ...but I would be hesitant to say the plane does not have a problem." The demonstration employed a subjective, simple task that did not duplicate the conditions under which the display is normally employed. To improve the demonstration and better quantify the display would have required more time and resources than were available at the time of the CCMFD evaluation. As noted earlier, observers were not all pilots. Most observers did not have a clear idea about how NVGs and NVIS lighting interact with the human visual system. Observers were also allowed to assess their own visual performance since time did not allow for a more objective assessment. In addition, observers were allowed to look at the display longer than what a pilot would, improving their visual performance since target duration often affects target visibility.[2]

There were a number of concerns raised by the pilots who saw the cockpit simulation. The first issue was with the additional NVIS cockpit lighting. Pilots felt that the lighting present in the simulation was not bright enough and there were too few light sources placed around the cockpit. In addition, it was determined through questioning that pilots fly with their cockpits brighter than simulated in the demonstration. A number of small but critical displays, the Horizontal Situation Indicator and fuel totalizer in particular, must be bright enough for the pilot to read in flight. In order to increase the luminance of those displays, pilots are forced to increase the luminance of all of their cockpit instruments since the luminance of a particular instrument cannot be adjusted independently of the others in the cockpit.

Non-pilot observers tended to have their attention drawn to large, easy to see objects in the FLIR video, such as the airplane on the runway (Figure 4). Targets of interest to a pilot attacking a ground target will be relatively small and probably camouflaged. There were a number of small, low contrast details in the video. But only one observer noticed any of these. Therefore, it is difficult to conclude that the relevant details would always be visible when displayed at the luminance levels examined. Observers could not comment on the visibility of targets they simply could not see if they did not know they were there. There was no easy alternative by which more realistic targets could be embedded in the marketing demonstration video, making this aspect of the demonstration more realistic.

Visibility Requirements

In order to meet the radiance limits set in the military NVIS lighting specifications, MIL-L-85762A and its current revision MIL-STD-3009, display luminance can become somewhat limited. The added complexity of balancing the three primary colors to create an acceptable white forces extra restrictions on the display manufacturer. These two factors combine to limit the output luminance of color NVIS displays. Historically, NVIS display maximum luminance was limited to about one or two footLamberts to avoid the potential for the NVG wearer to encounter bright adaptation to their 1.6 fL goggle output, which was thought to make reading and interpreting cockpit instruments difficult. Current research shows that NVG bright adaptation does not interfere with the legibility of cockpit instruments until goggle-to-cockpit luminance ratios of 100 to 1 or more are reached. In addition, pilots tend to fly with their instruments set to maximum luminance output in order to make certain all of their displays are visible, minimizing the luminance ratio. The information displayed should be tailored for good visibility under low luminance conditions.

Table 3. Minimum requirements for target visibility at the 50% probability of seeing. These results are an extrapolation of Cob and Moss's data. N/V – target not visible

	Acuity (MOA)			% Contrast		
Target Luminance	At 50% Contrast	At 10% Contrast	At 5% Contrast	For a 4 MOA Target	For a 2.4 MOA Target	For a 1.35 MOA Target
1.0 fL	1.5	3.3	5.8	7	16	59
0.1 fL	2.1	4.9	8.9	13	27	N/V
0.01 fL	3.0	7.4	13.6	22	47	N/V

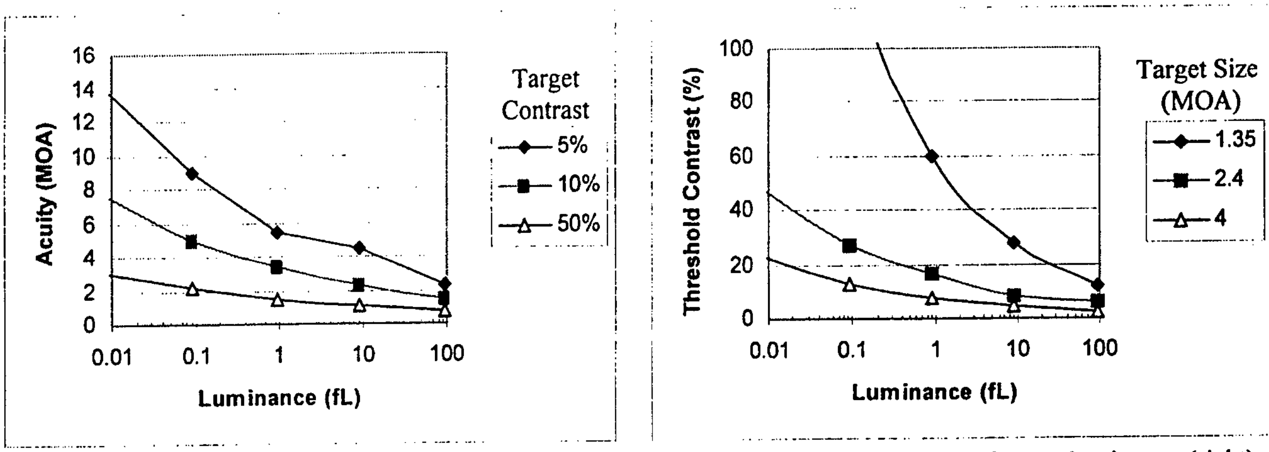

Figure 5. Acuity as a function of target luminance (left). Threshold contrast as a function of target luminance (right).

Cob and Moss did much work examining the effect of target luminance on visual performance.[1] An extrapolation of their results to target luminances lower than they examined appears in Figure 5 and Table 3. This extrapolation was made possible because of work done by Connor and Ganoung. Their work indicated that the trends in visual performance documented by Cob and Moss were still valid at luminance levels up to two orders of magnitude lower than those studied by Cob and Moss.[3] Figure 5 and Table 3 show that large objects of relatively high contrast should be visible in the FLIR imagery. However, they also show that the contrast needed to see smaller, dimmer tactically interesting (and probably camouflaged) targets is considerable. These targets would simply not be visible to an observer, not because the display cannot portray them with the appropriate fidelity, but because the targets themselves do not have the necessary contrast with their background to be seen when displayed at low luminance. Under these conditions, the human eye limits visual performance.

The extrapolation of Cob and Moss's data also shows that the characters used in the CCMFD tactical display should be visible (2.4 MOA on the display > 2.1 MOA required at 0.1 fL). However, two factors must be addressed before drawing a conclusion: Cob and Moss's threshold criteria and target duration. Cob and Moss's data and, thus, their visual models are based on the 50% probability of seeing. However, for relaying information to a busy pilot, a 50% probability of receiving the information they need is probably insufficient. Pilots would probably prefer a 100% probably of seeing. In addition, pilots do not have much time to dwell on their displays. Cob and Moss's research indicated that the length of time the target is visible impacts its visibility. This would further complicate extraction of information from a display for a pilot that would not manifest itself in a static assessment of visual performance.

CONCLUSIONS AND COMMENTS

The data gathered in this effort showed that the Honeywell CCMFD passed MIL-L-85762A NVIS B specification, as required. The color balance between red, green, and blue allowed the display to achieve the full color sought for applications like moving maps. Also, the color coordinates selected by Honeywell for red, green, and blue were well chosen, allowing for easy color discrimination and identification. In general the Honeywell CCMFD is not NVIS A compatible as it was capable of emitting a significant amount of red light. However, this was not a program requirement.

The visibility of the display was found to be acceptable but marginal. An examination of the acuity and contrast requirements for low luminance targets yielded some evidence as to why. Character sizes exceeded threshold requirements as defined by the 50% probability of seeing. However, a 50% probability of seeing may be insufficient for the acknowledgement of information from an aircraft cockpit display. The amount of time a pilot has to read their displays influences the display visibility, further compounding the problem. Display visibility could be improved by increasing the luminance in the NVIS mode. However, increasing the luminance could negatively impact NVIS compatibility. Characters on displays like the compass and the tactical display (bright characters on a dark background) could be made larger to improve visibility. Unfortunately, it is unlikely that the display itself could be made larger since the F-16 MFD is currently limited in size due to cockpit constraints.

In the future, a more controlled experiment should be conducted to accurately quantify visual performance under the luminances produced by the Honeywell CCMFD and study the interaction between the display and NVGs. This research should examine more realistic conditions. Additional and brighter cockpit lighting should be included to more accurately simulate the NVIS cockpit. Observers should be given a primary task that occupies most of their attention and be restricted to quick glances at the display symbology. Finally, a real F-16 canopy should be included in the simulated cockpit to induce the proper reflection intensities and geometries, which may play a larger role than initially suspected.

ACKNOWLEDGEMENTS

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BIOGRAPHY

Peter L. Marasco joined the U.S. Air Force community in 1991 as a civilian research physicist. His work as an optical engineer has concentrated primarily in the areas of Aerospace Transparency Technology and Night Vision, conducting basic research, guiding and executing optical and opto-mechanical design efforts, evaluating concepts and prototypes, and developing and improving optical test methods. Dr. Marasco received a BS degree from the University of Rochester in 1991 and an MS degree from the University of Arizona in 1993, both in Optical Engineering. In 2000, he received his Ph.D. from the University of Dayton in Electro-Optical Engineering. Dr. Marasco is currently examining and modeling visual interference mechanisms common in modern aircraft cockpits.

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Task, H. L. (1998). Chemical lightsticks as a night vision goggle compatible lighting technique for aircraft cockpits: characteristics, pros and cons. *Proceedings of the 36th Annual Symposium, SAFE Association* (pp. 34-38).

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Chemical Lightsticks as a Night Vision Goggle Compatible Lighting Technique for Aircraft Cockpits: Characteristics, Pros and Cons

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ABSTRACT

Night vision goggles (NVGs) are used for night flying in many military aircraft in the US Army, Navy, and Air Force. NVGs are seen as a means of improving flying safety by providing aircrew with a direct view of the outside world scene thereby improving situation awareness. However, NVGs cannot operate effectively in a cockpit environment unless the interior lighting is NVG compatible. NVG compatible means the lighting is sufficient for the aircrew to view their instruments with their unaided vision but the lighting does not interfere with the NVG's view of the outside world. There are several ways to achieve NVG compatibility by using plastic and glass filters, and by changing light sources to eliminate near infra-red light from the cockpit. One less desirable technique for achieving NVG compatible lighting is to use chemical lightsticks to flood-light the cockpit instrumentation. This paper presents a number of issues associated with using "chemsticks" as a means of achieving NVG compatibility including spectral effects, temporal effects, and temperature effects. It is concluded that chemsticks are marginal as a means of achieving NVG compatibility. Also, if they are used, then pilots and associated support personnel need to be informed of the chemstick's limitations and characteristics to assure safe NVG flight operations.

INTRODUCTION AND BACKGROUND

During the past decade, night vision goggles (NVGs) have found their way into most USAF aircraft cockpits as a means of enhancing both safety and capability during night operations. However, before NVGs can reach their full potential in an aircraft cockpit, the cockpit instruments, displays, and lighting must be made NVG compatible. Standard cockpit lighting typically involves incandescent lamps with filters to provide red, white, or blue-white illumination for night flight [5]. Unfortunately, incandescent lighting produces far more near infra-red energy than it does visible and the NVGs are highly sensitive to this near infra-red light. The effect of this is that the internal cockpit lights overpower the NVGs and the pilot cannot see the outside world through the aircraft windscreen and canopy. The primary technique for making an aircraft cockpit "NVG compatible" is to greatly reduce or eliminate light within the cockpit in the red and near infra-red spectral regions where the NVGs are highly sensitive. In addition, there must be sufficient visible light in the green or blue-green spectral regions for direct viewing of the aircraft instruments and displays [4]. Figure 1 shows the human visual system photopic sensitivity curve in comparison to the spectral sensitivity of the third generation ANVIS (aviator's night vision imaging system) night vision goggles with Type A and Type B coatings on the objective lenses [2]. It is clear from Figure 1 that there is a relatively small (but highly significant) overlap between the visual sensitivity curve and the NVG sensitivity curves. Although this overlap looks to be somewhat small, one must remember that the NVGs amplify light on the order of 5000 to 6000 times. Therefore, even a small overlap can cause lighting incompatibility problems. This is especially true for light which is perceived by the human visual system as being red (wavelengths between about 620 and 700 nanometers) since the eye is not very sensitive here but the NVGs are. The NVIS (night vision imaging system) B coating was devised to shift the NVG spectral sensitivity away from some of the lower red wavelengths so that red could be used in the cockpit without significantly interfering with the NVGs.

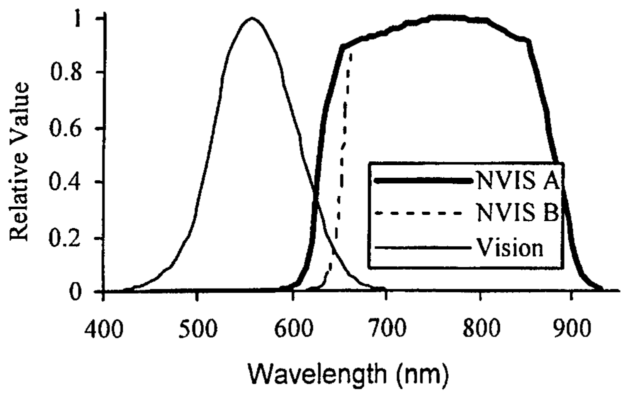

Figure 1. Relative spectral sensitivity of night vision goggles (with NVIS A and B coatings) compared to human vision.

Techniques have existed for some time to make the aircraft cockpit NVG compatible [4] and these techniques have continued to be improved. However, modifying an aircraft cockpit to make it properly NVG compatible according to the NVG compatible lighting Mil Spec [2] can be expensive. For this reason, operational squadrons have looked for cheaper and hopefully, temporary means of making the cockpit NVG compatible. One of these approaches is to use inexpensive green chemical light sticks [3], commonly referred to as "chemsticks", to provide flood-lighting of aircraft instruments. Not surprisingly, the list of military uses on the packaging of these lightsticks does not include use as a means of obtaining aircraft cockpit NVG compatibility [3]. The chemsticks emit no infra-red radiation (unlike incandescent lights) but they do have a relatively long emission tail in the red part of the spectrum. Figure 2 is a composite graph showing the typical chemstick emission spectrum (for green chemsticks [3]; they do come in other colors including near-infra-red), the human visual sensitivity curve, and the NVIS A and B curves. From this graph it is apparent that the chemsticks have a good spectral distribution in terms of providing light that the human visual system can easily see, but they do have a somewhat long tail that overlaps the low end of the NVG sensitivity curves.

The chemsticks that have been used for NVG compatible cockpit lighting come in 3 sizes of cylindrical shapes as shown in Table 1. Chemical light sticks have been produced in other shapes but they contain the same chemicals as the ones measured for this study.

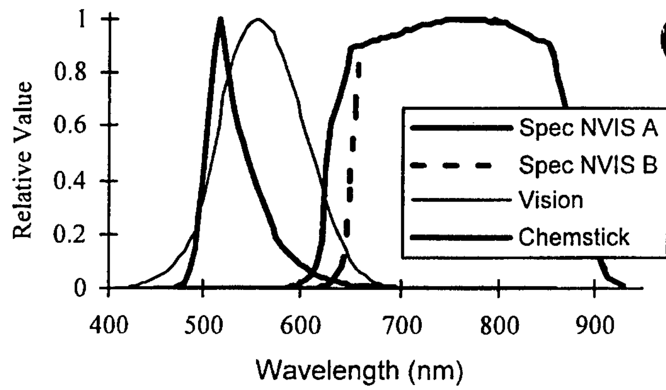

Figure 2. A typical chemstick emission spectrum compared to human vision spectral sensitivity and NVG spectral sensitivity

Table 1. Chemstick sizes typically used in aviation

Size	Length (in)	Diameter (in)
Small	1.5	3/16
Medium	4	1/2
Large	6	5/8

The chemsticks are activated by physically breaking the glass ampule that is contained within the plastic outer casing. This releases the chemical inside the glass ampule which mixes with the chemical in the outer case. The light stick is usually vigorously shaken to mix the two chemicals together thoroughly. The light stick begins to emit light immediately after activation.

CHEMSTICK CHARACTERISTICS

Spectral shift with time

Prior to this investigation, it was thought that the chemsticks had fairly stable spectral distributions. However, spectral distribution measurements of fourteen lightsticks showed that there was a greater than expected variance. In an effort to track down the source of this variance, several lightsticks were measured at different times after activation. Figure 3 shows the results of these measurements. The spectral distribution of the lightstick output shifts toward the red as a function of time after activation. It is possible to calculate the NVG compatibility of these spectral distributions using the methods called out in military specification (Mil Spec) MIL-L-85762A [2]. Table 2 is a summary of these calculations that show that the chemstick spectral distribution is not in compliance with this NVG light specification and that it becomes somewhat worse with time after activation. According to Table 2, after 92 minutes the chemstick spectral emission produces radiation in the NVIS A spectral region that is 10.82 times higher than the Mil Spec allows. This means that chemsticks are not in compliance with the Mil Spec, although, from a practical standpoint, they are considerably better than incandescent lighting by many orders of magnitude.

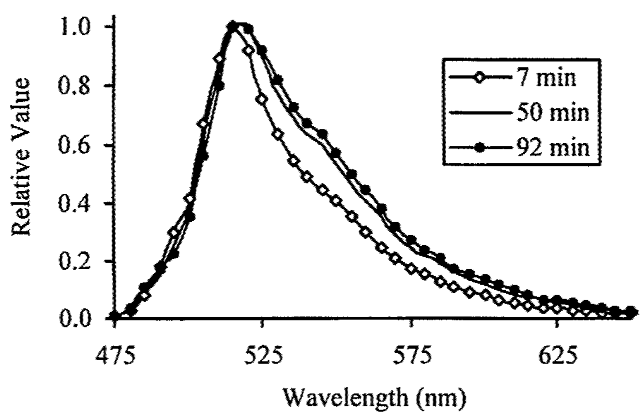

Figure 3. Chemstick spectral emission shift as a function of time after activation.

Table 2. Effects of time after activation on NVG compatibility. Each value is the average of measurements made on 3 chemsticks.

Time after Activation	X spec value NVIS A	X spec value NVIS B
7 min	7.69x	3.34x
50	10.12	4.46
92	10.82	4.75

Luminous output versus time

One of the worst characteristics of chemsticks is that they slowly decay with time. That is to say, their light output decreases slowly with time, which makes it difficult for a crewmember to notice when the light level is getting too low until it is too late. Figure 4 is a graph showing the luminous decay characteristics of 14 chemsticks. These were all designated as "12 hour" chemsticks [3] and correspond to the "large" size chemstick described in Table 1. There are three main points to notice regarding this figure. First, there is a fairly significant variation in the luminance level as a function of time from lightstick to lightstick (the upper and lower dashed lines are +/- 2 standard deviations). Second, the light level drops off rapidly in the first few minutes and then drops off somewhat more slowly after that. Third, even though these are designated as "12 hour" light sticks, it is apparent from the graphs that after only 3 1/2 hours the light level is down quite substantially from starting light levels. It is the variability from stick to stick and the insidiously slow light fall off with time that make chemsticks a potentially dangerous method of making an aircraft cockpit NVG compatible. The variability makes it difficult to establish specific guidelines on how to set up a cockpit for NVG compatibility using chemsticks and the slow light loss with time makes it hard for the pilot to determine when the sticks have gotten too dim to be able to see critical instrument readings.

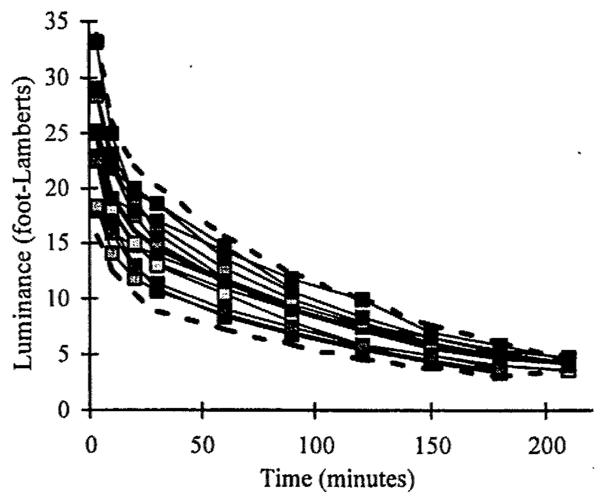

Figure 4. Variation in chemstick luminance decay with time for 14 chemsticks. The dotted lines are +/- 2 standard deviations.

Temperature effects on luminous output

In order to determine if temperature affects the luminous decay rate of the chemsticks, a special apparatus was designed and fabricated. The chemsticks, after activation, were placed in a transparent cylindrical cell that contained a holding mount to clamp onto the chemstick and a circulating, cooling/heating liquid. The liquid was set to the desired temperature and maintained physical contact during the time the chemstick was being measured. Both 4 inch and 6 inch chemsticks were tested at 3 different temperatures: 50, 70, and 80 degrees F. Figure 5 shows a summary of the results for the 4 inch chemsticks (the results for the 6 inch sticks were similar). Each curve is the average of 5 chemsticks. The decay effects of the 70F and 80F temperatures are similar although it appears the 70F starts off higher, decays more rapidly at first, and then decays more slowly after about 30 minutes. The 50F luminous decay is dramatically different. When first activated it is considerably lower in luminous output than either of the other two temperatures and it stays substantially lower throughout the two hour time period that it was measured for this graph. However, it should be noted that after about 20 minutes the 50F light output is relatively constant for this two hour measurement period unlike the higher temperatures.

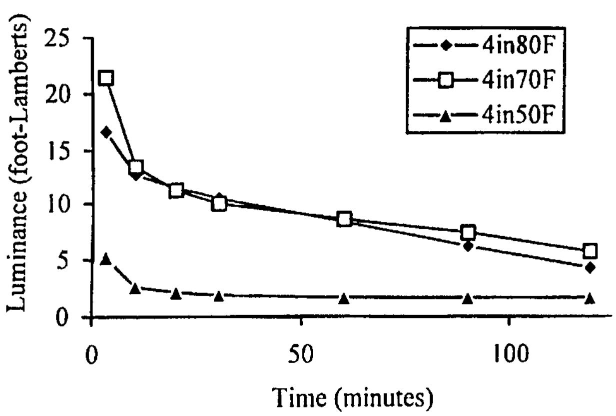

Figure 5. Effect of temperature on chemstick luminance decay.

During the time these chemsticks were being measured under various conditions a useful trick was discovered [1]. If the chemsticks were refrigerated (about 35F - NOT frozen) and then immediately activated in a room temperature (about 70F) air environment, then the luminous decay characteristics were significantly modified. Figure 6 shows the average of 2 chemsticks that were refrigerated (about 35F) before activation in a 70F air environment (dashed line) compared to the average of 2 chemsticks that were kept at room temperature and then activated (solid line). The refrigerated chemsticks started with a lower luminous output and dropped rapidly similar to the liquid cooled 50F sticks of Figure 5. However, as the chemsticks gradually warmed up in the 70F room temperature environment the luminous output actually increased until about the 1 hour point. After the 1 hour point these sticks slowly decayed. The significance of this effect is that it is possible to obtain a more uniform luminous output for a relatively long time (about 3 hours) if the chemsticks are thoroughly cooled prior to being activated in a room temperature cockpit environment. The chemsticks in this experiment remained overnight in the refrigerator to make sure they were completely cooled throughout. They were also taken directly from the refrigerator to the measurement room so only about 5 to 10 minutes elapsed between the time they were taken from the refrigerator and the time they were activated as shown on the graph. If a longer time elapses between removal from refrigeration and activation then one would expect somewhat different results.

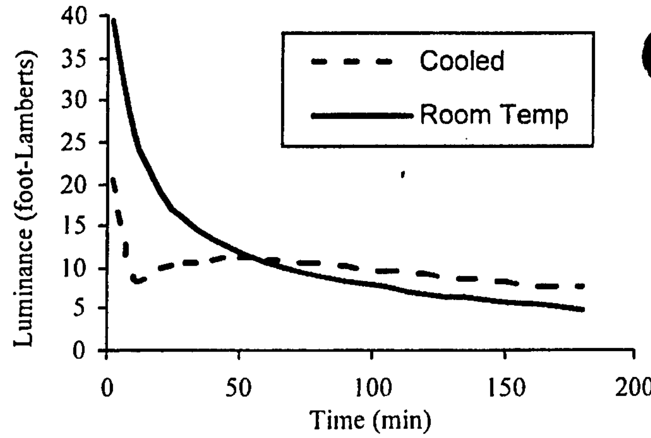

Figure 6. Demonstration of technique to reduce the rate of chemstick luminance decay by refrigerating the chemstick prior to use. The solid line is a chemstick at room temperature activated in room temperature; the dashed line is a chemstick refrigerated to about 35 degrees F then activated in room temperature (70 deg F).

DISCUSSION AND CONCLUSIONS

Although these chemsticks do not meet the MIL-L-85762A requirements for NVIS radiance by several times as noted in Table 2, their spectral distribution is such that they are reasonably compatible with the NVG spectral sensitivity. This assumes the chemsticks are positioned in the cockpit such that the NVGs cannot directly view them and such that they do not cause a direct reflection in the windscreen or canopy. The rationale for the Mil Spec on NVIS radiance was that no light source in the cockpit would have an apparent luminance, when viewing through the NVGs, any greater than tree bark (about 10% reflective) in starlight. This is a very stringent specification level.

All measurements of light output in this effort were actually a measure of the surface luminance of the chemstick itself. This provided a convenient and repeatable means of investigating the effects of time and temperature on the output of the chemsticks. The light levels measured (typically several foot-Lamberts to tens of foot-Lamberts) are far brighter than what the instrument panel indicia should be in order to provide sufficient, but low level, lighting for NVG operation (or ordinary night flying, for that matter). Instrument panel lighting would normally be set to less than a tenth of a foot-Lambert by the pilot in order to achieve comfortable lighting levels for night flying. However, if one is flying with NVGs, which have a light output of a few hundredths of a foot-Lambert (for very low outside illumination nights) to a couple of foot-Lamberts (for high moon illumination nights), it might be necessary for the pilot to adjust his/her instrument lighting somewhat higher to be compatible with the light output level of the NVGs. The problem with chemsticks is that adjusting the lighting level is very difficult, especially during flight. Since the chemsticks are used as an illumination source, the apparent luminance of the instruments they illuminate becomes lower the further the chemstick is positioned from the instrument and the more off-axis it is positioned. Typically, multiple chemsticks are used to illuminate the instrument panel; which means the resultant apparent luminance of any particular instrument indicia depends on the summation of light from all the chemsticks within a direct line of sight of the indicia. This is a very complex and interdependent situation. It is impossible to obtain a uniform instrument panel luminance distribution using the chemsticks; which is what, for normal lighting, cockpit lighting engineers strive for in order to meet pilot demands.

Other characteristics of chemsticks that have not been a part of the study reported here are the effects of humidity, age, and light exposure on the light output and spectral distribution of the chemsticks. These are subjects for future study.

Based on the data collected to date, it is concluded that chemsticks are marginally suitable for use as NVG compatible cockpit lighting. BUT, pilots need to LEARN and MAINTAIN awareness of the potential dangers of chemsticks. It is recommend that chemsticks be kept refrigerated and sealed in their packaging prior to transport and activation for use in the cockpit. The bottom line is that everyone involved should EXERCISE EXTREME CAUTION WHEN USING OR ADVOCATING CHEMSTICKS FOR NVG COMPATIBLE COCKPIT LIGHTING!

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BIOGRAPHY

H. Lee Task has been employed as a research scientist for the US Air Force since 1971. He has served as chief scientist for the Armstrong Aerospace Medical Research Laboratory (prior to its reorganization and disestablishment in 1991) and in March of 1997 was selected as the Senior Scientist for Human-Systems Interface of the new Air Force Research Laboratory at Wright-Patterson AFB, Ohio. He is currently involved in research and development in the areas of helmet-mounted displays, vision through night vision goggles, optical characteristics of aircraft windscreens, vision, and display systems. He has a BS Degree in Physics (Ohio University), MS degrees in Solid State Physics (Purdue, 1971), Optical Sciences (University of Arizona, 1978), and Management of Technology (MIT, 1985) and a PhD in Optical Sciences from the University of Arizona Optical Sciences Center (1978). During his career he has earned 39 patents and has published more than 80 journal articles, proceedings papers, technical reports, and other technical publications. He is a member of the Human Factors and Ergonomics Society (HFES), the American Society for Testing and Materials (where he is chairman of Subcommittee F7.08 on Aerospace Transparencies and is a Fellow of the Society), the Association of Aviation Psychologists, SAFE association where he is the editor of the SAFE Journal, the Society for Information Display (SID), and SPIE (the optical engineering society).

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3. PANORAMIC NIGHT VISION GOGGLES

In the mid 1990s, a new and unique NVG design was conceived at AFRL/HEC, Wright-Patterson AFB, Ohio. A small business innovative research (SBIR) program developed wide field-of-view panoramic night vision goggles (PNVGs) using four image intensifier tubes instead of two. Results of previous surveys of aircrew members showed that the top two requested improvements were (1) increased field of view (FOV), closely followed by (2) improved resolution. However, these two parameters are closely and inversely related (see Section 1, Donohue-Perry, et al., 1994). Prior to this innovation, if one wanted a wider field of view, one had to settle for lower resolution. All of the articles in the present section describe various aspects of the development of these PNVGs and some unique issues that arise because of the optical design requirements

These articles are reprinted to provide the reader with a reference and background to better understand PNVGs.

Craig, J. L., Task, H. L., & Filipovich, D. (1997). **Development and evaluation of the panoramic night vision goggle.** *Proceedings of Shephard's Sixth International Night Vision Conference & Exhibition.* Arlington, VA, http://www.shephard.co.uk

Craig, J. L., & Geiselman, E. E. (1998). **Further development of the panoramic night vision goggle.** *Proceedings of the 36th Annual Symposium SAFE Association* (pp. 26-30).

Craig, J. L. (2000). **Integrated panoramic night vision goggle.** *Proceedings of the 38th Annual Symposium SAFE Association,* http://www.safeassociation.com

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Jackson, T. W., & Craig, J. L. (1999). **Design, development, fabrication, and safety-of-flight testing of a panoramic night vision goggle.** *Proceedings of SPIE – The International Society for Optical Engineering Helmet- and Head-Mounted Displays IV, USA, 3689,* 98-109.

Marasco, P. L., & Task, H. L. (2000). **Panoramic night vision goggle testing for diagnosis and repair.** *Proceedings of the 38th Annual Symposium SAFE Association,* http://www.safeassociation.com

Sedillo, M. R. (1999). **Panoramic night vision goggle-maintainer's perspective.** *Proceedings of the 37th Annual Symposium SAFE Association,* http://www.safeassociation.com

Task, H. L. (2000). **Integrated panoramic night vision goggles fixed-focus eyepieces: selecting a diopter setting.** *Proceedings of the 38th SAFE Association,* http://www.safeassociation.com

Angel, S. P. (2001). **NVG eyepiece focus (diopter) study.** *Proceedings of SPIE - The International Society for Optical Engineering, Helmet- and Head-Mounted Displays VI, USA, 4361,* 138-147.

Craig, J. L., Task, H. L., & Filipovich, D. (1997). Development and evaluation of the panoramic night vision goggle. *Proceedings of Shephard's Sixth International Night Vision Conference & Exhibition.* Arlington, VA, http://www.shephard.co.uk

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Development and Evaluation of the Panoramic Night Vision Goggle

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D. Filipovich
Night Vision Corporation, Lincolnwood IL

Abstract

A novel approach to significantly increasing the field of view (FOV) of night vision goggles (NVGs) has been developed and demonstrated. This approach uses four image intensifier tubes instead of the usual two to produce a very wide 100 degree horizontal by about 40 degree vertical FOV. A conceptual working model, designated the Panoramic NVG, has been fabricated and evaluated.

Introduction

The Panoramic NVG (PNVG) [1], [2] is a revolutionary change to traditional image intensifier-based night vision devices. The initial focus of the PNVG project centered around developing an "enhanced capability" NVG. A primary candidate parameter for enhancement was the NVG FOV with other parameters such as resolution, weight, center of gravity, and integrated display symbology overlay as secondary objective enhancements.

A conceptual working model was developed and fabricated (Figure 1) that displays a 100 degree horizontal by 40 degree vertical intensified FOV (Figure 2). This increased the intensified image seen by the wearer by 160 percent compared to the currently fielded 40 degree circular field of view systems. The larger FOV was achieved by using four off-the-shelf image intensifier tubes to produce four ocular channels. Two channels were used to produce a full 30 degree by 40 degree binocular FOV, and the other two were used to produce monocular left and right eye channels of about 35 degrees by 40 degrees. The PNVG's folded optical system resulted in a much better center of gravity compared to the currently fielded AN/AVS-6 and AN/AVS-9 type NVG configuration. Even with the added image intensifier tubes and associated optics, the overall weight of the device was comparable to currently fielded NVGs. The larger FOV and better center of gravity should reduce fatigue effects during long missions and potentially permit the PNVG to be retained upon ejection for use in evasion, escape, and rescue.

Fig. 1 PNVG Conceptual Working Model

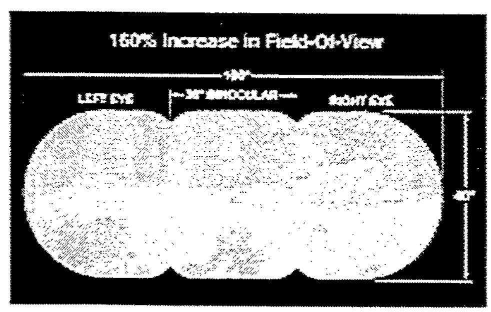

Fig. 2 PNVG simulated FOV

This paper was cleared by ASC97-0507 on 10 Mar 1997

Background

NVGs have been used in military aviation for more than 20 years with FOVs ranging from 30 degrees (early Cat's Eyes NVGs from GEC-Marconi Avionics) to 45 degrees (NITE-OP and NITE-Bird NVGs, also GEC-Marconi Avionics). The vast majority of NVGs used in military aviation have a 40 degree field of view (Figure 3) (AN/AVS-6 and AN/AVS-9). One major design characteristic of these NVGs is that increased FOV could only be obtained at the expense of resolution [3], [4] since each ocular uses only a single image intensifier tube. The image intensifier tube has a fixed number of pixels (picture elements). Therefore, if these are spread over a larger FOV, then the angular subtense per pixel increases, which corresponds to reduced resolution.

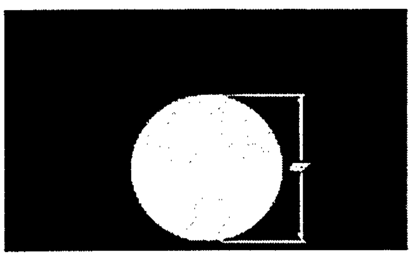

Fig. 3 Simulated AN/AVS-6 and AN/AVS-9 FOV for comparison with the PNVG

A fairly extensive survey of military (US Air Force) NVG users during 1992 and 1993 determined that increased FOV was the number one enhancement most desired by aircrew members closely followed by resolution [5], [6]. This was one of the major motivating factors in seeking an enhanced NVG capability.

PNVG Description

The PNVG features a partial overlap, 100 degree horizontal by approximately 40 degree vertical intensified FOV. The central 30 degree horizontal by 40 degree vertical FOV is completely binocular, while the right 35 degrees is seen with the right eye only and the left 35 degrees is viewed by the left eye only. A thin demarcation line separates the binocular scene from the outside monocular scenes. For this effort, four off-the-shelf PVS-7, third-generation, 18mm format, image intensifier tubes were used. These tubes were selected because they do not have an image-inverting fiber optics attached. Using dual fixed eyepieces, tilted and fused together, folded optics, and a total of four adjustable-focus objective lenses, it was possible to produce the PNVG conceptual working model. Only 16mm of the active 18mm format of the image intensifier tube was used, which enabled the corresponding optics to be significantly reduced. This smaller format and the use of remote AN/AVS-6 power supplies were the primary reasons the PNVG weight was kept to only 569 grams, very similar to the currently fielded AN/AVS-6 and AN/AVS-9 NVG systems. Due to space constraints, slower than desired F/1.44 inner objective lenses and F/1.7 outer objective lenses were incorporated along with an eyepiece effective focal length of 21.9mm. Physical eye relief was measured to be approximately 17mm (Figure 4).

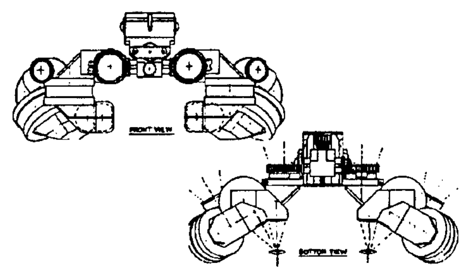

Fig. 4 Schematic diagram of the PNVG

A single inter-pupilary distance adjustment enables the wearer to align the eyepieces for their individual requirements. System power (AA alkaline batteries or standard military batteries) and mechanical mounting hardware are identical to the fielded systems thereby allowing for simple operation and compatibility for attachment, stow, and detachment of the PNVG.

PNVG Evaluation

Laboratory assessments were done on the PNVG for visual acuity under various illumination conditions (for the binocular FOV only) and for total visible FOV. To assess visual acuity, three trained observers looked through the PNVG at a chart composed of patches of square-wave gratings in a series of increasing spatial frequencies. The observer selected the highest spatial frequency grating that he/she could resolve then walked backward until the selected grating was barely resolvable. The baseline observation distance for the chart was 30 feet. The final angular spatial frequency of the grating (cycles/degree) was calculated by multiplying the base spatial frequency times the ratio of the walk-back distance to 30 feet. These data were then converted to cycles per milliradian (in parentheses below) and to Snellen acuities (numbers in front of the numbers in parentheses). This was done three times for each observer for each illumination condition. Each ocular of the PNVG was measured separately then a binocular assessment was made. The results shown below correspond to the median visual acuity (or resolution in cycles per milliradian) value obtained from the three observers:

MedianVisual Acuity (Resolution)

"Starlight Conditions"

Left channel	Rt. channel	Binocular
93(0.37)	93(0.37)	93(0.37)

"Quarter Moon Conditions"

Left channel	Rt. channel	Binocular
44(0.78)	40(0.86)	42(0.82)

Testing FOV was a bit more difficult due to the very large FOV and the nature of the partial binocular overlap. The PNVGs were positioned in a mount fixed to an optical bench, and observers viewed through the PNVGs to determine how far they could see to the edge of the FOV for each ocular. This spot was marked on the wall and trigonometry was used to determine the field angles. Since the far wall used for this assessment was only about 12 feet away, precise results could not be obtained. The median FOV values for the three observers are shown below:

Total FOV Per Channel

Channel	Median FOV degrees
Left outer	42
Left center	33
Rt. center	35
Rt. outer	41
Total Span	92

** Note that after testing, bent brackets on the PNVG were discovered, which accounted for lower than expected readings for FOV. Follow-on measurements by the Night Vision Corporation indicated a total span of about 101 degrees.

Field evaluations have consisted primarily of "quick look" flight tests and ground assessments. The flight tests were accomplished on both Air Force and Army fixed- and rotary-wing platforms but limited to dry, high illumination conditions. Ground assessments were mainly done in darkrooms simulating the night environment. Final reports have not yet been published documenting the official findings. However, comments regarding the PNVG and the greatly enhanced field of view have been mostly positive. Some researchers were concerned that "luning", or other effects associated with the "eye-divergent" partial overlap method of obtaining the large total FOV, might be a problem [7]. However, no comments were received indicating this phenomena was observed.

Future Directions

Ten new working models in three different configurations are currently under development as part of an advanced technology demonstration. Configuration 1 (four each) will be designed for ejection compatibility. The PNVG will be attached to the HGU-55/P helmet, fit underneath the visor, and mounted to a "universal connector" used in the Visually-Coupled Acquisition and Targeting System helmet-mounted display. Additionally, it will be equipped with an integrated head-up display (HUD) along with head tracker sensors and associated cables/electronic components. Configuration 2 (two each) will be designed for transport and rotary platforms. This configuration will attach to the HGU-55/P and SPH-4 helmet, mounted to the currently fielded AN/AVS-6 and AN/AVS-9 attachments, and will be equipped with the integrated HUD. Configuration 3 (four each) will be the same as configuration 2 but without the integrated HUD.

The primary objectives in this phase are to develop a 16mm format image intensifier tube and associated power supply; integrate an active matrix electroluminescent display for symbology purposes; optimize the folded optical design as well as the human engineering of the overall packaging, mechanical adjustments, and attachments. Additionally, four weight and space models will be fabricated and subjected to windblast, impact, penetration, ballistic, and ejection tower (if required) testing.

Conclusion

The PNVG conceptual working model demonstrates the feasibility and benefits of a very wide FOV image for night operations. Better situational awareness, reduced fatigue during long missions, possible ejection compatibility, and an overall increase in mission safety and effectiveness indicate the PNVG should have a tremendous impact on nighttime performance.

Acknowledgments

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Further Development of the Panoramic Night Vision Goggle

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ABSTRACT

A novel approach to significantly increasing the field of view (FOV) of night vision goggles (NVGs) has been developed. This approach uses four image intensifier tubes instead of the usual two to produce a 100 degree wide FOV. A conceptual demonstrator device was fabricated in November 1995 and limited flight evaluations were performed. Further development of this approach continues with eleven advanced technology demonstrators scheduled for delivery by the end of December 1998 that will feature five different design configurations. Some of the units will be earmarked for ejection seat equipped aircraft due to their low profile design allowing the goggle to be retained safely during and after ejection. Other deliverables will be more traditional in design approach and concentrate more on transport and helicopter aircraft as well as ground personnel. Planned testing to collect both subjective and quantitative data will begin in November 1998.

INTRODUCTION

Delivery of the conceptual demonstrator device (Figure 1), now referred to as the panoramic night vision goggle (PNVG), was quite impressive considering it was developed with very limited funding under a phase I small business innovative research (SBIR) program with Night Vision Corporation. The extremely positive feedback of this demonstrator from the warfighter community propelled the program into a phase II SBIR effort and also received the attention and supplemental funding support of the Air Force Research Laboratory's Helmet-Mounted Sensory Technologies program office. Phase II will further develop the PNVG by first addressing ejection seat aircraft with two configurations of a low profile design (designated PNVG I). This version with its better center of gravity should be less fatiguing during longer flights and will potentially allow for ejection by permitting retention of the system on the head throughout the ejection sequence. Retention of PNVG I may also permit quick evasion and rescue. Additionally, three configurations of a never-before-seen NVG for transports, helicopters, and ground personnel (designated PNVG II) are being developed. These models will look more like a traditional goggle. PNVG II, while weighing more than a PNVG I, should be more robust and will attach to any existing ANVIS mounting system. Both PNVG I and II, like the phase I conceptual demonstrator, will provide a 100 degree horizontal by 40 degree vertical (100° H X 40° V) intensified field of view (FOV) (Figure 2). This represents a 160% increase of the warfighter's intensified image FOV compared to currently fielded 40° circular FOV systems.

Figure 1. PNVG conceptual demonstrator (Patent Pending)

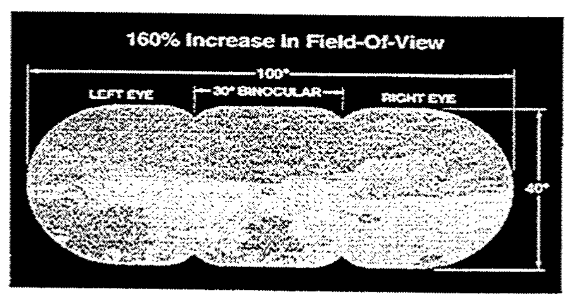

Figure 2. PNVG simulated FOV

BACKGROUND

NVGs with FOVs ranging from 30° (GEC-Marconi Avionics' early Cat's Eyes NVGs) to 45° (GEC-Marconi

Avionics' NITE-OP and NITE-Bird NVGs) have been used in military aviation for more than 20 years. The vast majority of NVGs (AN/AVS-6 and AN/AVS-9) provide a 40° FOV (Figure 3). Because each ocular uses only a single image intensifier tube, increased FOV for these NVGs can only be obtained at the expense of resolution (Donohue-Perry, Task, & Dixon, 1994 and Task, 1992). The image intensifier tube has a fixed number of pixels (picture elements). Therefore, if the pixels are spread over a larger FOV, the angular subtense per pixel increases proportionally. As a result, resolution is reduced.

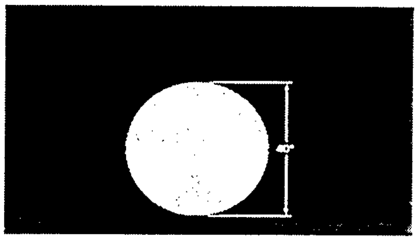

Figure 3. Simulated AN/AVS-6 and AN/AVS-9 FOV for comparison with the PNVG

An extensive survey of military (U.S. Air Force) NVG users conducted during 1992 and 1993 revealed that increased FOV was the number one enhancement most desired by aircrew members. Resolution followed closely (Hettinger, Donohue-Perry, Riegler, & Davis, 1993 and . Donohue-Perry, Hettinger, Riegler, & Davis, 1993). This was a major motivating factor for the development of an enhanced NVG capability.

PNVG I DESCRIPTION

PNVG I (figure 4) is similar in design approach to the conceptual demonstrator PNVG developed under the phase I SBIR program but has optimized the overall design and added several enhancements. PNVG I still features a partial overlap (100° H X approximately 40° V) intensified FOV. The central 30° H X 40° V FOV remains completely binocular while the right 35° is visible only to the right eye and the left 35° is visible only to the left eye.

Additionally, a thin demarcation line separates the binocular image from the monocular peripheral image. PNVG I features a newly developed 16mm image intensifier tube rather than the currently fielded 18mm format tube. Along with the goal of offering comparable performance to the recent Omni IV tubes, its weight will be reduced by more than 50%. Therefore, four 16mm PNVG tubes weigh less than two of the current 18mm tubes. The 16mm tubes have longer fiber optics on the

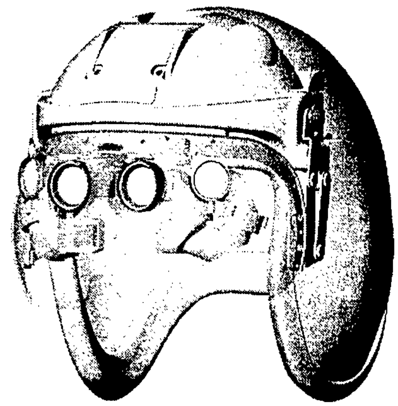

Figure 4. PNVG I (Patent Pending)

outside optical channel than the inner optical channel. The outer and inner channel fiber optics do not require image-inverting fiber optics. Dual fixed eyepieces (tilted and fused) and four objective lenses (the inner two adjustable and the outer two fixed) make up part of the folded optical approach. The inner optical channels include very fast F/1.17 objective lenses as compared with the F/1.25 objective lenses of the currently fielded AN/AVS-6 and AN/AVS-9 goggles. The outboard channels, due to size and weight constraints, incorporate F/1.30 objective lenses. All of the objective lenses will incorporate Class B, leaky green filters for compatibility with color cockpits and aircraft head-up displays. Eyepiece effective focal length is 24mm while the physical eye clearance has been designed for 22mm. A specially designed single left side and single right side power supply is remotely located but allows each side's inner and outer optical channels to be controlled independently. Multiple adjustments (i.e. tilt, independent inter-pupilary distance, up/down, and fore/aft) should permit an optimized optical fitting. Customized visors will also be incorporated for mechanical stability and escape protection. Individualized holes will be cut for the objective lenses to stick through. Also, a unique latching mechanism affords one-handed don/doff capability. A new linkage system enables the PNVG I to easily transition into a stow position (Figure 5).

During normal use, power is provided to the system by the aircraft. In the event of an ejection, two "AAA" alkaline batteries located in the remote electronics module (REM) provide power during the escape sequence, evasion, and rescue. Due to funding constraints, PNVG I is currently designed to attach to only the Air Force's HGU-55P helmet.

Two configurations of the PNVG I will be delivered. PNVG I-Configuration 1, will have four deliverables.

The PNVG module will attach to a unique "universal connector", the same connector used with the Visually Coupled Acquisition and Targeting System (VCATS) daytime helmet module. VCATS is currently being evaluated as part of an advanced technology

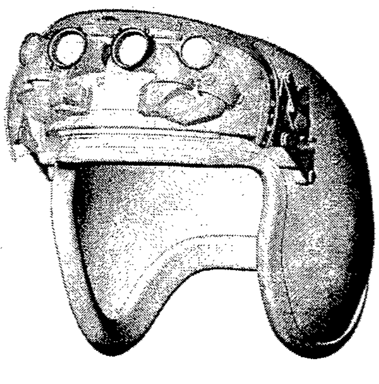

Figure 5. PNVG I in stow position (Patent Pending)

demonstration at the 422nd Test and Evaluation squadron at Nellis AFB. The universal connector provides aircraft data and power to the PNVG module. This configuration also features a 640x480 active matrix electroluminescent display (AMEL) for symbology overlay and a magnetic head-tracker with electronics located in the REM. PNVG I-Configuration 2, a stripped down version of Configuration 1, will have two deliverables. Configuration 2 does not include an AMEL display, magnetic head-tracker, or electronics package. Since the majority of the HGU-55P helmets are not equipped with the VCATS universal connector, a special banana clip mount has been designed that will accept the PNVG module on any HGU-55P helmet. Because there is no aircraft power being provided through a universal connector for configuration 2, system power will be supplied by the two "AAA" alkaline batteries located in the REM.

PNVG II DESCRIPTION

An alternative approach to PNVG I has been developed. The partial overlap 100° H X 40° V intensified FOV is maintained but the system resembles the currently fielded aviator NVGs (Melzer & Moffit, 1991). Whereas PNVG I mates to only the HGU-55P helmet, PNVG II (Figure 6) is compatible with any helmet that incorporates the standard ANVIS mounting bracket. This will allow any warfighter to assess the utility of a panoramic night vision scene given they have the proper bracket. If testing proves that the panoramic scene is required but the PNVG I approach is preferred, a development effort will have to address the specific design issues necessary to mate it with a particular helmet type.

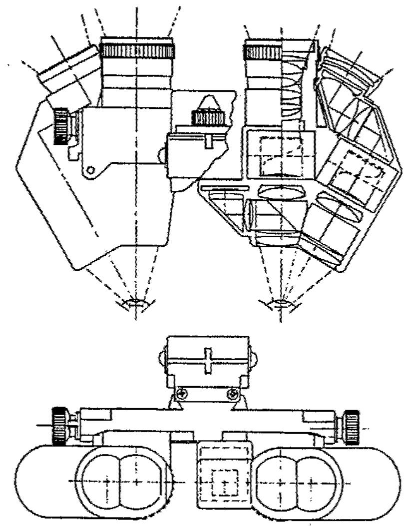

Figure 6. PNVG II (Patent Pending)

Similar to the PNVG I, the central 30° H X 40° V FOV is completely binocular while the right 35° is visible only to the right eye and the left 35° is visible only to the left eye. Additionally, a thin demarcation line separates the binocular image from the outside monocular image. PNVG II utilizes the newly developed 16mm image intensifier tube but requires image inverting fiber optics (the outer channel fiber optics are the same length as the inner channel). Dual fixed eyepieces, tilted and fused together, and four objective lenses (the inner two adjustable and the outer two fixed) remain part of the optical approach. The non-folded inner optical channels are designed with extremely fast F/1.05 objective lenses. The folded outboard channels use the PNVG I inner channel optics with F/1.17 objective lenses. Eyepiece effective focal length is 24mm while the physical eye clearance has been significantly increased to 27mm. All of the mechanical adjustments currently available on the AN/AVS-6 and AN/AVS-9 remain (i.e. tilt, independent inter-pupilary distance adjustment, up/down, fore/aft). Power for the PNVG II will be provided via the batteries that are currently integrated with the AN/AVS-6 and AN/AVS-9 mounting systems. Therefore, no special power provisions are necessary.

Three configurations of PNVG II will be delivered. PNVG II-Configuration 3 will have only one deliverable but it will feature a 640x480 AMEL display. Additionally it will have a Class B, leaky green filter incorporated into the objective lens. PNVG II-Configuration 4 will have three deliverables but will not include the AMEL display. One of the three will use the Class B, leaky green filter while the remaining two will use a Class A filter. The final deliverable, PNVG II-Configuration 5, is intended for ground applications and will be integrated to a special hand-held "PIRATE" mounting system including its own batteries and a single infrared diode. This configuration will not include an AMEL display and the objective lens will be unfiltered (i.e. no class A or B filters).

PNVG TEST PLAN

A critical step in the development of the PNVG system is the completion of performance-based field evaluations. It is important to have an empirical basis for determining the cost/benefit afforded by the capabilities of the PNVG compared to present NVGs. Toward this end, a two-pronged multi-phased evaluation program is being planned. The testing activities will occur both in the laboratory (simulation facilities) and during operational flights. Ideally, to maximize how well findings can be generalized from the laboratory to the field, subject matter experts (appropriately rated pilots) will serve as experiment participants for both phases. The evaluation and experimental design is being structured to include both fixed- and rotary-wing applications.

It is anticipated that the use of the PNVG technology will result in both performance and behavioral differences when compared to conventional NVGs. The evaluation methodology is being designed to investigate these differences via the performance operationally representative tasks which hold practical significance. Included are both flight and target search tasks. Subjective feedback will also be collected to compare the different FOV technologies in terms of pilot preference, subjective workload, and subjective situation awareness.

The first phase of the evaluation is comprised of a series of simulation trials. The purpose of using the simulator as an initial evaluation step is to validate the test methodology in a relatively quick and inexpensive manner. Unique to the simulation trials will be those tasks which are impractical or exceedingly dangerous for actual flight trials. The basic tasks which prove to be sensitive performance discriminators in simulation will be replicated in flight test.

The following are example tasks and measures presently being considered for the empirical evaluation:

Simulator Tasks: These tasks will include a manipulation of flight symbology in addition to the PNVG / conventional NVG comparison. The simulation trials will be developed for and run in the Air Force Research Laboratory's Synthesized Immersion Research Environment Facility (SIRE) or similar high-resolution large dome simulator (Geiselman, Brickman, Hettinger, Hughes, DeVilbiss, & Haas, 1998).

Fixed-wing simulator tasks: The purpose of the PNVG technology is to afford the pilot daytime-like performance under conditions of degraded vision (i.e. night). Representative tasks for the evaluation will include those which are difficult during extremely low light level night operational conditions. Also included are primary tasks such as target search and identification, low altitude navigation, dive-toss bombing, formation flight, blacked out runway landings, etc. For all of these tasks, simulation catch trials will be developed to include critical events such as terrain obstructions, airborne threats (potential midair), and runway incursion. These events will be included in the experimental design as secondary measures of situation awareness and task saturation.

Performance measures will be collected and analyzed to help determine the effects of changes in FOV and the addition of symbology on performance during trials of the aforementioned primary tasks and critical events. Behavioral measures in the form of head movement and position data will be analyzed to investigate the effects of the independent variables (e.g. no aid vs. NVG vs. PNVG with and without symbology) on pilot line-of-sight variability (including the proportion of head-out and head-up time as a result of the display manipulations), rate-of-translation, reversals, search patterns, and fixation area. Subjective feedback will include pilot preference questionnaires, subjective workload ratings (i.e. NASA task loading index: NASA-TLX (Hart & Staveland, 1988)) and subjective situation awareness comparisons (i.e. Cognitive Compatibility Situation Awareness Rating Technique: CC-SART (Taylor, 1995)).

Fixed-wing flight test: To the extent possible, the fixed-wing in-flight evaluation tasks will include replications of the simulation tasks. Similar objective and subjective measures will be collected and analyzed. The planned operational evaluations will be conducted in F-15C aircraft at Nellis AFB, Nevada by the 422nd Test and Evaluation Squadron.

Rotary-wing evaluation: The rotary-wing simulation tasks will include elements similar to the fixed-wing evaluations. These include target search and identification, landing, critical events (i.e. wire crossing during terrain masking maneuvers). In addition, methodology from previously performed simulation studies and flight evaluations will be replicated for the purposes of the present evaluation. For instance, standardized helicopter handling qualities maneuvers have been successfully demonstrated as sensitive evaluation variables for similar display FOV research (Szoboszlay, Haworth, Reynolds, Lee, & Halmos, 1995). These tasks, and their associated performance measures, will be modified for use as both simulation and flight trials to meet the objectives of the current evaluation. Flight testing will be completed at Ft. Belvoir and the NASA Ames Research Center (Szoboszlay et. al., 1995). The rotary wing tests will include behavioral and subjective measures similar to those presented in the fixed wing section.

CONCLUSION

The PNVG conceptual working model developed under the phase I SBIR demonstrated the feasibility of a very wide FOV image for night operations. The eleven advanced technology demonstrators being delivered under phase II will allow the warfighter to evaluate the operational utility of the PNVG. As a result of both the performance-based simulator and field evaluations, a better understanding will be gained of the PNVG's impact on such areas as improved situational awareness, reduced fatigue during long missions, ejection compatibility, and overall increased mission performance and safety.

ACKNOWLEDGEMENTS

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BIOGRAPHIES

Jeffery L. Craig is an Industrial and Systems Engineer working for the Air Force Research Laboratory. A graduate of Ohio State University in 1982, Mr. Craig has been employed at Wright-Patterson Air Force Base in Ohio since receiving his diploma. His current position is managing the Night Vision Operations Program within the Visual Display Systems Branch. Early projects to his credit are NVG compatible cockpit lighting, NVG head-up displays and NVG covert landing aides. More recent efforts have centered around enhanced NVG development in particular the panoramic NVG program.

Eric Geiselman received a M.A. in Human Factors/Experimental Psychology from the University of Dayton in 1991. In 1988 he received a B.S. in Psychology also from the University of Dayton. Mr. Geiselman is currently employed by Logicon Technical Services as a Senior Human Factors Engineer supporting the Air Force Research Laboratory (AFRL) Synthesized Immersion Research Environment (SIRE), Wright-Patterson Air Force Base, Ohio. Mr. Geiselman is a commercial pilot and flight instructor with instrument, seaplane, and glider ratings.

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Craig, J. L. (2000). Integrated panoramic night vision goggle. *Proceedings of the 38th Annual Symposium SAFE Association,* http://www.safeassociation.com

Integrated Panoramic Night Vision Goggle

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ABSTRACT
In July of 1999 the Air Force Research Laboratory (AFRL) took delivery of the last of twelve panoramic night vision goggle (PNVG) systems. Data on these systems has been collected onboard a variety of aircraft including the F-15C, F-15E, F-16, A-10, F-117, C-17, C-5, C-130, and HH-60 aircraft. Data will continue to be collected on these aircraft as well as other platforms over the next 12 months. In April of 2000 a follow-on development effort was initiated entitled "Integrated Panoramic Night Vision Goggle" (I-PNVG). Lessons learned from the PNVG effort are being incorporated into the I-PNVG program wherever possible. Specific objectives to be addressed under I-PNVG effort are wide field-of-view, integrated laser protection, fit/comfort, image quality, integrated symbology/imagery display, field support, ejection/crash/ground egress safety, compatibility with existing systems, affordability, supportability, maintainability, producibility, and reliability. This paper will briefly discuss pilot comments about the PNVG, provide further detail of the I-PNVG objectives, and address I-PNVG design considerations.

INTRODUCTION
A Small Business Innovative Research (SBIR) phase II program that ended in July 1999 resulted in the delivery of seven PNVG I and five PNVG II prototype systems. The PNVG I version is a low profile design for ejection seat aircraft with the goal of retaining the goggle safely on the head throughout the entire ejection sequence.

Figure 1: PNVG I in F-15E (front cockpit)

Figure 2: PNVG I in an F-15E (rear cockpit)

The PNVG II approach, which looks more like a traditional goggle, attaches to any existing AN/AVS-6 or F-4949 mounting system. This version was intended for transports, helicopters, and ground personnel. Both PNVG I (Figure 1 and Figure 2) and PNVG II (Figure 3) provide a 100 degree horizontal by 40 degree vertical (100° H X 40° V) intensified field of view (FOV) (Figure 4.). This represents a greater than 160% increase of the warfighter's intensified image compared to currently fielded 40° F-4949 system (Figure 5 and Figure 6.). A follow-on advanced technology development program, I-PNVG, was awarded in April 2000 to optimize the wide FOV concept and address deficiencies of the SBIR PNVG I and SBIR PNVG II systems identified during recent flight tests. Additionally, the I-PNVG will integrate (or have the "hooks" available to integrate) laser eye protection and laser hardening technologies as they become mature enough for insertion. The I-PNVG program was awarded to Insight Technology Incorporated with ITT Night Vision as their primary teaming member. The program is managed by the Helmet-Mounted Sensory Technologies Program Office within the Air Force Research

Laboratory at Wright-Patterson AFB OH. The Army has also joined the team to complement the Air Force's effort to develop this next-generation night vision goggle.

Figure 3: PNVG II in C-17 Cockpit

Figure 4: 100 x 40 Degree Field of View

BACKGROUND

NVGs with FOVs ranging from 30 degrees to 45 degrees have been used in military aviation for more than 20 years. The vast majority of NVGs (AN/AVS-6 and F-4949) provide a 40 degree binocular FOV. Because each ocular uses only a single Image intensifier (I^2) tube, increased FOV for these NVGs can only be obtained at the expense of resolution.[1,2] The I^2 tube has a fixed number of pixels (picture elements). If the pixels are spread over a larger FOV, the angular subtense per pixel increases proportionally thus reducing resolution. An extensive survey of U.S. Air Force NVG users showed that increased FOV was the most desired enhancement by aircrew members. Resolution was a close second.[3,4] This was a motivating factor for the development of an enhanced NVG capability. Previous studies suggest FOV produces performance advantages: A study using a critical tracking task showed best performance at 80 or 100 degrees. and an increase from 40 to 80 degrees greatly reduced subjects' workload.[5] Another study included a series of low altitude maneuvers in Cobra and Lynx rotorcraft and the results indicated 100 degree to unrestricted FOV required only moderate pilot compensation. The results also showed pilots flying with restricted FOV reported better flying performance than actually exhibited. Furthermore, restricted FOV inhibited detection of multiple cues concurrently. and the small FOV required more head movement and a different scan technique while large head movements led to aircraft control difficulty and disorientation.[6] A third study had subjects visually acquire targets, remember the location of the target, and monitor target threat status while performing a secondary task. Error decreased as FOV increased until a FOV of 90 degrees was reached. Secondary task performance increased as FOV inceased.[7]

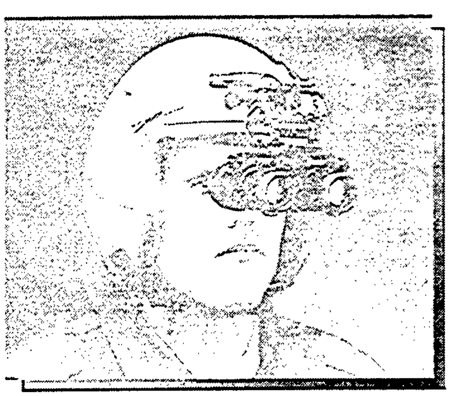

Figure 5: F-4949 NVG

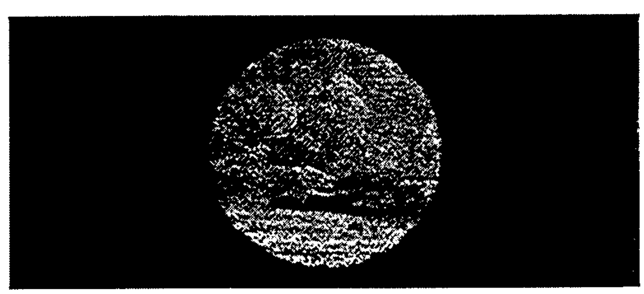

Figure 6: 40 Degree Field of View

PNVG COMMENTS

The following comments have been collected via post flight questionnaires. PNVG I comments represent feedback from F-15C and F-15E aircraft from the 422 Test and Evaluation Squadron at Nellis AFB, Nevada.[8] PNVG II comments represent C-130 feedback from the 50th and 61st Airlift Squadrons at Little Rock AFB, Arkansas and C-5 feedback from the 3rd and 9th Airlift Squadrons and 436th Air Wing at Dover AFB, Delaware.[9]

Representative PNVG I positive comments

"I did not experience any eye strain or headaches." "A must have." "A-10's need these!" "Closer to face, better FOV rather obvious!" "Outer channels were focused much better (20/25)." "Had better situational awareness of my surroundings." "Easier to fly at lower altitudes." "Could spend more time scanning for bandits and watching where my flight path is." "Less forward CG when looking through."

Representative PNVG I negative comments

"Lack of adjustability." "The battery change out is unsat." "I lost a battery down inside the helmet cover when trying to change out!" "In order to see the HMD display, I had to have the right channels way over to the left (toward the center of my face)." "This caused me to lose the outer part of the right outer channel." "Need to adjust focus rings." "They are too hard to work with gloves on." "Need more play in the areas that we normally focus (infinity)." "The "bridge" that holds the goggle is worn and breaks loose at 6 g's or greater." "Requires me to reach up and snap it back into place." "More difficult to see inside the cockpit, especially under g's." "Very difficult to set up the radar while in turn." "Not as crisp." "Flimsy trapeze, tilt sags under G." "Adjustments not user friendly." "Had to lower seat 2 inches to get proper eye height relative to HUD." "Delicate innards exposed when removed from helmet for stowing."

Representative PNVG II positive comments

"The panoramic vision greatly increased mission capabilities by decreasing the amount of head movement required for the pilot to scan. This in turn reduced the amount of work." "Overall very impressive--much less time scanning, much more time spent looking--situation awareness dramatically increased." "PNVGs definitely enhance mission effectiveness. The peripheral vision alone is a dramatic capability enhancement. The battery pack incorporated into the PNVG is also nice." "Panoramic vision greatly increases SA and clearing ability."

Representative PNVG II negative comments

"PNVGs need: wider range of focus. Outer tubes need focus ability, more field of view up and down would be nice too." "PNVG objective lens seem harder to adjust than 4949, the knobs are hard to turn. Very heavy when stowed. PNVG needs more near focusing for close up work (1 - 2 foot range)." "Suggest better focus on inner tubes and focus capability on outer tubes." "Also because you need the NVGs close to your eyes to eliminate the "lines" it makes viewing cockpit instruments difficult under the PNVGs compared to the 4949s."

I-PNVG OBJECTIVES

There are nine areas that address the key Air Force objectives of the I-PNVG program.[10] These areas are discussed in the following paragraph The first key objective is *wide FOV.* The PNVG I and PNVG II systems developed under the SBIR program did not perform trade studies to determine the optimal FOV. The I-PNVG program will review the literature and conduct trade studies to develop an optimal FOV design. The system will be required to have an instantaneous horizontal FOV ≥ 80 degrees with a binocular overlap ≥ 36 degrees, and a instantaneous vertical FOV ≥ 36 degrees. The second key objective is *laser eye protection*. Laser threats to military aircrew are real with reports from foreign sources and the presence of lasers are expected to grow on the battlefield. These incidents have raised concern for the health of aircrew eyes, for mission effectiveness, and for flight safety. I-PNVG will incorporate LEP technologies for protection of the human and the goggles. The design(s) will have to accommodate the latest LEP visor, LEP spectacles, and light interference filters. The third key objective area is *fit and comfort*. The fit and comfort of the operator while wearing the I-PNVG will be examined. The I-PNVG will need to accommodate a diverse population of operators that will be flying in different mission environments of varying mission duration. Design considerations will be weight and center of gravity (down and stowed positions), ease of mechanical adjustments, stability of the NVG/helmet to accommodate G loads and rapid head movements, cockpit compatibility, and adequate eye relief. The fourth key objective area is *image quality.* The device needs to have image quality equal to or better than NVGs delivered under the Army Omni V contract. Attributes for satisfying the requirement that need to be considered are the expected visual acuity (resolution) through the device for quarter moon and starlight levels, signal-to-noise ratio, image tube halo, optical distortion, optical image alignment, system modulation transfer function (MTF - on axis and at edges of the field), eyepiece focus, eye position tolerance and effects on optical MTF, objective lens focus, and maximum image luminance. If partial overlap of visual fields is used to produce the wide FOV, the image discontinuity tolerances at the overlap should be addressed including image luminance uniformity, image magnification, rotation, distortion, and horizontal and vertical off-set. The fifth key objective area is *integrated symbology/imagery display.* The electronic interface needs to be extended from the current symbology overlay technique to include imagery insertion by using a light-valve or similar technology (could even include turning image intensifier tube off) to block the NVG image during imagery display and single-channel miniature camera record. The inclusion of a full-color version of the miniature flat panel image source will also be considered. The I-PNVG will provide the capability to remove/replace either or both the flat panel image source and the miniature camera in the field. The I-PNVG will remain mission capable as a separate functioning system with either or both functions removed. The instantaneous FOV provided for the imagery insertion should be compatible with current navigation-FLIR sensors. Compatibility with Joint Helmet Mounted Cueing System, Visually-Coupled Acquisition & Targeting System, Air Warrior, and Land Warrior will be considered. Finally, the allocation of electronics between the I-PNVG device and its associated helmet vehicle interface module will be addressed with respect to its impact on operational use of the system. The sixth key objective area is *field support.* The device should be designed in order to minimize the need for any additional logistic support equipment. This means the design will allow field-level performance testing utilizing the ANV-126 Hoffman tester with little or no disassembly of the I-PNVG device or major modification to the tester. Adjustment knobs should be useable while wearing flight and chemical/biological gloves. The seventh key objective area is *ejection/crash/ground egress safety.*[11] Flight safety and environmental use have to be factored into the design. The following areas need to be examined in the performance of safety testing: Mertz criteria, Knox Box, USAARL curve, inertial properties, vertical impact, helmet impact, visor ballistics, helmet penetration, rapid and explosive decompression, ejection windblast, quick disconnect functionality, hanging harness, cockpit compatibility, electromagnetic compatibility, emergency ground egress, and electrical shock analysis. The eighth key objective area is *compatibility with existing systems.* The new system will need to be interoperable with existing systems. The items that need to be addressed are the helmet, oxygen mask, nuclear/biological/chemical masks, Aviator Night Vision Imaging System mount, survival vest, anti exposure suit, torso harness, aircrew spectacles, back style parachutes, and personal clothing. The ninth and final key objective area is – *ilities.* The I-PNVG design must optimize reliability, maintainability, affordability, producibility and supportability. System and system sub-components should be capable of mass production while consistently maintaining pre-established standards. A design that requires only minimal maintenance is desirable. Pre or post-flight checkout and maintenance procedures should be kept to a minimum. Major components should be interchangeable if a two-configuration approach is adopted.

I-PNVG PRELIMINARY DESIGN CONSIDERATIONS

A single I-PNVG design approach is preferred that would satisfy mission requirements for fighters, bombers, transports, helicopters, and ground personnel. If a two-design approach is deemed necessary commonality of components between the designs is to be emphasized. A trade-off of the above listed objectives is critical in order to optimize the desired approach(s). Some of the specific parameters of interest for the I-PNVG trade-off studies are total horizontal field-of-view, binocular overlap, resolution/visual acuity, eye relief/lens focal length, weight, center of gravity, F/Number (lens diameter), exit pupil, image quality/MTF, size/form factor, adjustments, manufacturability/maintainability, and cost. The following parameters are identified as "non-negotiable": must have same visual acuity as F-4949, must be compatible with standard flight spectacles, and must use 16mm tubes. Other important issues that need to be addressed are the tolerances at the inboard/outboard seam (rotation, vertical mismatch, horizontal mismatch, magnification mismatch, distortion), inboard/outboard mismatch for other than infinity objective lens settings, and alignment procedures for inboard/outboard channels. Initially, two approaches are being considered. The first is a low profile "periscope-like" design (referred to as I-PNVG 1) targeted for ejection seat aircraft (Figure 7). This design approach intends to permit the system to be retained on the head safely during the ejection sequence and additionally provide post-ejection evasion and rescue capability while on the ground. Each of the identical objective lenses are adjustable for distance focusing and feature a fixed, fused, and tilted eyepiece design. I-PNVG 1 utilizes folded optics in each of the four optical channels, fits underneath a standard Air Force visor, and attaches to the standard Air Force HGU-55/P helmet via a universal connector. This universal connector is hard mounted to the helmet and is the same mounting mechanism approach used for two daytime helmet mounted display systems currently being tested (1) AFRL's Visually-Coupled Acquisition and Targeting System [VCATS] (an advanced technology demonstration effort) and (2) Common Avionics System Program Office's Joint Helmet Mounted Cueing System [JHMCS]) (an engineering and manufacturing development program). A dummy universal connector will also be fabricated onto a banana clip-like mount for non-JHMCS and non-VCATS aircraft. An enhanced version of I-PNVG 1, referred to as Strike Helmet 21, will use the I-PNVG 1 as its baseline but will integrate some new technologies under development. These new technologies include an Active-Matrix Organic Light Emitting Diode for symbology or video display and an inertial head tracking system to help precisely deliver high off-boresight angle missiles. A CCD camera will also be integrated and used for battle damage assessment and training purposes. The second approach being considered (referred to as I-PNVG 2) is a more "traditional" design (Figure 8) for transports, helicopters, and ground personnel. This approach utilizes straight-through optics, similar to

AN/AVS-6 and F-4949, in each of the four optical channels and attaches to the standard Air Force HGU-55/P or SPH-4/AF helmet via an "ANVIS-like" mount. Each of the identical objective lenses (like I-PNVG 1) are adjustable for distance focusing and feature a fixed, fused, and tilted eyepiece design. A trade study has been initiated on whether it is possible and advantageous to adapt aspects of this second approach (i.e. straight-through optics) for the ejection seat aircraft design (i.e. I-PNVG 1) as well. There are some likely advantages of a straight-through optics approach that would benefit I-PNVG 1 such as improved optical performance, easier alignment in manufacturing, and commonality with the monocular used for the "traditional" straight-through optics on I-PNVG 2. Questions exist though on the weight and center of gravity of this straight-through optics approach and whether it would fit underneath a standard Air Force visor. This is where we will look to the trade study results. This straight-through optics approach, in addition to being common to both the I-PNVG 1 and the I-PNVG 2, would also be common to the Army's design which is being developed jointly under the I-PNVG program. The Army tracks their advanced technology demonstration design as the "Advanced Night Vision Goggle" (ANVG) (Figure 9) and manage it at the Night Vision and Electronic Sensors Directorate, Ft. Belvoir. The commonality of approaches between the services could provide tremendous synergism. Weight and Space Models of the I-PNVG 1 are scheduled for delivery in May 2001 and the first operational deliveries of the I-PNVG 2 are to begin in August 2001. I-PNVG 1 and ANVG deliveries will follow shortly thereafter.

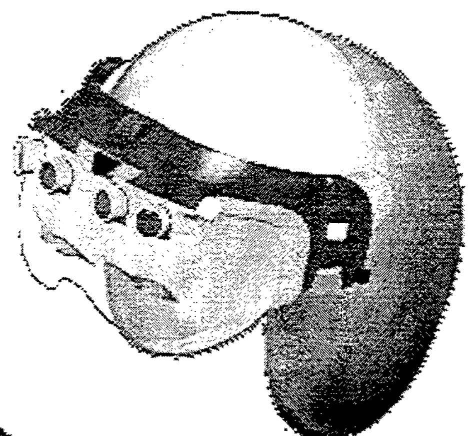

Figure 7: I-PNVG 1 (Periscope)

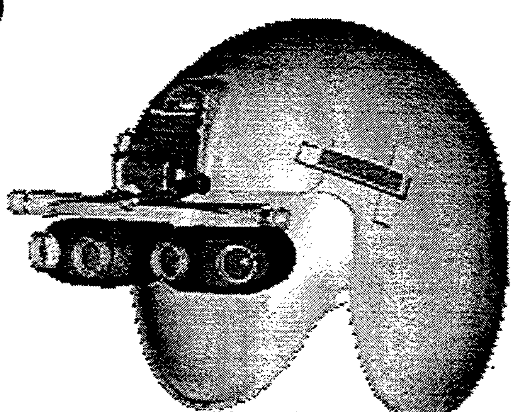

Figure 8: I-PNVG 2

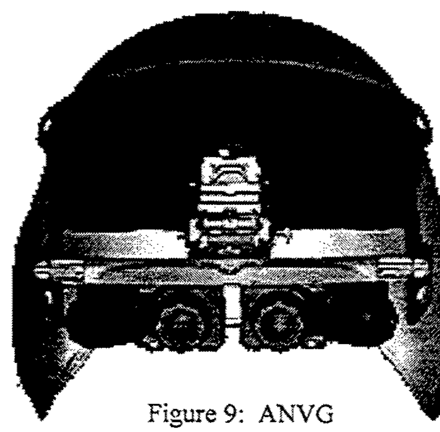

Figure 9: ANVG

CONCLUSION

The I-PNVG truly has the potential to become the next generation night vision goggle. Work continues towards finalizing the optical, mechanical, and electronics design details prior to the scheduled critical design review in January 2001. Stereo lithography models will be utilized extensively over the next several months by the designers and warfighters to explore and/or verify I-PNVG design options. Weight and space models will be available in May 2001 to enable safety of flight testing to begin followed by the first operational I-PNVG deliveries in August 2001. The Air Force is scheduled to receive a total of 25 I-PNVGs and the Army is scheduled to receive a total of 5 ANVGs for flight evaluation purposes.

ACKNOWLEDGMENTS

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BIOGRAPHY

Mr. Jeff Craig is an Industrial and Systems Engineer working for the Air Force Research Laboratory. A graduate of Ohio State University in 1982, Mr. Craig has been employed at Wright-Patterson Air Force Base in Ohio since receiving his diploma. His current position is managing the Night Vision Operations Program within the Air Force Research Laboratory. Early projects to his credit are NVG compatible cockpit lighting, NVG head-up displays, and NVG covert landing aides. More recent efforts have centered around new NVG developments in particular the PNVG and I-PNVG programs.

Franck, D. L., Geiselman, E. E., & Craig, J. L. (2000). Panoramic night vision goggle flight test results. *Proceedings of SPIE – The International Society for Optical Engineering Helmet- and Head-Mounted Displays V, USA, 4021*, 146-154.

Panoramic Night Vision Goggle Flight Test Results

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ABSTRACT

The Panoramic Night Vision Goggle (PNVG) has begun operational test and evaluation with its 100-degree horizontal by 40-degree vertical field of view (FOV) on different aircraft and at different locations. Two configurations of the PNVG are being evaluated. The first configuration design (PNVG I) is very low in profile and fits underneath a visor. PNVG I can be retained by the pilot during ejection. This configuration is interchangeable with a day helmet mounted tracker and display through a standard universal connector. The second configuration (PNVG II) resembles the currently fielded 40-degree circular FOV Aviator Night Vision Imaging System (ANVIS) and is designed for non-ejection seat aircraft and ground applications. Pilots completed subjective questionnaires after each flight to compare the capability of the 100-degree horizontal by 40-degree vertical PNVG to the 40-degree circular ANVIS across different operational tasks. This paper discusses current findings and pilot feedback from the flight trials Objectives of the next phase of the PNVG program are also discussed.

Keywords: Night Vision Goggles, Panoramic Night Vision Goggles, Helmet-Mounted Display, Wide Field of View, Flight Test, Night Operations, and Image Intensifiers Tubes

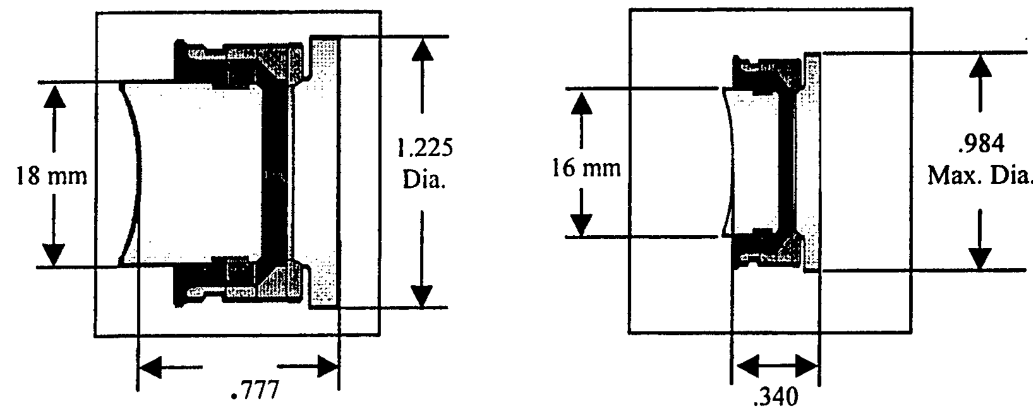
1. INTRODUCTION

The Panoramic Night Vision Goggle (PNVG) (Figures 1 and 2) provides pilots a larger viewing area than current night vision goggles. Unlike previous attempts to increase field of view (FOV), comfort, safety, and resolution have not been sacrificed.

Figure 1: PNVG I in a F-15E

Figure 2: PNVG II in a C-5

The PNVG approach uses four image intensifier (I^2) tubes that are each 60% smaller and lighter than conventional I^2 tubes. The Aviator Night Vision Imaging System (ANVIS) uses two standard I^2 tubes. The key to getting the I^2 tubes smaller and lighter was the design of a 16-mm format versus the standard 18-mm format (Figure 3). The use of four I^2 tubes provides the PNVG capability of a 100 horizontal degree by 40 degrees vertical FOV. The result is an increase of the viewing area by 160% versus current night vision goggles (NVGs) (Figures 4 and 5). Resolution is not compromised because the number of pixels per unit area is not decreased. For PNVG, the center 30 degrees horizontal by 40 degrees vertical is binocular with the right 35 degrees visible only to the right eye and the left 35 degrees visible only to the left eye. The PNVG has two different design configurations: PNVG I and PNVG II.



Existing AN/PVS-7 Module
18 mm Tube

New
16 mm Tube

Figure 3

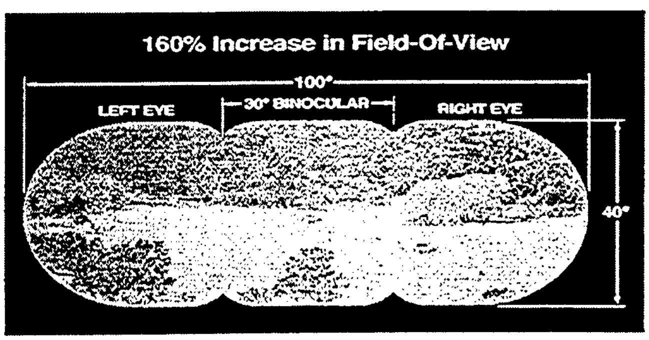


Figure 4: Simulated PNVG FOV

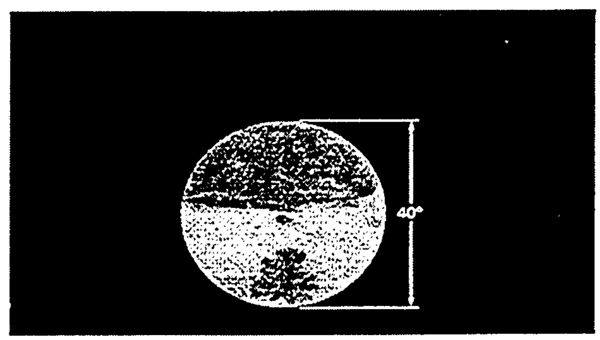


Figure 5: Simulated 40° NVG FOV

1.1 PNVG I

PNVG I (Figure 1) is a low-profile version that is designed to be used in ejection seat aircraft. The system is designed to be retained throughout the ejection sequence and to be used for escape and evasion versus the current NVGs that needs to be removed before ejection because of the risk of injury. The PNVG I had lower windblast loads than the standard HGU-55/P. [1] Figure 6 depicts the low-profile nature of PNVG I versus the standard NVGs. The center of gravity of the PNVG I is closer to the center of gravity of head to make it more comfortable and less fatiguing. The PNVG I is interchangeable with the Visually Coupled Acquisition and Targeting System (VCATS) module that is used for day missions. Both the PNVG and VCATS interface through the use Air Force Research Laboratory's (AFRL) Universal Connector (Figure 7) mounted on a lightweight HGU-55/P helmet. [2] The system can be powered via either aircraft power through AFRL's standardized helmet vehicle interface or the system can be powered using two "AAA" alkaline batteries. The PNVG I has demonstrated the capability to perform off-boresight cueing using the head tracker with the symbology overlay.

1.2 PNVG II

The PNVG II (Figure 2) is similar in design to the ANVIS goggles. The PNVG II is more rugged than PNVG I and will probably be cheaper to produce. The PNVG II was designed for the transport, helicopter, and ground force community who do not require the ejection safe goggles. The goggles will attach to any helmet that has an ANVIS mounting bracket. The system is powered by using one "AA" lithium battery.

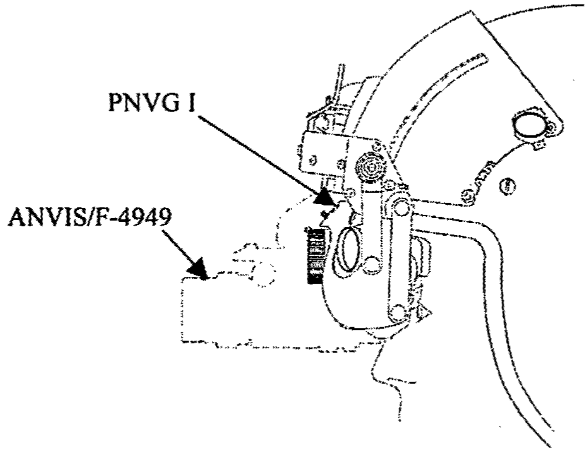


Figure 6: PNVG I Versus ANVIS Profile

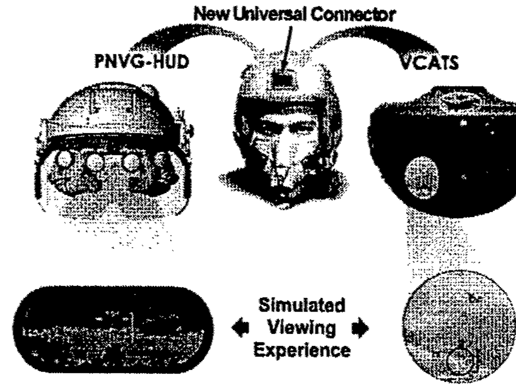


Figure 7: Universal Connector

2.0 EVALUATION METHOD

Several operational utility evaluation (OUE) efforts have been initiated to evaluate PNVG I and PNVG II. Laboratory experiments are also being performed to address specific questions regarding performance and SA effects attributable to the PNVG FOV. The objective of the OUE is to expose the PNVG to the operational environment to investigate the impact the technology has on mission effectiveness and survivability. The OUE process includes the development of new tactics which result from the application of new technology. The data presented here were produced via questionnaires completed by operational test pilots who flew with the PNVG I and PNVG II during evaluation flights. The PNVG I data were collected at the 422nd Test and Evaluation Squadron at Nellis AFB, Nevada. Data are included from 16 different F-15E flights and 10 F-15C flights. At the date of this writing, a total of 12 pilots participated in the PNVG I evaluation flights. Four of the 12 pilots each flew two different sorties. Three of the four duplication flights were in F-15C's. Both air-to-air and air-to-ground missions were completed. Crews from 50th and 61st Airlift Squadrons flew with PNVG II during evaluation flights at Little Rock AFB, Arkansas. A total of nine crewmembers flew with PNVGII aboard the C-130 aircraft. The evaluators included six pilots and three navigators. The majority of these missions were multi-ship formation flights. Twelve crewmembers from the 3rd and 9th Airlift Squadron and 436th Air Wing at Dover AFB, Delaware evaluated PNVG II during C-5 missions. The C-5 flights were mostly single ship low-level airdrop missions. The C-5 evaluators included six pilots, four navigators, one flight engineer, and one loadmaster. All of the C-130 and C-5 crewmembers reported significant experience with conventional F-4949 NVGs. A post-flight questionnaire was developed to collect evaluators' impression of PNVG I and II across different areas of interest during each evaluation flight.

2.1 Questionnaire and rating scale

A rating scale was developed to compare pilots' experience with PNVGs versus their previous experience with F-4949s. It was not feasible to directly compare the PNVG (I and II) to F-4949 on a flight by flight basis. Instead, the questionnaire instructions asked pilots to compare their recent experience with PNVG I or II vs. their past experience with F-4949s. All of the participants had significant flight experience with the conventional F-4949 NVGs. A rating methodology was developed to allow the evaluators to quantify their comparison of the NVGs. Table 1 shows the rating scale developed for the questionnaire. Questions were formed for the following categories: 1) Fit, Function, and Human Factors, 2) Cockpit/Cockpit Lighting Compatibility, 3) Image Quality, and 4) Operational Employment. Where possible, comparison ratings were collected. Where appropriate, yes/no format questions were asked. Comments were solicited at the end of each category section of the questionnaire. A final section of the questionnaire was dedicated to additional comments designed to collect information about the advantages and disadvantages of the PNVG.

RATING SCALE		RESPONSE
1	Very Ineffective	PNVG performance is significantly less than that of the F-4949 and significantly affects safety of flight or detracts from successful task/mission accomplishment.
2	Ineffective	PNVG does not perform as well as the F-4949 and detracts from task/mission accomplishment.
3	Same	PNVG and F-4949 performance does not differ.
4	Effective	PNVG performs better than the F-4949 and enhances task/mission accomplishment.
5	Very Effective	PNVG performance is significantly better than the F-4949 and significantly enhances safety of flight or adds to successful task/mission accomplishment.

Table 1. PNVG questionnaire rating scale.

3.0 RESULTS

3.1 F-15 PNVG I evaluation

The following paragraphs present the questionnaire data collected to date. The information represents averages derived across all 16 sorties. It is indicated where feedback is specific to an aircraft type (F-15C or F-15E). A statistical analyses (two-tailed t tests) were performed to determine if the recorded ratings differed reliably from a rating of 3 (a rating of 3 would indicate that PNVG I and F-4949 performance was the same).

3.1.1 Descriptive information

Average takeoff time was 42 minutes after local sunset. Average duration of the flight was 1 hour 32 minutes (1:32). Illumination conditions were described as high for slightly more than half the flights (62.5%). Average moon presence was 68.3% and the observed weather was described as clear for the majority of the flights (91.6%).

3.1.2 Fit, function, and human factors ratings:

Pilots found the PNVG I to be easier to don than the F-4949 (mean rating = 4.25, p. < 0.0001). For weight and center of gravity, the operating comfort of the PNVG I was rated as better than the F-4949 (mean rating = 3.94, p. < 0.005). In the stowed position, ratings indicated greater comfort compared to the F-4949 (mean rating = 3.67, p. < 0.05). Stability of the PNVG I during head movements, G loading, and vibration was rated as slightly better than F-4949 (mean rating = 3.66, p. < 0.05). In some cases, the helmet was not custom fit to the pilot. Questions concerning PNVG I position and focus adjustability indicate that this is an area of design criticism. Both position and focus were rated as the "same" compared to F-4949. Peripheral vision around the PNVG I and the ability to look under the PNVG I to view cockpit instrumentation was rated as very similar to F-4949. The compatibility of the PNVG I with the use of a clear visor was rated as better than F-4949 compatibility (mean rating = 3.75, p. < 0.05). For pilot comments, please refer to Geiselman and Craig (1999). [3.]

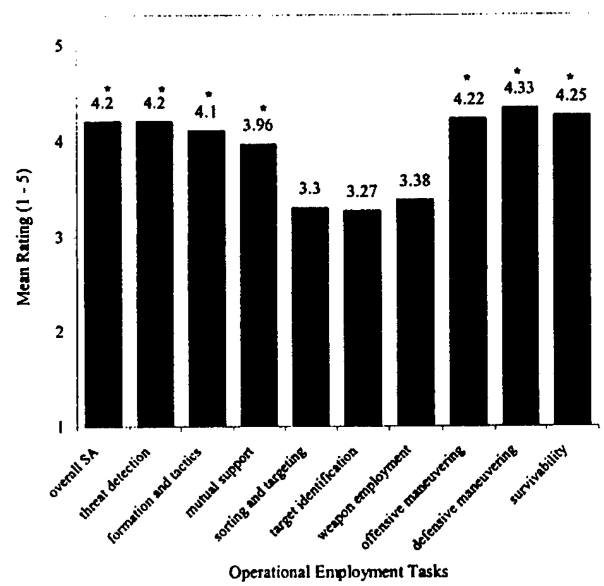


Figure 8. PNVG I ratings as a function of operational employment task

3.1.3 Cockpit/cockpit lighting compatibility

Cockpit clearance of the PNVG I was rated during scanning behavior. In the operational position, clearance was rated better with PNVG I than with F-4949 (mean rating = 3.81, p. = 0.01). In stowed position, clearance was similar that of the F-4949 (mean rating = 3.31, p. = 0.13). Cockpit display compatibility for PNVG I was rated as similar to F-4949. This was true also for HUD and NVIS lighting compatibility. PNVG I was rated as more compatible with "Christmas tree" lighting (mean rating = 4.14, p. = 0.01) than the F-4949.

3.1.4 Image Quality

Overall PNVG I image quality was rated as similar to F-4949 (mean rating = 3.47, p. = 0.13). Similar findings were recorded for a question addressing the ability to distinguish cultural (mean rating = 3.5, p. < 0.05) and terrain features (mean rating = 3.5, p. = 0.1). PNVG I image brightness acceptability was rated higher than F-4949 (mean rating = 3.59, p. = 0.007). Image brightness consistency across the tubes was indicated during 69% of the sorties. The acceptability of image noise for PNVG I was rated to be similar to F-4949.

3.1.5 Operational employment

Pilots reported that 5.5 G's could be sustained comfortably while using the PNVG I. The maximum reported G load across these test flights was 8.0. Pilots were asked if the PNVG I ever inadvertently came down from the stowed position during the flight. This occurred during 2 of the 16 flights (12.5%). The pilots reported that overall, SA was enhanced by the use of PNVG I compared to F-4949 (mean rating = 4.2, p. < 0.0001). Figure 8 shows the pilots' mean ratings comparing PNVG I and F-4949 across different tactical tasks. An "*" indicates statistical significance at the alpha < 0.01 level. PNVG I appears to have been most beneficial during threat detection, formation and tactics, offensive maneuvering, defensive maneuvering, and for survivability.

3.1.6 Overall comparison

Pilots were asked to rate the suitability of the PNVG I FOV compared to the F-4949 FOV. The results indicate that the pilots feel that the PNVG I FOV is very effective (mean rating = 4.66, p. < 0.00001). When asked to make an overall preference comparison of the PNVG I vs. F-4949, 15 of the 16 responses indicate a preference for PNVG I (93.33%).

3.1.7 Representative PNVG I positive comments

"I did not experience any eye strain or headaches." "A must have." "A-10's need these!" "Closer to face, better FOV rather obvious!" "Outer channels were focused much better (20/25)." "Had better SA awareness of my surroundings." "Easier to fly at lower altitudes." "Could spend more time scanning for bandits and watching where my flight path is." "Less forward CG when looking through."

3.1.8 Representative PNVG I negative comments

"Lack of adjustability." "The battery change out is unsat." "I lost a battery down inside the helmet cover when trying to change out!" "In order to see the HMD display, I had to have the right channels way over to the left (toward the center of my face)." "This caused me to lose the outer part of the right outer channel." "Need to adjust focus rings." "They are too hard to work with gloves on." "Need more play in the areas that we normally focus (infinity)." "The "bridge" that holds the goggle is worn and breaks loose at 6 g's or greater." "Requires me to reach up and snap it back into place." "More difficult to see inside the cockpit, especially under g's." "Very difficult to set up the radar while in turn." "Not as crisp." "Flimsy trapeze, tilt sags under G." "Adjustments not user friendly." "Had to lower seat 2 inches to get proper eye height relative to HUD." "Delicate innards exposed when removed from helmet for stowing."

3.2 C-5 / C-130 PNVG II evaluation

The following paragraphs present the questionnaire data collected to date. The information represents averages derived across all survey 21 respondents. It is indicated where feedback is specific to an aircraft type (C-5 or C-130). Statistical analyses (two-tailed t tests) were performed to determine if the recorded ratings differed reliably from a rating of 3 (a rating of 3 indicates that PNVG II and F-4949 performance was the same).

3.2.1 Descriptive information

Average duration of PNVG II experience during the C-130 and C-5 flights were 1.1 hours. Illumination conditions were described as low for all (25% moon or less) of the flights. Observed weather was described as clear for all of the flights.

3.2.2 Fit, function, and human factors ratings

Pilots found the PNVG II to be significantly less fatiguing compared to F-4949 (mean rating = 3.42, p. < 0.05). The ability to adjust PNVG II was rated as significantly worse compared to F-4949 (mean rating = 2.10, p. = 0.001). None of the other fit, function, and human factors ratings for PNVG II differed significantly from the same as F-4949. These questions included the ability to adjust the PNVG II with gloved hand: up/down, in/out, or diopter setting. Ease to don and doff PNVG II was rated as similar to F-4949. Also the same were overall comfort, comfort in the operational and stowed position, neck strain, helmet fit, compatibility with eyewear, stability under G, weight, balance, hot spots, integration with life support equipment, and the ability to detect the "battery weak" indicator.

3.2.3 Cockpit/cockpit lighting compatibility

For the questions asked, PNVG II and F-4949 were not rated as differing. The questions addressed the view below the PNVG II (to see controls and displays), the use of lapboards/notes/flight cards, and compatibility with cockpit lighting.

3.2.4 Image quality

Image quality of PNVG II was rated as greater than that of F-4949 (mean rating = 3.55, p. < 0.05). Field of view through PNVG II was rated as significantly greater than F-4949 (mean rating = 4.5, p. < 0.0001). The following ratings also indicated a preference for PNVG II: Response to cultural lighting (mean rating = 3.79, p. = 0.001), lack of blooming (mean rating = 3.65, p. = 0.011), lack of fogging (mean rating = 3.56, p. = 0.007), acceptability of image brightness (mean rating = 3.62, p. 0.004), acceptability of noise level (mean rating = 3.68, p. = 0.002), performance at low (moon < 25%) light levels (mean rating = 3.65, p. < 0.05), and performance when viewing cultural lighting (mean rating = 3.63, p. = 0.01). For the following, PNVG II performance was rated as no different than F-4949: Freedom from visual obstructions, near focus visual accommodation, far focus accommodation, and performance at high (moon > 25%) light levels.

3.2.5 Operational employment

The participants reported that overall, SA was enhanced by the use of PNVG II compared to F-4949 (mean rating = 4.1, p. < 0.0001). Figure 9 shows the mean ratings comparing PNVG II and F-4949 across different operational tasks. An "*" indicates statistical significance at alpha at least less than 0.01 level. PNVG II appears to have been most beneficial during threat detection, formation holding, and area clearing.

3.2.6 Overall comparison

Pilots were asked to rate the overall acceptability and desirability of the PNVG II system compared to the F-4949 NVG. The results indicate a strong preference for PNVG II (mean rating = 3.95, p. < 0.0001). Similarly, pilots were asked to rate the overall mission and task performance benefit of the PNVG II compared to the F-4949. Again, the PNVG II system was rated as most beneficial (mean rating = 4.0, p. < 0.0001).

3.2.7 Representative PNVG II positive comments

"The panoramic vision greatly increased mission capabilities by decreasing the amount of head movement required for the pilot to scan. This in turn reduced the amount of work." "Overall very impressive--much less time scanning, much more time spent looking--situation awareness dramatically increased." "PNVGs definitely enhance mission effectiveness. The peripheral vision alone is a dramatic capability enhancement. The battery pack incorporated into the PNVG is also nice." "Panoramic vision greatly increases SA and clearing ability."

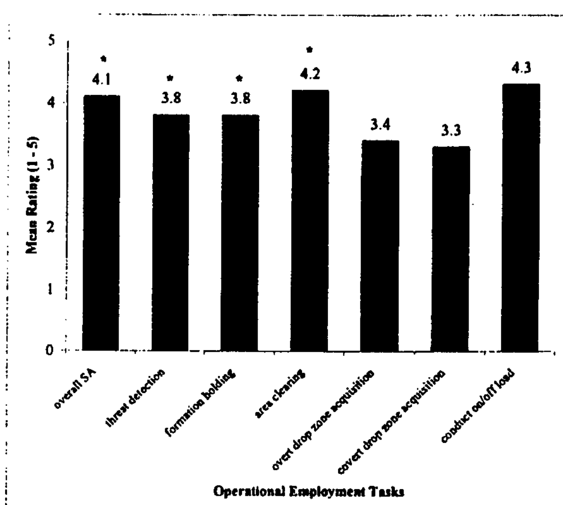


Figure 9. PNVG II ratings as a function of operational employment task

3.2.8 Representative PNVG II negative comments

"PNVGs need: wider range of focus. Outer tubes need focus ability, more field of view up and down would be nice too." "PNVG objective lens seem harder to adjust than 4949, the knobs are hard to turn. Very heavy when stowed. PNVG needs more near focusing for close up work (1 - 2 foot range)." "Suggest better focus on inner tubes and focus capability on outer tubes." "Also because you need the NVGs close to your eyes to eliminate the "lines" it makes viewing cockpit instruments difficult under the PNVGs compared to the 4949s."

4. OBJECTIVES FOR NEXT PHASE OF PNVG

The PNVG program is scheduled to complete source selection for the next phase in April 2000 to optimize the wide FOV concept and correct deficiencies identified in the current round of flight test. In addition, the Army has joined the team to complement the Air Force's effort to develop the next-generation PNVG. The preferred approach would be to develop one design to satisfy the mission requirements versus the current two-configuration approach. The next few paragraphs will summarize some of the key objectives of the next PNVG effort. [4.]

4.1 Wide Field-of-View

The current PNVGs were developed under the Small Business Innovative Research (SBIR) program that program did not perform trade studies to determine the optimal FOV. This next phase will review the literature and conduct trade studies to develop an optimal FOV design. The system will be required to have an instantaneous horizontal FOV $\geq$ 80 degrees with a binocular overlap $\geq$ 36 degrees, and a instantaneous vertical FOV $\geq$ 36 degrees.

4.2 Laser Eye Protection (LEP)

Laser threats to military aircrew are real with reports from foreign sources and the presence lasers are expected to grow on the battlefield. These incidents have raised concern for the health of aircrew eyes, for mission effectiveness, and for flight safety. This new contract will incorporate LEP technologies for protection of the human and the goggles. The designs will have to accommodate the latest LEP visor, spectacles, and light interference filters. Laser hardening of the image intensifier tube should be incorporated.

4.3 Fit/Comfort

The fit and comfort to the operator while wearing the PNVG will be examined. The PNVG will need to accommodate a diverse population of operators that will be flying in different mission environments with varying mission durations. Some of different items that will be considered in the design are weight and center of gravity (down and stowed positions), ease of mechanical adjustments, stability of the NVG/helmet to accommodate G loads and rapid head movements, cockpit compatibility, and adequate eye relief.

4.4 Image Quality

The device needs to have image quality equal to or better than NVGs delivered under the Army Omni V contract. Attributes for satisfying the requirement that need to be considered are the expected visual acuity (resolution) through the device for quarter moon and starlight light levels, signal-to-noise ratio, image tube halo, optical distortion, optical image alignment, system modulation transfer function (MTF - on axis and at edges of the field), eyepiece focus, eye position tolerance and effects on optical MTF, objective lens focus, and maximum image luminance. If partial overlap of visual fields is used to produce the wide FOV, the image discontinuity tolerances at the overlap should be addressed including image luminance uniformity, image magnification, rotation, distortion, and horizontal and vertical off-set.

4.5 Integrated Symbology/Imagery Display

The electronic interface needs to be extended from the current symbology overlay technique to include imagery insertion by using a light-valve or similar technology to block the NVG image during imagery display and single-channel miniature camera record. The inclusion of a full-color version of the miniature flat panel image source will also be considered. The

PNVG will provide the capability to remove/replace either or both the flat panel image source and the miniature camera in the field. The PNVG will remain mission capable as a separate functioning system with either or both functions removed. The instantaneous FOV provided for the imagery insertion should be compatible with current navigation-FLIR sensors. Compatibility with Joint Helmet Mounted Cueing System (JHMCS), VCATS, Air Warrior, and Land Warrior will be considered. Finally, the allocation of electronics between the PNVG device and its associated helmet vehicle interface module will be addressed with respect to its impact on operational use of the system.

4.6 Field Support

The device should be designed in order to minimize the need for any additional logistic support equipment. This means the design will allow field-level performance testing utilizing the ANV-126 Hoffman tester with little or no disassembly of the PNVG device or major modification to the tester. Adjustment knobs should be useable while wearing flight and chemical/biological gloves.

4.7 Ejection/Crash/Ground Egress Safety

Flight safety and environmental use have to be factored into the design. The following areas need to be examined in the performing of safety testing: Mertz criteria, Knox Box, USAARL curve, inertial properties testing, vertical impact testing, helmet impact testing, visor ballistics testing, helmet penetration testing, rapid and explosive decompression testing, ejection windblast testing, quick disconnect functionality, hanging harness testing, cockpit compatibility testing, electromagnetic compatibility testing, emergency ground egress testing, and electrical shock analysis.

4.8 Compatible with Existing Systems

The new system will need to be interoperable with existing systems. The items that need to be addressed are the helmet, oxygen mask, nuclear/biological/chemical masks, Aviator Night Vision Imaging System mount, survival vest, anti exposure suit, torso harness, aircrew spectacles, back style parachutes, and personal clothing.

4.9 - Ilities

The PNVG design must optimize reliability, maintainability, affordability, producibility and supportability. System and System sub-components should be capable of mass production while consistently maintaining pre-established standards. A design that requires only minimal maintenance is desirable. Pre or post-flight checkout and maintenance procedures should be kept to a minimum. Major components should be interchangeable if a two-configuration approach is adopted.

5. CONCLUSION

The PNVG feedback has been very positive and indicates that a 100-degree FOV significantly improves pilot performance across different operational tasks compared to the 40-degree F-4949. The significant increase in intensified FOV not only enhances mission effectiveness, but also gets us even closer to our goal of being able to do daytime-like tactics at night. This pilot feedback is not complete though. Additional flights on F-15s as well as other aircraft are planned and will be used for further evaluation. Suggested areas for PNVG improvements will be addressed in an upcoming follow-on advanced technology demonstration program.

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Design, Development, Fabrication, and Safety-of-Flight Testing of a Panoramic Night Vision Goggle

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ABSTRACT

A novel approach to significantly increasing the field of view (FOV) of night vision goggles (NVGs) has been developed. This approach uses four image intensifier tubes instead of the usual two to produce a 100 degree wide FOV. A conceptual demonstrator device was fabricated in November 1995 and limited flight evaluations were performed. Further development of this approach continues with eleven advanced technology demonstrators delivered in March 1999 that feature five different design configurations. Some of the units will be earmarked for ejection seat equipped aircraft due to their low profile design allowing the goggle to be retained safely during and after ejection. Other deliverables will be more traditional in design approach and lends itself to transport and helicopter aircraft as well as ground personnel. Extensive safety-of-flight testing has been accomplished as a precursor to the F-15C operational utility evaluation flight testing at Nellis AFB that began in March 1999.

Keywords: Night vision goggle, helmet-mounted display, image intensification, field of view, night operations, head-up display, safety-of-flight, flight safety, windblast testing, aircraft ejection

1. INTRODUCTION

Delivery of the conceptual demonstrator device, now referred to as the panoramic night vision goggle (PNVG), was quite impressive considering it was developed with very limited funding under a phase I small business innovative research (SBIR) program with Night Vision Corporation. The extremely positive feedback of this demonstrator from the warfighter community propelled the program into a phase II SBIR effort and also received the attention and supplemental funding support of the Air Force Research Laboratory's Helmet-Mounted Sensory Technologies program office. Phase II will further develop the PNVG by first addressing ejection seat aircraft with two configurations of a low profile design (designated PNVG I, Figure 1). This version with its better center of gravity should be less fatiguing during longer flights and will potentially allow for ejection by permitting retention of the system on the head throughout the ejection sequence. Retention of PNVG I may also permit evasion and rescue. Additionally, three configurations of a never-before-seen NVG for transports, helicopters, and ground personnel (designated PNVG II) are being developed. These models will look more like a traditional goggle. PNVG II, while weighing more than a PNVG I, should be more robust and will attach to any existing ANVIS mounting system. Both PNVG I and II, like the phase I conceptual demonstrator, will provide a 100 degree horizontal by 40 degree vertical (100° H X 40° V) intensified field of view (FOV) (Figure 2a). This represents a 160% increase of the warfighter's intensified image FOV compared to currently fielded 40° circular FOV systems.

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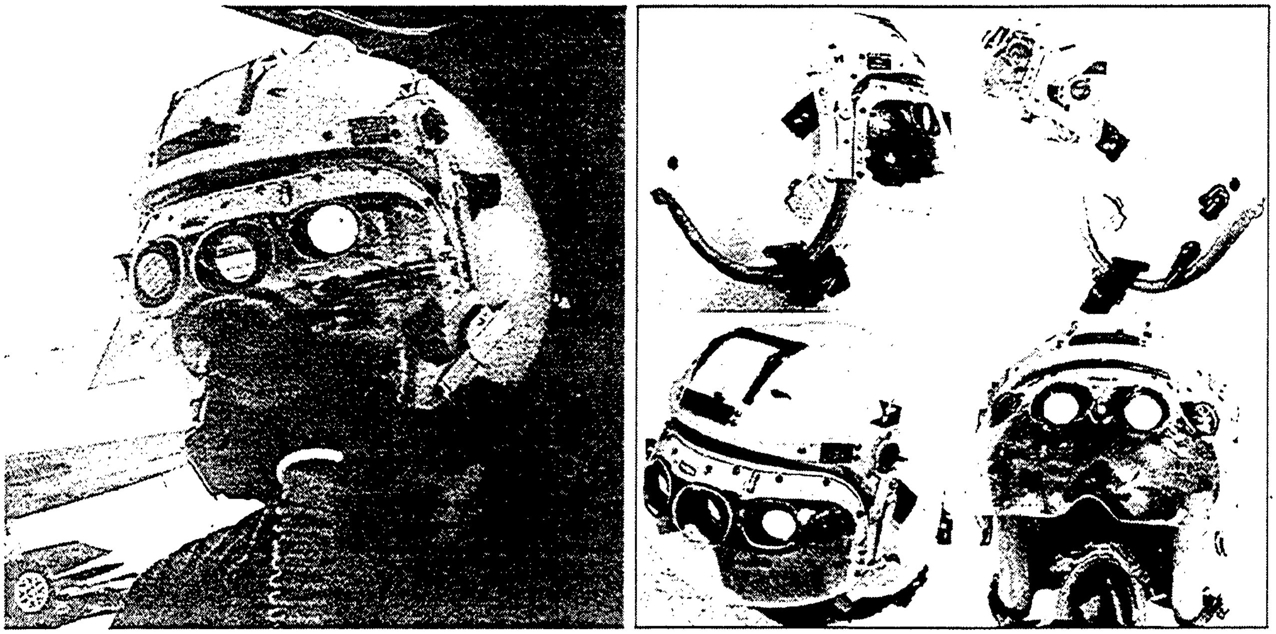


Figure 1. PNVG I, low profile design (Patent # 5,416,315. Other patents pending)

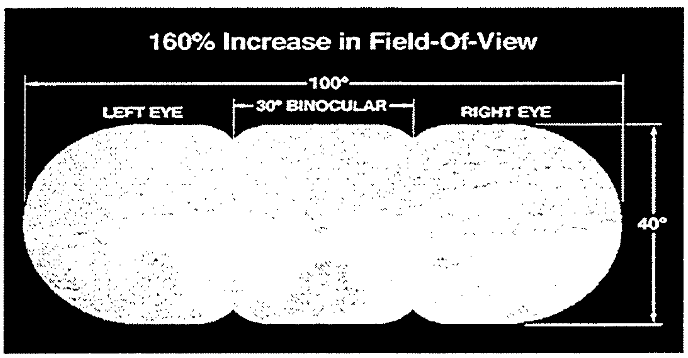


Figure 2a. Simulated PNVG 100°H x 40°V FOV

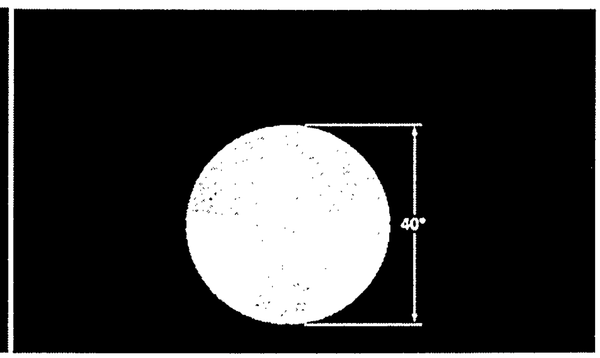


Figure 2b. Simulated 40° AN/AVS-6 and AN/AVS-9 FOV

2. BACKGROUND

NVGs with FOVs ranging from 30° (GEC-Marconi Avionics' Cat's Eyes NVGs) to 45° (GEC-Marconi Avionics' NITE-OP and NITE-Bird NVGs) have been used in military aviation for more than 20 years. The vast majority of NVGs (AN/AVS-6 and AN/AVS-9) provide a 40° FOV (Figure 2b). Because each ocular uses only a single image intensifier tube, increased FOV for these NVGs can only be obtained at the expense of resolution.[1,2] The image intensifier tube has a fixed number of pixels (picture elements). Therefore, if the pixels are spread over a larger FOV, the angular subtense per pixel increases proportionally. As a result, resolution is reduced.

An extensive survey of military (U.S. Air Force) NVG users conducted during 1992 and 1993 revealed that increased FOV was the number one enhancement most desired by aircrew members followed closely by resolution.[3] This was a major motivating factor for the development of an enhanced NVG capability.

3. PNVG I DESCRIPTION

PNVG I (Figure 1) is similar in design approach to the conceptual demonstrator PNVG. However, PNVG I has optimized the overall design and added several enhancements. PNVG I still features a partial overlap (100° H X approximately 40° V) intensified FOV. The central 30° H X 40° V FOV remains completely binocular while the right 35° is visible only to the right eye and the left 35° is visible only to the left eye. Additionally, a thin demarcation line separates the binocular image from the monocular peripheral image.

PNVG I features a newly developed 16-mm image intensifier tube rather than the currently fielded 18-mm format tube. Along with the goal of offering comparable performance to the recent Omni IV tubes, its weight will be reduced by nearly 50%. Therefore, four 16-mm PNVG tubes weigh about the same as two of the current 18-mm tubes. The 16-mm tubes have longer fiber optics on the outside optical channel than the inner optical channel. The outer and inner channel fiber optics do not require image-inverting fiber optics. Dual fixed eyepieces (tilted and fused) and four objective lenses (the inner two adjustable and the outer two fixed) make up part of the folded optical approach. The inner optical channels include very fast F/1.17 objective lenses as compared with the F/1.25 objective lenses of the currently fielded AN/AVS-6 and AN/AVS-9 goggles. The outboard channels, due to size and weight constraints, incorporate F/1.30 objective lenses. All of the objective lenses will incorporate Class B, leaky green filters for compatibility with color cockpits and aircraft head-up displays. Eyepiece effective focal length is 24 mm while the physical eye clearance has been designed for 20 mm.

A specially designed single left side and single right side power supply is remotely located but allows each side's inner and outer optical channels to be controlled independently. Multiple adjustments (i.e. tilt, independent inter-pupilary distance, up/down, and fore/aft) should permit an optimized optical fitting. Customized visors will also be incorporated cockpit compatibility, mechanical stability, and escape protection. Individualized holes will be cut for the objective lenses to protrude. Also, a unique latching mechanism affords one-handed don/doff capability. A new linkage system enables the PNVG I to easily transition into a stow position (Figure 3).

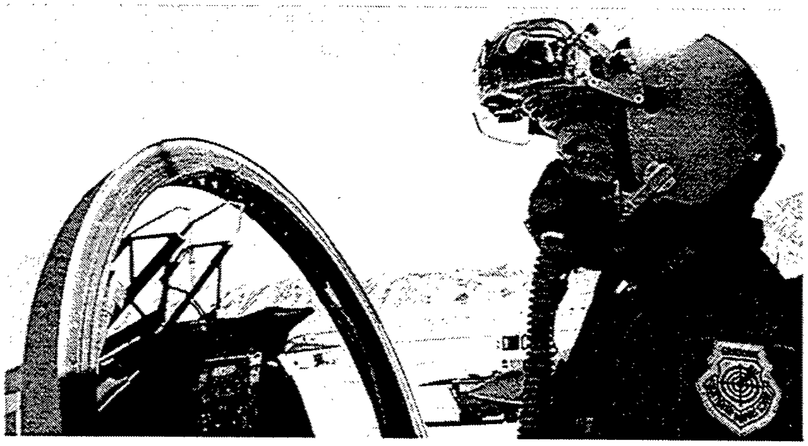


Figure 3. PNVG I, stow position (Patent # 5,416,315, other patents pending)

Power on certain aircraft test platforms is provided to the PNVG system by the aircraft itself. In the event of an ejection, two "AAA" alkaline batteries located in the remote electronics module (REM) provide power during the escape sequence, evasion, and rescue. These batteries provide up to 16 hours of operation. Due to funding constraints, PNVG I is currently designed to attach with only the Air Force's HGU-55/P helmet.

Two configurations of the PNVG I will be built. PNVG I-Configuration 1, will have four deliverables. The PNVG REM will attach to a unique "universal connector", the same connector used with the Visually Coupled Acquisition and Targeting System (VCATS) daytime helmet module. VCATS is currently being evaluated on F-15C aircraft as part of an advanced technology demonstration (ATD) at the 422nd Test and Evaluation Squadron (422 TES) at Nellis AFB. The universal connector provides aircraft data and power to the PNVG. This configuration also features a 640x480 active matrix electroluminescent display (AMEL) for symbology overlay, a magnetic head-tracker, class B "leaky green" objective lens filter, and an electronics package. PNVG I-Configuration 2, a stripped down version of Configuration 1, will have two

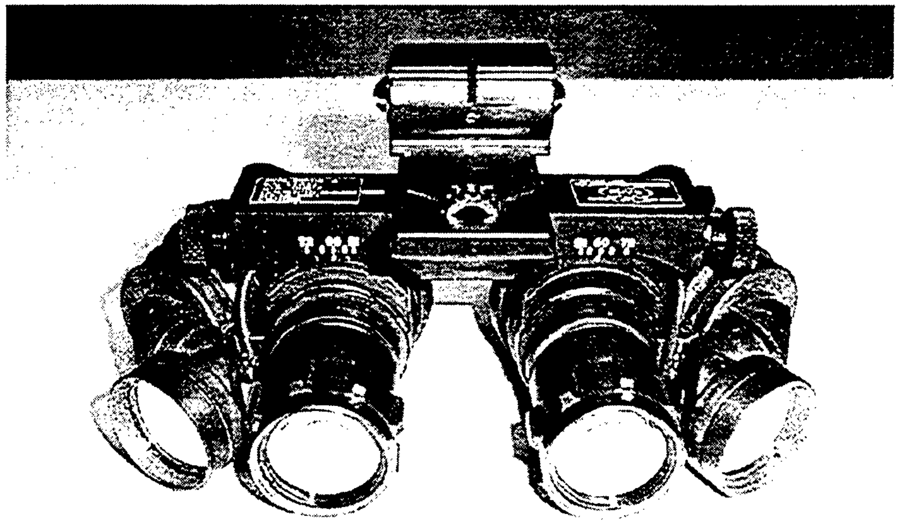


Figure 4. PNVG II (Patent # 5,416,315, other patents pending)

deliverables. Configuration 2 does not include an AMEL display, magnetic head-tracker, or electronics package. Since the majority of the HGU-55/P helmets are not equipped with the VCATS universal connector, a special banana clip mount has been designed that will accept the PNVG module on any HGU-55/P helmet. Because there is no aircraft power being provided through a universal connector for configuration 2, system power will be supplied by the two "AAA" alkaline batteries located in the REM.

4. PNVG II DESCRIPTION

An alternative approach to PNVG I has been developed. The partial overlap 100° H X 40° V intensified FOV is maintained, but the system resembles the currently fielded aviator NVGs.[4] Whereas PNVG I mates to only the HGU-55/P helmet, PNVG II (figure 4) is compatible with any helmet that incorporates the standard ANVIS mounting bracket. This will allow any warfighter to assess the utility of a panoramic night vision scene given they have the proper bracket. If testing proves that the panoramic scene is required but the PNVG I approach is preferred, a development effort will have to address the specific design issues necessary to mate it with a particular helmet type.

Similar to the PNVG I, the central 30° H X 40° V FOV is completely binocular while the right 35° is visible only to the right eye and the left 35° is visible only to the left eye. Additionally, like PNVG I, a thin demarcation line separates the binocular image from the outside monocular image. PNVG II utilizes the newly developed 16-mm image intensifier tube but requires image inverting fiber optics (the outer channel fiber optics are the same length as the inner channel). Dual fixed eyepieces, tilted and fused together, and four objective lenses (the inner two adjustable and the outer two fixed) remain part of the optical approach. The non-folded inner optical channels are designed with extremely fast F/1.05 objective lenses. The folded outboard channels use the PNVG I inner channel optics with F/1.17 objective lenses. Eyepiece effective focal length is 24 mm while the physical eye clearance has been significantly increased to 27 mm. All of the mechanical adjustments currently available on the AN/AVS-6 and AN/AVS-9 remain (i.e. tilt, independent inter-pupilary distance adjustment, up/down, fore/aft). Power for the PNVG II will be provided via the batteries that are currently integrated with the AN/AVS-6 and AN/AVS-9 mounting systems. Therefore, no special power provisions are necessary.

Three configurations of PNVG II will be built. PNVG II-Configuration 3 will have only one deliverable but will feature a 640x480 AMEL display. Additionally it will have a Class B, leaky green filter incorporated into the objective lens. PNVG II-Configuration 4 will have three deliverables but will not include the AMEL display. One of the three will use the Class B "leaky green" filter, while the remaining two will use a Class A filter. The final deliverable, PNVG II-Configuration 5, is intended for ground applications and will be integrated to a special hand-held "PIRATE" mounting system including its own batteries and a single infrared diode. This configuration will not include an AMEL display and the objective lens will be unfiltered (i.e. no class A or B filters).

5. SAFETY-OF-FLIGHT-TESTING AND ANALYSIS

5.1 Overview

Safety-of-flight testing and analysis for advanced fighter helmets involves many different test and analysis areas. The AFRL team investigated seventeen of these areas for PNVG I-configuration 1, which began OUE flight testing on F-15C aircraft in March 1999. See Table 1 for a summarized listing of the areas. The following sections detail the outcome of these test and analysis. A System Safety Executive Board (SSEB) was convened at Wright-Patterson AFB, Ohio on 6 January 1999 to evaluate the results. The SSEB gave its approval for limited flight testing of the PNVG I at Nellis AFB, Nevada on the F-15C fighter. Then, a flight readiness review was convened at Nellis AFB in late January 1999 to brief the details to the flight safety officer, who makes the ultimate decision to fly the new advanced NVG helmet system.

For more detail on safety-of-flight testing, there are several SPIE papers that contain useful information. A paper by MacMillan, Brown, and Wiley describes the process in detail for performing safety-of-flight testing for advanced fighter helmets.[5] Another paper by Wiley, Brown, and MacMillan provides details on safety during ejection.[6] Lastly, a paper by MacMillan discusses the complications behind determining neck loading experienced during ejection, with particular emphasis on the combination of windblast and catapult forces.[7]

Table 1. Summary of PNVG safety-of-flight testing and analysis

Inertial Properties Testing	Weight, center of gravity, and static torque effects on neck loading
Vertical Impact Testing	Effects of catapult phase of ejection on neck and shoulder loading
Helmet Impact Testing	Protection provided by helmet shell and liner against high G impacts
Visor Ballistics Testing	Protection provided by helmet visor against small projectiles traveling up to 550 fps
Helmet Penetration Testing	Protection provided by helmet shell and liner against penetrations
Rapid and Explosive Decompression Testing	Performance of the PNVG in a rapidly changing atmosphere and an explosively changing atmosphere, such as canopy jettison during ejection
Ejection Windblast Testing	Effects of windblast phase of ejection on neck loading, contact of the PNVG with the eyes, structural integrity of the PNVG, and proper functioning of ACES II pitot tubes
Quick Disconnect Functionality	Effect of cable tether on safe separation from the aircraft during ejection
Comfort	General comfort and fit with no hot spots during prolonged wear of PNVG system
Communications and Sound Attenuation	Ability to communicate effectively and have external sound attenuated to appropriate safe levels
Hanging Harness Testing	Investigates possible interference with risers and pilot's ability to carry out the descent checklist, including landing procedures
Cockpit Compatibility Testing	Affect on performing flying mission safely, limits on range of motion, viewing flight instruments, stow position clearance, and canopy clearance of PNVG compared to breaker
Electromagnetic Compatibility Testing	Affect of electromagnetic emissions from the PNVG on its own systems and other systems, and the affect of other systems emission on the PNVG, with particular emphasis on flight instrument safety
Emergency Ground Egress Testing	Ensure PNVG does not interfere with pilot's ability to quickly exit the aircraft during emergency egress while on the ground with open canopy
Electrical Shock Analysis	Ensures the addition of an electrical assembly to the helmet does not impose an excessive risk of electrical shock to the pilot during normal flight operations and even conditions such as ejecting into water
Optical Performance Testing	Ensures the pilot can see accurately and without distortion when operating the aircraft and wearing the PNVG; also quantifies performance of PNVG
Symbology Analysis	Identifies any symbology issues that my cause disorientation to the pilot

5.2 Inertial Properties Testing

The PNVG helmet system's inertial property data for center of gravity (CG), weight, and static torque meets the AFRL Head and Neck Criteria.[8] This testing was completed in November 1998 by the AFRL Biodynamics and Acceleration Branch (AFRL/HEPA) at Wright-Patterson AFB, Ohio. The PNVG center of gravity data (cgx = 0.23 in., cgy = -0.01 in., cgz = 1.20 in.) is within the AFRL Head and Neck Criteria's Knox box (cgx = -0.8 to 0.25 in., cgy = -0.15 to 0.15 in., cgz = 0.5 to 1.5 in.). This Knox box was developed by Dr. Ted Knox to provide a means for determining the safety of helmets with respect to neck loading during the catapult phase of ejection.[8] In addition to CG effects, the overall head-supported weight (including the helmet system with six inches of signal and power cable and the MBU-20/P oxygen mask with 3 inches of hose) exceeded the 5.0 lb. criteria by 0.31 lb. However, an analysis of vertical impact testing data by Mr. Chris E. Perry of AFRL/HEPA showed this only increased the compressive neck load by less than 5%, which is well under maximum safe limits.[9] Therefore, the overall head-supported weight of PNVG does not seem to cause any safety concerns. In addition, the static torque value of 93 lb-in^2 was well under the safe criteria of 120 lb-in^2 for maximum static torque.

5.3 Vertical Impact Testing

The AFRL/HEPA evaluated effects of inertial property differences of PNVG as compared to a baseline HGU-55/P in October 1998.[9] They performed testing using the AFRL vertical deceleration tower to simulate an 11-12 G catapult shock on an Advanced Dynamic Anthropomorphic Manikin (ADAM) (Figure 5b). Five vertical deceleration tests were performed for both the HGU-55/P helmet as well as the PNVG I system. Testing showed that PNVG does not increase the risk of injury during the catapult phase of ejection with an ACES II seat. PNVG will not induce neck loads greater than established human tolerance (Table 2). Dynamic evaluation also found no structural failures to PNVG mounting points.

Table 2. Vertical impact testing results

Load Parameter	Baseline HGU-55/P Helmet	PNVG Helmet	Criteria
(-) X-Axis Shoulder Load (lb)	−82.90 ± 13.74	−93.07 ± 22.65	N/A
(-) X-Axis Neck Load (lb)	−40.07 ± 2.58	−57.11 ± 1.38	80
(+) X-Axis Neck Load (lb)	27.60 ± 2.85	27.87 ± 2.89	80
Z-Axis Neck Load (lb)	165.44 ± 8.68	213.04 ± 3.07	260
Neck Moment (in-lb)	130.17 ± 4.76	152.12 ± 13.89	400
Neck Moment (in-lb) *	294.37	333.79	400
* ADAM data was converted to estimated human data for neck moment. Note, for other types of loading, this conversion is not necessary.			

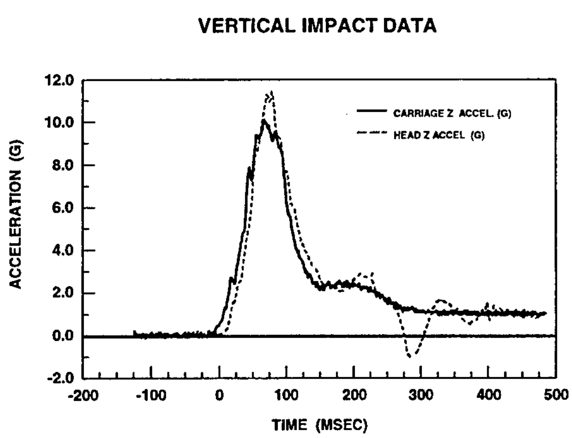


Figure 5a. Vertical impact acceleration response

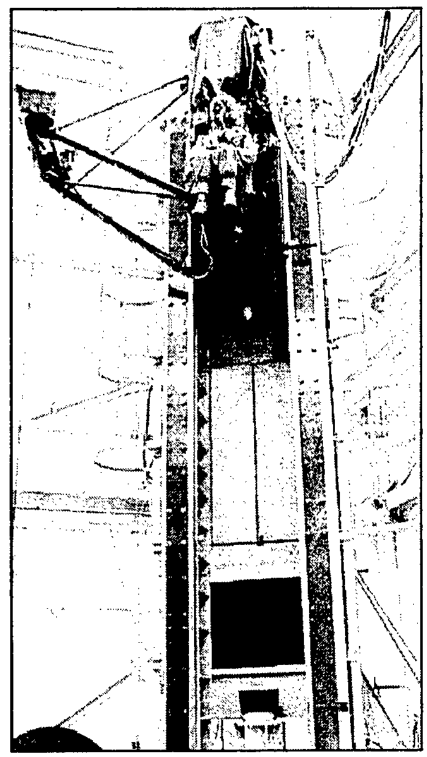


Figure 5b. Vertical impact tower

5.4 Helmet Impact Testing

Helmet impact testing was performed at Gentex East in Carbondale, Pennsylvania in November 1998. The PNVG helmet system provides adequate impact energy attenuation by meeting the HGU-55/P helmet specification MIL-H-87174, showing that the addition of the PNVG components to the baseline helmet do not increase the pilot's risk of injury from impact.[10] The PNVG system allowed the pilot's head to be subjected to a maximum G load of only 134 G's. The military specification requirement is less than 400 G instantaneous, less than 200 G for 3 ms or less, and less than 150 G for 6 ms or less.[10]

5.5 Visor Ballistics Testing

Visor ballistics testing was also performed at Gentex East in Carbondale, Pennsylvania in November 1998. The PNVG helmet visor provides adequate projectile fragment protection by meeting the HGU-55/P helmet visor specification MIL-V-43511C, showing that the clear visor does not allow any penetration from the specified 0.22 caliber T37 fragment simulating projectile at 550 fps, nor does the impact cause cracks on the visor.[11] The test was conducted in accordance with MIL-STD-622. The test is formally known as the "impact resistance" test, while Gentex refers to it as the "ballistics" test.

5.6 Helmet Penetration Testing

In addition to impact and ballistics, penetration testing was also performed at Gentex East in Carbondale, Pennsylvania in November 1998. The PNVG helmet system meets the HGU-55/P helmet specification MIL-H-87174, showing that the addition of the PNVG components to the baseline helmet do not increase the pilot's risk of injury from penetration.[10] The PNVG system allowed a maximum penetration depth of 1/16th of an inch, while the requirement is less than 1/4th of an inch.

5.7 Rapid and Explosive Decompression Testing

National Technical Systems completed rapid decompression testing in December 1998. The PNVG helmet system passed all safety and operational criteria with no exceptions during the rapid decompression testing at NTS in Saugus, CA. These tests were tailored from rapid decompression test procedures in MIL-STD-810E, indicates the goggle is safe up to 50,000 feet, in the event of a rapid (60-seconds) decompression. Two tests were performed: (1) decompression from 8k feet to 22k feet in 44 sec, and (2) decompression from 25k feet to 50k feet in 59 sec. These times and pressures were chosen due to the nature of the flight testing at Nellis. In both tests, the PNVG integrity was maintained. No visible structural damage to the PNVG was evidenced nor was there any internal damage visible by looking through the lenses. Nothing came off the PNVG during either test. The PNVG operated flawlessly both before and after the tests and was left on during the tests. Also, there was no movement of the focus rings or eyepieces. These tests were considered a complete success.

In addition to this rapid decompression testing, an explosive decompression test of 1k feet to 17k feet and 1k feet to 8k feet within 10 ms was successfully performed in March 1999 at Wright-Patterson AFB, Ohio. An explosive decompression can occur when ejecting during canopy jettison or during an mid-air accident.

5.8 Ejection Windblast Testing

Windblast testing was completed at Dayton T. Brown in October 1998. Testing was performed at 350, 450, and 600 KEAS at both the 17 and 34.5 degree seatback angles. Compared to the baseline HGU-55/P helmet (with the integrated chin-nape strap (ICNS) and bungee visor), Mertz criteria evaluation indicates that PNVG does not increase the risk of neck injury to the pilot during the windblast phase of ejection up to 600 KEAS. This is for ejection using an ACES II seat for both 17- and 34.5-degrees seatback angle. Overall, PNVG and HGU-55/P (with ICNS and bungee visor) have very similar neck loading, with PNVG actually performing better than HGU-55/P at some speeds, likely due to a more favorable aerodynamic shape.

Considering peak neck loads only (no duration of load consideration), the probability of neck injury during an ejection while wearing PNVG is: 9.91% at 350 KEAS, 21.4% at 450 KEAS, and 41% at 600 KEAS. This is identical to the baseline HGU-55/P (with ICNS and bungee visor). Note the standard breakaway chinstrap helmet has the same probability of injury at 600 KEAS as it does at 450 KEAS (21.4%). This is because the pilot looses the protection of the helmet around 300 pounds of axial neck loading. All of this probability data is for 17-degree seatback angle only. One can factor in the USAF non-combat ejection history, which is a distribution of ejections at various speeds (Figure 6). This gives an overall probability of neck injury, given an ejection occurs when flying with PNVG within a certain flight envelop (Table 2). Note that 90% of all USAF non-combat ejections occur below 400 KEAS. Also note, the table shows results for VCATS Uplook advanced flight helmet as well as the HGU-55/P (with ICNS and standard bungee visor).

However, at a 17-degrees seatback angle, the PNVG interrupts airflow enough to cause marginal pitot tube compatibility, therefore, warranting the use of deployable pitot tubes (Figure 7). The F-15Cs that will be used for PNVG testing at Nellis are equipped with deployable pitots.

The PNVG helmet system only experienced minor (tiny cracks) structural damage during windblasts up to 600 knots equivalent airspeed (KEAS), which would add no risk of injury to the pilot. Windblast testing did uncover a problem with the universal connector latch handle popping up due to forces during the blast, resulting in a re-design of this handle that fixed the problem. This new handle was re-tested and stayed latched throughout the blast. During the eleven windblast tests at speeds from 350 to 600 KEAS, at no time did any part of the PNVG system come into contact with the pilot's eyes. While the power supplies and eyepieces did contact the forehead, this contact was deemed to be low risk due to the smooth, curved shape of these pieces and the relatively large contact area.

Figure 6. USAF ejection history

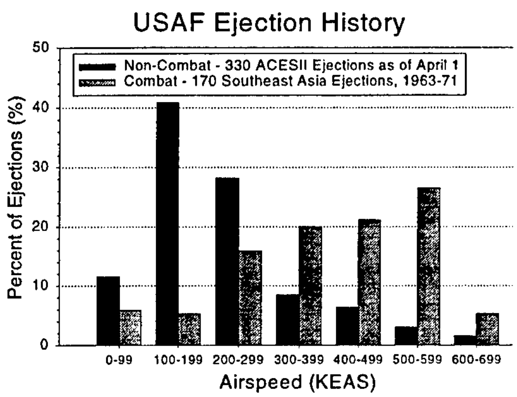
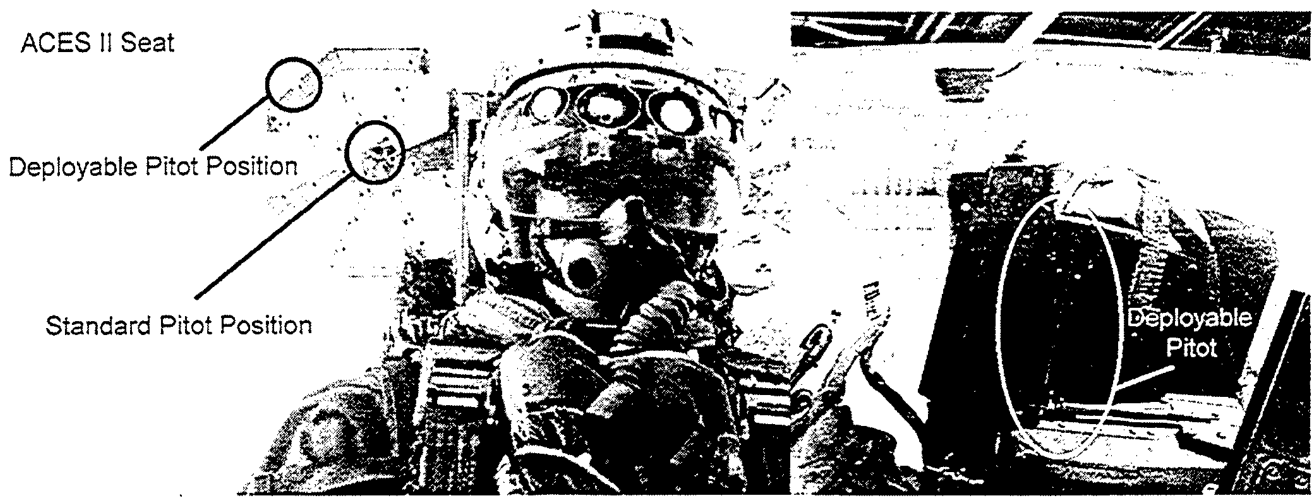


Table 2. PNVG windblast testing results using probability of neck injury, given pilot ejects within certain flight envelope

Probability of Injury (%) for certain flight envelope			
Flight Envelope (KEAS)	**PNVG**	**VCATS Uplook**	**HGU-55/P With ICNS**
< 700	**1.10**	**7.57**	**1.17**
< 600	0.69	6.53	0.92
< 500	0.33	4.95	0.62
< 400	0.08	2.88	0.31



(a) (b)

Figure 7. Windblast testing of PNVG I with pitot tube positions noted. Note, the picture on the left (a) is of the windblast test apparatus and manikin, showing the pressure-sensing rake array or "Mickey Mouse" ears. The picture on the right (b) shows an actual F-15C ACES II seat fitted with the deployable pitot tube.

5.9 Quick Disconnect Functionality Testing

Quick disconnect connector (QDC) functionality testing was performed at Reynolds Industries, Inc. in October 1996. PNVG test pilots will utilize the same helmet, and hence the same cable connection to the aircraft as the VCATS helmet. The cable connection electrically connects the helmet to the aircraft and has a QDC. The QDC will safely disconnect at speeds up to 240 in/sec without significantly increasing the potential risk of injury to the pilot's neck or head. The placement of the QDC at the left side, lower torso minimizes the risk of injury to the pilot's arms and legs. The peak separation force was shown to be less than 54 pounds (typically 30 lb.) in all cases, different pull speeds (quasi-static and 240 in/sec) and angles (straight, 15 degrees forward, and 15 degrees aft). In all cases during emergency egress, there is minimal risk of injury to pilot due to the QDC.

5.10 Comfort Analysis

PNVG helmets are not expected to cause hot spots or other discomfort to the pilot after periods of prolonged wear (4 hours). 422 TES pilots will utilize the same helmets currently used for VCATS testing, which is the Gentex Lightweight HGU-55/P. VCATS uses a thermoplastic liner (TPL) fitting scheme with a minimum of 2 layers and custom poured energy absorbing liner (EAL) to ensure a good fit and comfort. The EAL uses a 6-lb/ft^2 material rather the standard 4.5-lb/ft^2 material. Internal dimensions of VCATS helmets versus the standard operational HGU-55/P helmet are reduced by no more than 0.10 inches, which can be made up by removing one TPL layer.

5.11 Communication and Sound Attenuation Analysis

The PNVG helmet system should also meet minimum sound attenuation requirements to ensure pilot communication is not hindered during flying operations. PNVG test pilots will utilize the same helmets currently used for VCATS testing, which have been successfully used for several years. VCATS uses the H154 earcup. Sound attenuation requirements for the Air Force are outlined in the specification for the H154 earcup (MIL-E-83425). However, no "VCATS specific" testing was performed because the H154 earcup is standard issue and meets USAF requirements for sound attenuation. Flight test experience from VCATS and Vista Sabre II HMDs (Kaiser Mark-III and Mark-IV) have revealed no sound attenuation or communication problems with the Kaiser Lightweight HGU-55/A/P helmet shell and H154 earcup.

5.12 Hanging Harness Testing

Hanging harness testing was completed at Ohio Air National Guard's 162nd Fighter Squadron on 5 January 1999 (Figure 8). This test investigated any possible riser interference and the pilot's ability to carry out the descent checklist, including landing procedures. The test indicated there are no significant concerns for a pilot completing the post ejection procedures checklist while under the canopy during decent and during the parachute landing fall. In addition, PNVG test pilots will utilize the same helmet as VCATS, and hence the same cable connection to the aircraft. Hanging harness testing was previously performed successfully for VCATS on 23 August 1995, revealing no problems. It should be noted that because the pilot would be ejecting at night while wearing the PNVG, he/she would be much safer with this NVG capability retained than without it. The practice for standard NVGs is to remove them prior to ejection, while the PNVG was designed to stay on during ejection. Having the ability to see the ground and your canopy significantly reduces risk during a nighttime ejection.

Figure 8. Hanging harness testing of PNVG I

5.13 Cockpit compatibility Testing

The PNVG helmet was tested for F-15C cockpit compatibility at Nellis AFB, 422 TES in January 1999. This test investigated the affect of PNVG on performing the flying mission safely, range of motion, and viewing flight instruments. The test also checked stow position clearance and canopy clearance of PNVG system versus canopy breaker position during ejection. The test was performed in a darkened hangar with a fully operational PNVG. Changes and additions to the baseline helmet system were found to not interfere with the pilot's ability to perform the flying mission. The pilot's range of motion in the cockpit is not limited by PNVG's increased helmet bulk or electrical harness routing in such a way as to cause compatibility problems. This testing was performed with the PNVG down and also flipped up in the stow position. The pilot was able to see all of the flight instruments without obstruction and was able to safely perform all standard procedures in a timely manner. It was noted, however, that the bottom edge of the PNVG visor needs to be custom trimmed for each pilot so that it does not cut through the view of the cockpit instrument panel. An improperly trimmed visor can cause annoying discontinuities that tend to reflect light from the head-up or head-down displays into the pilot's eyes.

With PNVG in down position, the HMD module does not protrude above the baseline HGU-55/P in such a way that it contacts the canopy before the canopy breaker does even for the maximum sitting height pilots. With PNVG in the stow position, it can contact the canopy before the breaker does for taller pilots. However, the PNVG latching mechanism, which holds the goggles in the up position, is designed to break away due to a 6 G or more catapult force in a controlled manner to allow PNVG to come down and lock into position before the pilot's head enters the wind stream.

In general, the best cockpit compatibility data is taken from actual pilots flying with the PNVG, which is the point of the operational utility evaluation. From a safety standpoint, basic information can be gained by analysis on the ground in a real cockpit inside of hangar, such as was described above. Another tool that can be useful is a physically realistic flight simulator.

5.14 Electromagnetic Compatibility Testing

The PNVG helmet was tested for F-15C electromagnetic compatibility both at Boeing in St. Louis and at Nellis AFB at the 422 TES in January 1999. The Boeing testing was performed using an electromagnetic interference chamber, while the Nellis AFB testing was performed in a powered up F-15C cockpit with an operational PNVG. The pilot performed a checklist verifying all cockpit instruments were functioning properly. This testing took into account guidance from MIL-STD-461 (Requirements for the control of electromagnetic interference emissions and susceptibility), MIL-STD-462 (Measurement of electromagnetic interference characteristics), and MIL-STD-464 (Electromagnetic environmental effects, requirements for systems). In all tests, no significant problems were discovered.

5.15 Emergency Ground Egress Testing

Emergency ground egress testing was performed at Nellis AFB, Nevada in January 1999 using both a ground egress trainer and an operational F-15C inside of a hangar (Figure 9). The addition of PNVG to the helmet system will add extra cables to the pilot's head that become entangled or snagged as the pilot attempts to perform an emergency egress. This test ensured that PNVG does not interfere with pilot's ability to exit the aircraft during emergency egress while on the ground with open canopy. Additionally, the quick disconnect must also reliably separate during ground egress with the pilot making no manual disconnects. This test was performed with PNVG in the stow position. It was noticed that the PNVG could possibly snag the forward canopy hook unless the pilot carefully maneuvers around it.

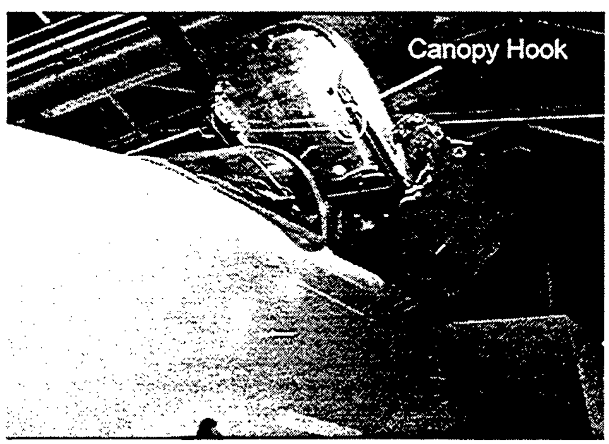


Figure 9. Emergency egress testing of PNVG I (note forward canopy hook can snag PNVG)

5.16 Electrical Shock Analysis

The addition of an electrical assembly to the helmet must not impose an excessive risk of electrical shock to the pilot during normal flight operations and even conditions such as ejecting into water. A preliminary electrical shock analysis has been performed at Wright-Patterson AFB, Ohio, which has identified some areas that need to be investigated more closely. These areas include the remoted power supply connection and exposed circuit boards and flex circuitry. In Phase III of the program, Night Vision Corporation shall perform a more detailed analysis.

The PNVG uses relatively low voltage (less than 12 volts DC) connections from the aircraft to the pilot through the wiring harness. The VCATS program has proven the safety of this harness through many successful flight hours. In fact, the PNVG should actually be safer than VCATS, because it does not use a high voltage connection from the aircraft power.

Inside of the helmet, Module IV flex cables are routed between the helmet shell and the protective EAL, thus minimizing the risk of electrical shock. The universal connector has several fail-safe mechanisms engineered into it to prevent inadvertent electrical shock. In addition, the display controller is coated with a spray-on non-conducting conformal coating to both protect the electronics and add safety. Also, voltages and power in the controller should be low enough to not cause any significant risk to the pilot.

The Image Intensifier Tube (IIT) power supplies on the PNVG helmet module are separated from the IITs by a few inches, and four insulated wires connect each of the two IITs. However, this power supply is only driven with 3 volts at a maximum of 60 milliamps. This means that the device uses a maximum of 180 milliwatts, which should be of little safety concern. Epoxy potting insulation on both ends of these wires provides protection and keeps out moisture. If aircraft power is not present, only the goggle power supplies receive their 3-volt DC supply from two AAA alkaline batteries.

5.17 Optical Performance Testing

The optical performance of the PNVG is extremely important for safety-of-flight certification. Internal laboratory testing of the PNVG unit was performed in early January 1999 at the AFRL Night Vision Operation Laboratory. This analysis revealed the PNVG has similar optical performance when compared to the standard F4949 NVG. Additional testing is necessary to verify these preliminary results, which is why no performance numbers are presented in this paper.

5.18 Symbology Analysis

The PNVG displays flight symbology identical to VCATS except the symbology is yellow rather than green. The pilots who use the PNVG symbology should be aware of the possibility of being disoriented by looking at the attitude reference indicator's artificial horizon, which is referenced to the aircraft symbol on the PNVG display. The aircraft symbol is referenced to the pilot's helmet and not the aircraft, as it is with a head-up display (HUD) mounted on top of the instrument panel. Therefore, unless the pilot is looking straight ahead and perfectly level using PNVG, the artificial horizon will not match the outside world horizon, either viewed directly or through the PNVG. In other words, the artificial horizon symbology no longer matches the exterior world scene as displayed. This cannot be avoided on a helmet-mounted system because the pilot's helmet does move with respect to the aircraft (tilt, look over shoulder, etc). This mismatch could be disorienting to the pilot if not properly taken into consideration. All Nellis AFB VCATS-trained pilots are quite familiar with this issue and will have no surprises with PNVG. Any new pilots will be properly trained prior to use of PNVG. In most cases, the pilot will simply shut off the HMD attitude reference indicator.

6. CONCLUSION

The PNVG conceptual working model developed under the phase I SBIR demonstrated the feasibility of a very wide FOV image for night operations. The eleven advanced technology demonstrators delivered under Phase II and successful completion of safety-of-flight testing will allow the warfighter to evaluate the operational utility of the PNVG in actual flight tests on aircraft. It is noted that for flight testing on aircraft other than the F-15C, additional safety-of-flight testing and analysis will be necessary, such as cockpit compatibility, electromagnetic compatibility, and emergency ground egress. As a result of performance-based evaluations in both simulators and in operational aircraft, a better understanding will be gained of the PNVG's impact on such areas as improved situational awareness, reduced fatigue during long missions, ejection compatibility, and overall increased mission performance and safety.

ACKNOWLEDGEMENTS

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BRIEF BIOGRAPHIES

Timothy W. Jackson is an officer in the United States Air Force currently serving as a Developmental Electrical Engineer at Air Force Research Laboratory, Wright-Patterson AFB in Ohio. 1Lt Jackson received a bachelor's and a master's degree in Electrical Engineering at Oklahoma State University in 1994 and 1996, respectively. His current position is chief, high performance network engineering group. He recently served as manager, panoramic night vision goggle safety-of-flight test program for the Visual Display Systems Branch. Lt Jackson has worked in the area of visual displays, since September 1996, as a project manager in the areas of ruggedization of commercial AMLCDs, field emission display development, display test and evaluation laboratory, and AC-130U Gunship video system characterization.

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Panoramic Night Vision Goggle Testing for Diagnosis and Repair

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ABSTRACT

During operational testing of the panoramic night vision goggles (PNVG) over the past eighteen months, the prototype systems have shown wear which has resulted in degraded performance. When a PNVG degrades to a point that pilots find objectionable, the PNVGs are sent back to the lab for repair. The lab has set up a program to assess the PNVGs received from the field to verify the probable source of the objectionable characteristic(s). Once determined, the PNVGs are shipped back to the manufacturer for repair. After repair, the PNVGs are again shipped to the lab to verify repairs and assess the overall condition before returning the PNVG to the field for further operational testing. This paper discusses the selected series of tests that are performed to diagnose the more common recurring problems and to determine if the manufacturer satisfactorily repaired them. These tests include the assessment of: gain, maximum luminance output, visual acuity ("resolution"), objective lens focus range, eyepiece diopter setting, and image discontinuity at the inboard/outboard channel boundary. The results of this testing are presented along with a comparison of data taken before and after repair with data taken during previous evaluations.

INTRODUCTION

Under a Phase II Small Business Innovative Research (SBIR) program, a total of 10 PNVGs were delivered to the Air Force Research Laboratory for testing and for eventual operational utility evaluations (OUEs) conducted by pilots in the field. Although these PNVGs were designed for flight evaluation, they were not built to the level of ruggedness that might be achieved in a final, fielded design. As a result, the PNVGs required repair during flight testing. Since the PNVGs were not designed for any level of field maintenance, the only way to repair the PNVGs is to send them back to the manufacturer. However, because of the sometimes ambiguous deficiencies noted by the pilots, and the relatively high cost of PNVGs repaired, it was decided that a controlled procedure should be established to: 1) verify and document the nature of the pilots complaints through measurements of the PNVGs and 2) verify the condition of the PNVGs after repair and prior to returning them to the field. This paper describes the tests that were selected and some of the results obtained from PNVGs sent back for repairs.

PROCEDURES

Gain/Maximum Output Luminance

The gain of a night vision goggle (NVG) is an assessment of its ability to amplify available light. The maximum output luminance of an NVG is determined by providing a uniform input luminance (that fills the field of view) and increasing the input luminance until the output luminance no longer increases. This is the point at which the auto gain feature of the NVGs starts to control the system gain. These are measured using a Hoffman ANV-120. This device implements a test outlined in earlier documents [Task, 1993] in which the luminance output of the NVG is measured and compared to the luminance input from a spatially large, Lambertian, 2856K blackbody source. Gain is calculated simply by dividing the luminance output by the luminance input.

Visual Acuity

Visual Acuity [Marasco & Task, 1999] measures how well a human observer can see high contrast targets at specified light levels through the PNVG. The targets are a series of high contrast, square-wave gratings in steps of one Snellen acuity point (e.g. 20/24, 20/25, etc), illuminated to 5.8×10^{-3} foot-Lamberts (fL) (quarter moon) and to 5.8×10^{-4} fL (starlight) with a light source having a blackbody color temperature of 2856K. The test PNVG is placed 30 feet from the targets. Trained observers focus the NVGs on the target gratings and view the gratings through each ocular of the PNVG, one at a time using their dominant eye. The targets with the highest horizontal and vertical spatial frequencies the observer can clearly see, in terms of Snellen acuity, are then recorded. The trained observers (typically 3 are used and their results averaged) are required to be highly practiced with the test procedure and must have 20/20 vision or vision corrected to 20/20 and no astigmatism.

Objective Lens Focus Adjustment Range

The objective lenses of the inboard channels of the PNVGs are adjustable, permitting the observer to focus on objects located about 2 feet away to infinity. However, in order to give the PNVG user confidence that the objective lens focus is indeed set for best image quality at the infinity end, it is desirable to have the objective lens go "past" infinity. This enables the observer to adjust back and forth across the infinity setting to obtain the best possible focus. If the objective lens focus mechanism is not adjusted correctly, it may stop the lens travel short so that it does not go through infinity. This test is designed to insure the objective lens can be focused at and through the infinity setting. An IR LED, which serves as a point source of light, is located about 190 feet (anything past about 150 feet can be considered optical infinity for the PNVG objective lens) from the PNVGs. The objective lens focusing knob is then adjusted until the image of the LED is as small as possible such that this setting is not at the end of travel. Ideally, one would like the image to get smaller as the objective lens is focused at a distant object, then get larger as the adjustment is pushed past the minimum size image. This insures the PNVGs can be focused "past" infinity.

Eyepiece Focus

The current PNVG design has a fixed focus eyepiece. This means the virtual image of the image intensifier tube output screen is located at a fixed distance from the observer's eye. For various reasons beyond the scope of this paper, the original specification for the PNVG called for the eyepiece focus to be set to –0.75 diopters. To verify this focus setting, a hand-held dioptometer is used (Task, 2000). For this procedure, a single observer measured the diopter setting three times and the average was recorded as the diopter value.

Image Discontinuity

Extending a night vision device's horizontal field of view by combining the output of multiple image intensifier tubes creates the possibility of image discontinuities between the in-board and out-board channels due to the difficulties in aligning the optical systems. These discontinuities may be manifested as excessive overlap, gaps, magnification differences, image rotation differences, or image shifts. This procedure is designed to photographically assess and measure these defects by imaging a large 8 ft by 8 ft grid through the PNVG in-board and out-board channels simultaneously and comparing the defects to the size of grid features (Marasco & Task, 1999).

The PNVGs are mounted and positioned a known distance from the back-illuminated grid board (grid lines are spaced 8 inches apart). With the room lights off and the grid board lighting set to a very low level, both the in-board and out-board PNVG ocular fields of view are simultaneously photographed using a camera with a wide angle lens. Using the distance to the grid board and the grid board line spacing, it is possible to calculate the angular subtense of each of the 8-inch grid squares. Using this information to scale the photograph, it is possible to quantitatively assess image discontinuity.

Spectral Measurements

During operational testing of the PNVG, Army pilots noticed some color smearing in a PNVG II image. It was the observation of researchers at USAARL, Ft. Rucker, AL, that the problem could be corrected by attaching yellow absorption filters. However, Air Force fliers did not report this image anomaly. The question went largely uninvestigated until after the review of several PNVG image discontinuity photos. In these photos, a faint blue double image was found at the edges of the PNVG II output. Analysis of photos showed that the double image was not found in the PNVG I.

This issue is due in part to the spectral characteristics of the image intensifier tube's P43 phosphor. The P43 phosphor is attractive for use in the PNVG because the phosphor's primary emission spike is spectrally narrow. In order to take advantage of the narrow central spike, the two dim, secondary emissions (known as side lobes) must be attenuated. The PNVGs are equipped with an interference filter to block the side lobes and pass only the primary P43 phosphor spike.

Spectral measurements were used to examine the relative intensity of the blue image. The PNVG was prepared for these measurements by mounting it on an optical table and focusing them to infinity. A single PNVG objective lens was then aligned to the aperture of an integrating sphere so that the entire field of view is filled. The integrating sphere was illuminated with a 2856K source producing a luminance of approximately $0.7X10^{-3}$ fL. The spectroradiometer measurement head, having a 4.1-degree field of view, is positioned several inches behind the test NVG on the test channel's optical axis and focused into the eyepiece. NVG output is then measured for two different view angles: on axis and 15 degrees off axis.

EXAMPLES OF RESULTS

The following is an example of the kind of data obtained from the field that accompanies a PNVG that has been returned for repair or refurbishment. Only the comment in parentheses was added for emphasis in this paper:

PNVG II, Config. 4, S/N 02 **- 5 JUN 0**
Got opportunity to check out:
- Left inner channel is dim. Appears to be "gained down."
- Very difficult to focus.
Left outer - 20/60
Left inner - 20/50 very dark
Right inner - 20/40
Right outer - 20/60
Headache after wearing for 20 min
* compared with Oct 27, 99 entry (7 months prior to this entry). The goggles have experienced a large reduction in performance

PNVG I, Config. 1, S/N 08 **- 8 JUN 00**
- Return to Sytronics for MX.
- Visual acuity is poor - focus at infinity needs work
- Loose VA. Please tighten
- Scratch in Rt outer channel

As illustrated above, the nature of the complaint was not always exactly clear. For the first case (the PNVG II), there were two characteristics to check: 1) the left inboard channel appeared to have lower gain than it used to compared to the other channels, and 2) the visual acuity may have been reduced. It was hard to determine what the cause might be (as evidenced by the comment that the "goggles have experienced a large reduction in performance" since the previous entry of Oct 27, 99). The reference to focus difficulty could be due to mechanical friction (i.e. it is physically hard to turn the knobs) or could be a reference to the image quality obtained (i.e. it does not focus as clearly as it used to). Gain and visual acuity assessments were considered the two key parameters to concentrate on in the evaluation. The comment about headache after wearing for 20 minutes could be caused by any number of things. One possible culprit could be image alignment problems, making it another parameter to investigate closely.

The second case (PNVG I) provided a hint that the focus range of one of the oculars may not be focusable to or past infinity. The reference to VA was presumably "visual acuity" although it was difficult to determine how to "tighten" the visual acuity. The following are the log entries for these PNVGs when they came back from the repair:

PNVG II, Config. 4, S/N 02 **13 JUN 00**
Received goggle from Sytronics. Initial observations:
All four tubes exhibit dark shaded areas. These are caused by "poison" in the cathode and will most likely kill entire tube within few months. I notified Sytronics before any repairs.
Left outer, right inner and right outer tubes re-adjusted for gain and Automatic Brightness Control (ABC). Focus on all four objectives re-adjusted. Inner channels read 20-22.

PNVG I, Config. I, S/N 08 **21 JUN 00**
Goggle received from Sytronics.
a. Initial check showed left side dead.
b. Right side misaligned and soft image.
c. Stow mechanism (trapeze) loose.
d. Left inner tube has dark shading (poison of photocathode)
e. Left outer tube has dark shading [diagram]
All items (except tube shadings) were corrected between June 30 and July 5, 2000.
1. Left power supply re-wired.
2. Right monocular re-adjusted, but central intensifier is soft (see 27 March comments).
3. Stow mechanism re-tightened.

4. Goggle shipped July 6, 2000 to Sytronics.

The following sections show the test results for these two PNVGs with their reported problems before and after repair.

Gain

Since there is a certain amount of variability in repeatability and reproducibility of gain measurements, only changes in gain of greater than 13% are considered significant [Aleva, 1998]. Although the repair contractor stated that gain and ABC (i.e. maximum luminance) was adjusted for 3 of the 4 channels of the PNVG II (all but the left inner channel) it is apparent from Table 1 that only the right channels had a significant increase in gain as a result of the repair. It should also be noted that even before repair the left inner channel, which was stated to be "dim," had the highest gain of all 4 channels (PNVG II) and the second highest maximum luminance. This makes it unclear as to what conditions caused the pilots to note the luminance deficiency in the left inner channel. Table 2 summarizes the results of the maximum luminance output measurements, showing an increase in maximum output luminance for the left outboard and right inboard channels of the PNVG II after repair. The PNVG I data for both Tables 1 and 2 indicate essentially no change before and after repair, which makes sense since the pilot complaints did not involve any gain or luminance related issues.

Table 1. Gain measured at 3.7×10^{-4} fL input before and after repair.

	PNVG I		**PNVG II**	
	Before	**After**	**Before**	**After**
LFT OUTB.	3568	3919	3132	2993
LEFT	4422	4405	3655	3567
RIGHT	4878	5027	3602	4954
RT OUTB.	4846	5189	2981	4181

Table 2. Maximum output luminance (fL) measured on three different dates.

	PNVG I		**PNVG II**	
	Before	**After**	**Before**	**After**
LFT OUTB.	2.74	2.72	2.19	3.06
LEFT	2.74	2.89	2.41	2.41
RIGHT	2.41	2.49	1.84	2.33
RT OUTB.	2.48	2.70	2.52	2.47

Visual Acuity (Resolution)

Table 3 and Table 4 list the results of acuity testing at starlight and quarter moon luminance conditions respectively. These tables show minor improvements in visual acuity (smaller numbers) for most of the channels after repair, which is expected based on the pilot complaints and the stated repairs. However, previous research on the techniques to measure visual acuity indicates that the magnitude of these changes is probably insignificant compared to the repeatability/reproducibility of the measurements [Pinkus et al., 1999].

Table 3. Starlight Snellen Acuity (20/XX) measured before and after repair.

	PNVG I		**PNVG II**	
	Before	**After**	**Before**	**After**
LFT OUTB.	44	42	40	38
LEFT	32	37	29	29
BINOCULAR	35	35	27	28
RIGHT	43	41	29	28
RT OUTB.	43	41	43	40

Table 4. Quarter Moon Snellen Acuity (20/XX) measured before and after repair.

	PNVG I		PNVG II	
	Before	**After**	**Before**	**After**
LFT OUTB.	39	39	34	32
LEFT	29	30	25	26
BINOCULAR	28	32	25	25
RIGHT	39	35	25	26
RT OUTB.	38	38	39	34

Objective Lens Focus Adjustment
Focus issues noted in PNVG II, Configuration 4, serial number 02 were corrected by insuring the objective lens focus range went past infinity.

Eyepiece Diopter Setting
None of the pilot complaints seemed to be a result of eyepiece focus setting. Although the diopter settings of Table 5 are somewhat varied, they do not indicate that there should be any difficulties due to this parameter.

Table 5. Mean Eyepiece Setting (in Diopters) measured on three different dates.

	PNVG I		PNVG II	
	Before	**After**	**Before**	**After**
LFT OUTB.	-0.8	-0.6	-0.7	-0.6
LEFT	-0.6	-0.5	-0.4	-0.5
RIGHT	-0.5	-0.5	-0.3	-0.5
RT OUTB.	-0.4	-0.2	-0.2	-0.3

Image Discontinuity

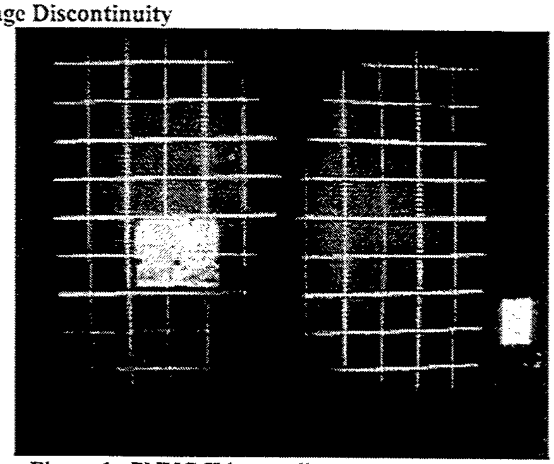

Figure 1. PNVG II image discontinuity before repair.

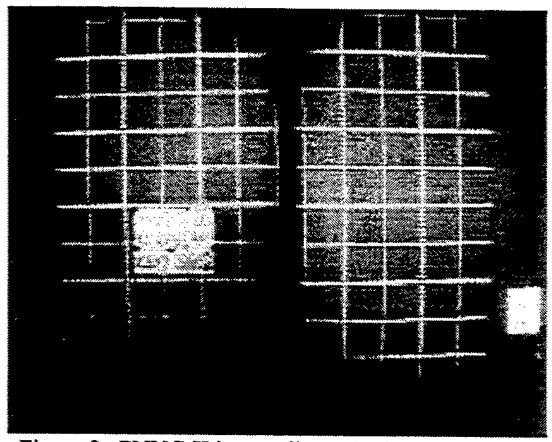

Figure 2. PNVG II image discontinuity after repair.

Since the manufacturer's procedure for adjusting image intensifier tube gain was unknown, changing the relative position of the tube to the eyepiece, thus changing PNVG image discontinuity, was considered possible during repair. Image discontinuity photos taken before and after repairs were compared (Figure 1 and Figure 2). Little change was noted in photos of either PNVG I or PNVG II.

Spectral Measurements
Figure 3 shows the spectral distribution for PNVG II, Configuration 4, serial number 0003, on axis and 15 degrees off axis. The spectral measurements indicate that the current filter is sufficient to block the blue and red side lobes on axis. However, at 15 degrees off-axis the blue side lobe appears. The intensity of the blue lobe ranged from 2% to 17% of the corresponding green primary emission depending on the ocular.

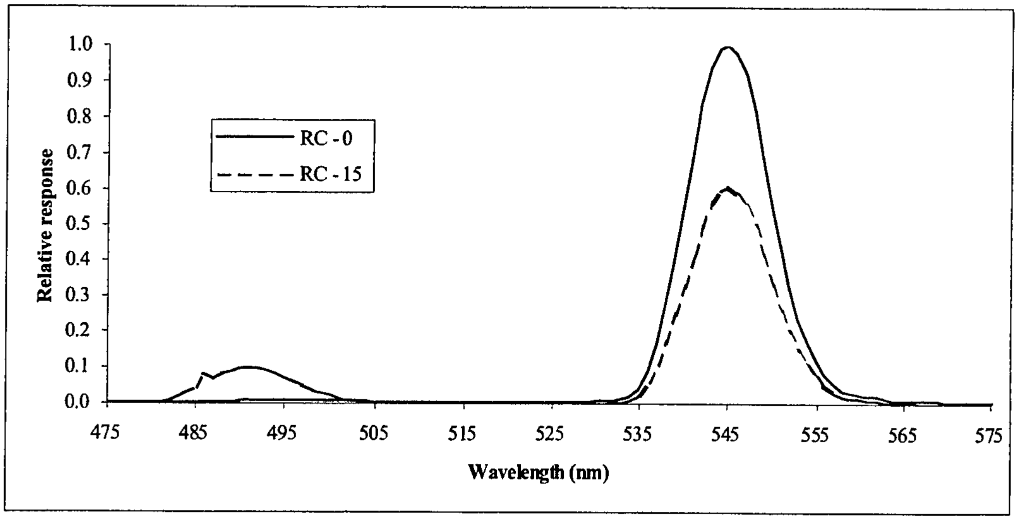

Figure 3. Normalized spectral measurements of PNVG II, Config. 4, S/N 0003, Right Central Channel, at 0 and 15 degrees off axis.

DISCUSSION AND CONCLUSIONS

The characterization of PNVGs for diagnosis of image quality problems and post repair assessment yielded a number of observations. Given the sometimes ambiguous comments from the pilots regarding the deficiencies of the PNVGs due to wear and tear in the field, it is apparent that a controlled process of quantitatively verifying PNVG performance before and after repair is needed. One curious item of note is the large difference in visual acuity ascribed to the PNVGs from the field compared to the more controlled assessment of PNVG visual acuity accomplished in the laboratory. The repeatability and reproducibility of NVG visual acuity is a good topic for future research.

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Panoramic Night Vision Goggle-Maintainer's Perspective

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ABSTRACT

Future night vision goggle (NVG) capabilities have dramatically improved with the advent of the "Panoramic Night Vision Goggle" (PNVG) systems. Ingenious uses of optics and image intensifier tubes have significantly expanded the pilots' field of view (FOV) wearing NVGs from 40 degrees to a 100 degrees FOV. Flight and laboratory tests have demonstrated a marked increase in situational awareness in concert with the 160 percent-increased FOV. Additionally, test and evaluation sorties on multi-type airframes have won high accolades from pilots all too familiar with flying with the older 40-degree FOV goggles. However, despite these innovations, there remain design hurdles critical to fielding and sustaining these new devises. A modular platform concept is proposed for the PNVG II version. This would give maintainers flexibility in minimizing maintenance downtime by eliminating common solder repairs typically found in current NVG designs. A modular design would also allow the image performance to be assessed using the recently purchased and costly Hoffman ANV-126 tester. Advanced optical designs on the PNVG prohibit the same field level repairs that are being performed on currently fielded NVGs with more simple lenses. Modular lens sections would allow a lens change as quick as a photographer using a 35mm camera would. This modular design concept will prevent services from having to revert to a centralized depot-level repair of these high demand devises. An item that can be repaired in the field is an item that's available for sortie generation. Night vision goggle maintenance in the Air Force has evolved into a self-sustained operation that's given it's users shorter maintenance repair times and higher availability rates for these devises. There's never been a better time for a modular NVG design than with the advent of the PNVG system.

INTRODUCTION

There are two configurations of the Panoramic Night Vision Goggles and several versions of each, incorporating various features. The first configuration, PNVG I, was designed primarily for use in high performance aircraft. Its robust design integrates frame, lens and goggle components enabling retention of the devise during an ejection. PNVG II incorporate the same field of view as version I, but utilizes the more traditional frame assembly designed to integrate with current NVG helmet mounts. The PNVG II prototype design borrowed off-the-shelf frame components for its frame and mount assemblies. This allowed the PNVG II to integrate with all the conventional NVG aviator helmet mounts in the US inventory. In addition to aligning the NVG mount design with helmet mounts already in service, it also saved the cost of redesigning a new frame assembly. The uses of these type frames were convenient in allowing test and evaluations of the PNVG's advances in optics and image intensifiers. However, many of the benefits gained using off-the-shelf frame assemblies will be significantly offset if they're used during production. This paper will primarily focus on improvement opportunities desired for current NVG frame assemblies and required for future PNVG II assemblies. The term PNVG will refer to the PNVG II configuration unless otherwise indicated.

BACKGROUND-MAINTENANCE HISTORY

PNVG's technological design advancement brings with it sustainment issues common to most system advances. Typically the more complex a system, the larger the logistical footprint. This point becomes more critical when considering the hazardous two-prong arenas the PNVGs will be used, flight and war. This paper will discuss some of the challenges and concerns anticipated during the final design and sustainment phases of this important new system. To appreciate these issues, one must be familiar with the evolution of NVG maintenance in the Air Force.

In the "early days" of NVGs in the Air Force, field technicians performed only visual inspections of NVG systems. If there were any anomalies noted, the goggles were packaged and sent to the depot for more in-depth examination. Aircrew Life Support technicians maintaining the goggles wouldn't see the goggles again for several weeks. This created an unacceptable turn-around time for these high demand devises. This drove the evolution of a two-tier *field* maintenance program, Intermediate-Level (I-Level) and Organizational-Levels (O-Level).

The O-level technicians still performed only visual inspections but began utilizing a hand-held *Assessor* that provided a resolution grid. The *Assessor* allowed technicians to quickly assess the NVG's image qualities for obvious defects in various light conditions. Distortion inspections however, required the technician to fabricate a tic-tac-toe type grid to access the goggles for image distortion. Another target was necessary to measure the size and position of dark spots in the image intensifier tubes that would obscure the pilots' view. Once again, if any defects were suspected, the goggles were sent to the higher I-level maintenance.

Avionics (Sensors) technicians assumed the I-Level maintenance duties. I-Level maintenance tasks included all inspections and repairs necessary to maintain the goggles. With the additional maintenance tasking came a more sophisticated test set, the TS-3895. Like the hand-held Assessor, the TS-3895 test set provided a basic resolution target that allowed the technician to assess the NVGs visual clarity, in both the high and low light conditions. It also provided the means to check the goggles' electrical functions for excessive current drain and the operation of the power packs. I-level technicians were qualified to perform all authorized repairs on the night vision goggles including soldering and nitrogen purging.

Although very dedicated, the Avionics technician's support of the NVG program was often secondary to their primary support of the aircraft's' ship-side avionics. This two-tier maintenance program did reduce repair times compared to sending NVGs off base, but still lagged behind the ever-increasing demand for an even shorter turn around time by the user.

The proliferation of NVGs further burdened the Avionics branches as reflected in the increased turn-time for I-level NVG maintenance. Another factor was the aggressive force reductions that lessened the maintainers available to perform the maintenance.

Life Support Command Managers saw opportunities to reduce the maintenance turn-time by further reducing the maintenance levels maintaining their NVGs. They began training their O-Level technicians to assume I-Level duties. Those trained were provided the TS-3895 tester in addition to nitrogen for purging. These new I-Level maintainers performed all NVG inspections and repairs except soldering.

Soldering night vision goggles requires a "High Reliability" solder certification due to the goggles critical nature. Due to the frequent turnover of active duty technicians, it was frustrating to continually pay for this training. Many units continued to rely on the Avionics technicians for solder support via local support agreements. Since solder-repairs were relatively uncommon NVG maintenance tasks, it made more fiscal sense to establish local support agreements for soldering than to invest in costly repetitive solder training. Once again the goggles were being sent away for solder-type repairs. Avionics frequently lacked either the manpower or time to quickly perform these solder repairs while also maintaining their own equipment. Although mission-ready rates for night vision goggles are not tracked, any experienced NVG technician would attest to the lengthy downtimes for goggles requiring extensive repairs.

Life Support Command Manager's once again moved to make for more mission ready devises. They increased the manning at units maintaining night vision goggles. Additionally, solder training was added as a recommended *optional* training requirement to the Aircrew Life Support career field. However, many Life Support units have opted for continued use of the local support agreement with the Avionics shops.

The following discussions propose particular design concerns to current NVG systems that could and should be resolved with production of any PNVG II systems. They are areas affecting reliability and ready-rates for these critical devises.

MAINTENANCE/DESIGN LIMITATIONS

a. Soldering

Despite the simplicity in design, NVG repairs requiring soldering are extremely time-consuming. Two thin wires bring current via the helmet mount, from the power pack into the image intensifier tubes inside the monocular housing. Very often these wires break from another design flaw that will be described later. Anytime the wires break, the monocular housing holding the wires must be either replaced or the wires reattached to their solder point. Prior to any soldering, the image intensifier tubes *must* be removed. Any heat conduction down the wires from the solder iron would irreparably damage the costly image intensifier tubes. This leads to lengthy repairs and excessive down times.

b. Lengthy Repairs

Even the most common and simple NVG repairs are very time consuming. Scratched lenses and broken monocular housings have become common as both the use and life of the goggles increase. Replacing the lenses or tubes first require draining the goggles of their nitrogen charge. The lens assemblies are first removed to gain access to the intensifier tube. After the tube is removed, the monocular housing is disassembled from the pivot adjustment shelf (PAS) to gain access to the wires requiring soldering. The damaged housing is then removed by de-soldering the wires joining the housing to the printed circuit board. The new housing is installed and the new wires soldered in place. The goggles' components are then reattached to the housing. However, as part of the re-assembly of the NVG, the technician must still adjust the eyepiece and objective lens assemblies for proper focus.

This lengthy repair process is very common and takes an _experienced_ technician at least two hours. If the technician is not familiar with these procedures and forced to rely on the technical order, add at least four more hours. However, if the damaged goggles were sent to an Avionics back-shop, an average of at least *two days* turn time can be expected. This time-consuming repair process has become even more common as the aging goggles require replacement of tubes, lenses and housings.

Many units currently maintain *several* spare goggles to allow for this now accepted high maintenance down time. This costly way of ensuring mission readiness is an unlikely answer when considering the potential high-cost of PNVGs. The maintenance downtime of NVGs could be significantly reduced with basic design improvements.

c. Purge Valves

Night vision goggles' current design require a nitrogen charge in the monocular housing to prevent damaging moisture from entering the inner housing where the image intensifiers are stored. NVG's are charged with nitrogen through a process called Purging.

During purging, the outer purge valve is removed to allow insertion of a metallic adapter into the plastic sleeve. Inserting the metallic adapter into the threaded plastic sleeve frequently results in stripped threads. When this occurs, the entire monocular housing must be replaced as described above. Once the adapter is in place, the inner purge valve is loosened to allow a flow of nitrogen that's being blown in from the outer valve.

To gain access to the inner valve, an offset (L-shaped) screwdriver is recommended in the technical order. Despite using the proper tool, the space between the housings is too tight to effectively accommodate any tools. This usually results in damaged aluminum valves or plastic valve sleeves as the technician tries to vent the nitrogen. The purge procedure was rewritten establishing an alternate purge method that called for use of only the outer valve. Although this eliminated further damage to the inner purge valve and port, it was not as effective a purge method.

The new procedure, "Zero Pressure," required the removal of the outer purge valve to allow insertion of the nitrogen. Once the system was charged, the nitrogen line was removed so that the valve could be reinstalled. This exposed the nitrogen filled chamber to the atmosphere as the technician reinstalled the valve, leaving zero pressure in the chamber.

Cross threading is an extremely common problem while inserting either the metal purge adapter or the metal purge valve into the plastic sleeve. When cross threading occurs the entire monocular housing must be replaced.

The system's design would be dramatically improved by providing more creative and less labor intensive means to eliminate moisture from the image intensifier tube chamber. Perhaps the use of a moisture absorbent liner or a desiccant-type devise could be incorporated in future designs.

Improved purge valves could also be the answer to this dilemma. Future housing designs could utilize valves similar in design to those found on pneumatic tires. This would allow the technician to quickly purge the chamber with nitrogen by attaching a gas-station type hose to the valve. Depressing the valve's nipple would easily purge the chamber during both filling and repairs. This would dramatically extend the life of the housing by eliminating damages incurred during the purging processes utilizing today's methods and designs.

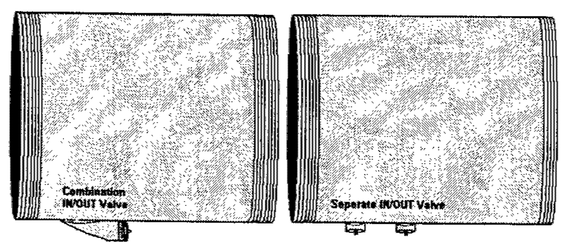

Figure 1. Purge Valves

d. Housings

Housings were recently improved by eliminating the saddle to housing configuration. Previously, the "saddle" was glued to the monocular housing and served to join the housing to the PAS. This saddle to housing bond point was often damage by aircrews during removal of the goggles. They would remove the NVGs by grasping them with one hand and forcing the goggles away. Although not recommended, this action was sometimes necessary as the flyers were often flying the jet with their other hand.

This removal process would often over-torque the bond joint causing it to snap.

Another housing design limitation is the threaded sleeve on top of the housing that holds the adjustment Inter-Pupillary Distance (IPD) screw. The metal screw turning within the plastic threads quickly strips the threads requiring the replacement of the entire monocular housing.

The addition of metallic threaded sleeve into the plastic housing would dramatically extent the housing's life. A replaceable *lightweight* durable sleeve made from advanced composites would be ideal. This low cost alternative would allow technicians to replace the damaged threaded section instead of the entire housing. Although this might add some weight to the goggle, it would significantly improve the goggle's durability while lowering the overall maintenance cost.

e. Knobs

Ergonomically designed adjustment knobs for Tilt, Fore/AFT, and IPD would dramatically enhance any future designs. Compare the infinity focus adjustment knobs of the AN/AVS-6 to the AN/AVS-9 (F4949). The F4949's knobs are superior to the knobs of the AN/AVS-6. They're designed for flyers wearing flight gloves. Bigger knobs are easier to find and use.

The current Tilt lever is difficult to locate and cumbersome to use-especially while wearing flight gloves. Imagine performing these adjustments while wearing three layers of gloves, as is done when flyers' are suited for a chemical environment. Keep in mind that the Tilt, Vertical & Fore/Aft are actually used *in flight,* as opposed to the IPD and diopter focus knobs which are only used during preflight adjustments. Rocker-type knobs, like those found on many binoculars might prove ideal for most of the NVG adjustments.

f. In-Flight Goggle Storage

An A-10 mishap involving a NVG storage case tangling with the flight controls has drawn new concern for the design of NVG storage cases and alternate storage methods. This is particularly true for the fighter community since there's limited cockpit space to store a box-shaped case. A small, firmly padded helmet bag-type design would protect the goggles and could be easily stored in either their flight suit leg pocket or map bins. Another concept is a hard-mount on the interior of the flight station. The pilot could remove the goggles and attach them to this mount.

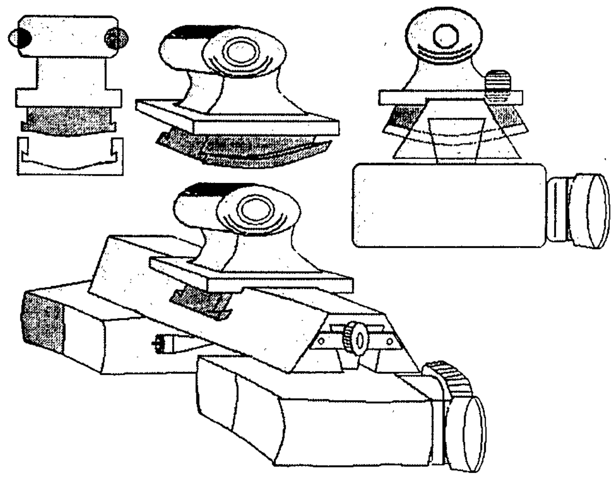

Figure 2. Increased Tilt

g. Increased Adjustment Range

Increasing the range of mechanical motion in future goggle designs would allow better fit for the aircrews. One way is to provide a wider range of tilt. Current goggles provide only ± 4 degrees tilt from the center position. A wider range would improve the optical alignment process by making it quicker and more personally accommodating. It would also help helicopter gunners and loadmasters look down easier with less neck strain.

Increased Fore and Aft movement would allow a more comfortable wear for flyer's wearing prescription spectacles. It would also improve the look-under capability required when scanning gages.

h. Wire-to-Circuit Board Design

Current from the helmet mount is delivered to a flexible circuit board in the pivot and adjustment shelf (PAS). The current is then delivered to the image intensifier tubes via two wires extending from the monocular housing. The two wires are soldered to the flexible circuit board and tend to flex at the solder joint as the housing is moved side-to-side during IPD adjustments. These adjustments are performed during the preflight optical alignment process. The flexing of the wires at the solder joint eventually causes either a cold solder joint where no current is flowing, or causes the wire to completely break. When this occurs, the image either flickers or will not illuminate, thus requiring the extensive repairs described earlier in "Lengthy Repair."

A more durable electrical system is needed to enhance in the next generation of night vision goggles and is proposed in the following section.

i. Excessive Housing "Wobble"

The monocular housings rest on a pin that runs the length of the pivot adjustment shelf. The housings slide side-to-side along the pin as the user adjusts the goggles for proper inter-pupillary distance or IPD. There's an inherent wobble of the monocular housings as they ride on this pin. The wobble is not dramatic, but certainly effects how the image is transmitted to the user's retina.

Technicians invest time ensuring the focal points on the eyepiece lenses are parallel or collimated. The monocular housings are held parallel when they're inserted into the ANV-126 tester's ports. The housings wobble defeats the collimating efforts attained during optical adjustments. Improved precision in the mechanical movements of future NVG designs is needed to eliminate or reduce this wobble.

MODULAR DESIGNS

Current NVGs utilize designs requiring lengthy repair processes to perform even the most simple repair tasks. The following modular designs proposals attempt to suggest various design improvement opportunities that would dramatically reduce the maintenance turn-times while extending the overall life of future NVG systems.

a. Rapid Repair

A more robust electrical system requiring minimal (or none) solder repairs would be ideal. One such system could be a *track-type* system similar to those found in track lighting systems. This concept would allow rapid repairs to extensively damaged systems. The technician could quickly "slide" the faulty component from the track and replace it with a spare. This would enable the technician to quickly replace the damaged component with a serviceable one without hampering the mission.

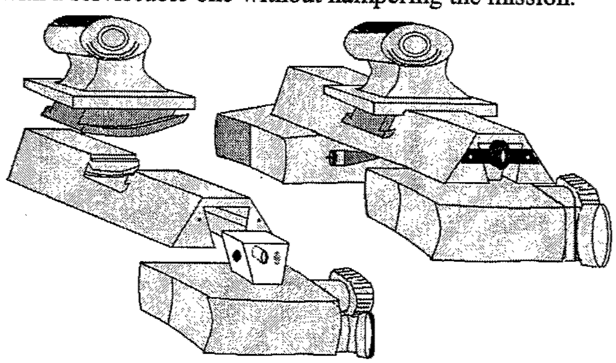

Figure 3. Modular NVG Design

b. Preventive Maintenance

A modular NVG design would allow incorporation of preventative maintenance procedures to current maintenance schedules. Removing abrasive components such as sand would decrease the maintenance downtime while extending the life of the overall system. A modular design would allow the goggles to be easily "broken-down" and cleaned in the way someone might breakdown a weapon for cleaning.

c. Tester Compatibility

PNVGs will require routine inspections for image qualities such as resolution and gain that are currently performed using the newly purchased ANV-126 Hoffman testers. The ANV-126 tester has two ports to accommodate the two objective lenses found in current NVG designs. However, the *four* objective lenses found on the PNVG will prevent technicians from performing these critical checks using the tester's current design. The tester would require extensive modification to accommodate the four objective lenses.

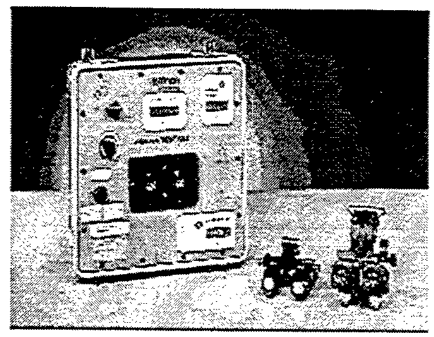

Figure 4. Hoffman AN-126 Tester

According to the tester's item manager, the Air Force recently spent approximately $5M outfitting units with these new high-tech testers. A modular design would allow the PNVG to easily integrate with the new ANV-126 tester by allowing the technician to separate the goggle sides and independently inspect them in the tester. The tester would still require minor modifications such as an adapter plate and power cord. The cost associated with these modifications would pale compared to a complete redesign and/or purchase of the new testers.

d. Optics

It's assumed the lenses on any future NVG designs will eventually require repairs due to normal wear. The complexity of the folded optics on the PNVG's outboard objective lenses is beyond the repair capabilities of both technicians and support equipment currently in the field. Based on the problems described earlier, returning to a depot-level repair system is a highly undesirable scenario.

A modular lens design would solve this dilemma. Lenses could be designed in modular sections and would incorporate the complex folded optics found in the outboard objective lenses. Additionally, the PNVG eyepiece lenses incorporate a two-section lens design. Any damage to either of the sections will require the replacement of both lenses. Like the objective lenses described earlier, repair of these lenses is beyond the capabilities of both technicians and equipment currently in the field.

Lens modules could be designed with bayonet-type fitting like those found on camera lenses. This would allow for quick repairs to damaged lenses. Modular lenses would also allow NVGs to be quickly modified with different coated lenses to meet various cockpit and mission configurations. The ability to easily change lenses will so ensure the ability of the PNVGs to evolve with the development of new optical coatings and lens configurations.

e. Pivot Adjustment Shelf Components

A system utilizing individual components for its pivot adjustment shelf would provide several advantages. It would allow the technician to replace the specific faulty sub-component instead of the entire assembly. Cost savings are the obvious benefits realized with this concept. Another benefit would be allowing technicians to disassemble the NVG for preventive maintenance as described above.

Conclusion

Lessons learned in recent and not-too-distant conflicts demand inter-changeable components and rapid repair capabilities in modern weapon systems. Users have grown to rely heavily on night vision technologies and expect these important systems to be available when needed in the next conflict. Any future NVG system must be easily maintained at the field level.

Although these design suggestions would require some investment, they are long over due. Their incorporation would certainly yield a product that's much easier to use, maintain and sustain during any future war-environment. The current monocular housing and PAS designs were great 15 years ago, but have been slow to evolve into more maintenance and user-friendly designs. There are many improvement opportunities available for those willing to invest in them.

The push in optical and tube design that PNVG's have made needs to be met with a similar advances platform design. Hopefully this will spark innovation in creating a new NVG mount design that blends weight concerns with both the functionality and sustainability of the devises.

Tomorrow's combat missions will be built on the assumption of the availability of night vision goggles and regardless of their complexities, will be expected to be available and ready for mission use-not awaiting repairs. The advent of Panoramic Night Vision (PNVG) escalates this concern. The PNVG will have twice as many lenses and tubes as do conventional NVGs. Logically, the potential for system failure is multiplied by as many.

ACKNOWLEDGEMENTS

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BIOGRAPHY

MSgt Mike Sedillo is the Superintendent, Visual Display System's Branch at the Air Force Research Laboratory. He maintained NVG systems for ten years and helped write two NVG technical orders and several Life Support-related manuals. He recently spent 5 years teaching NVG maintenance as the senior military instructor at the Aircrew Life Support technical school. He has a BS in Occupational Education and is currently assisting in the test and evaluation of the PNVG system.

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Integrated Panoramic Night Vision Goggles Fixed-Focus Eyepieces: Selecting A Diopter Setting

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ABSTRACT
Due to the design of the eyepieces of the panoramic night vision goggles (PNVG) and the newer integrated panoramic night vision goggles (IPNVG), the eyepiece will have a fixed focus. This means the eyepiece will be set to some fixed value resulting in a virtual image of the image intensifier tube at some fixed distance between infinity and the observer. This eyepiece setting is specified in terms of diopters where the diopter value is the negative of the reciprocal of the virtual image distance in meters. Cat's Eyes night vision goggles (NVGs) used by the US Navy reportedly had a fixed focus of about -1.0 diopters. This paper will discuss the theoretical basis for the diopter setting and the results of various field surveys and in-house tests to determine observers' preferences regarding eyepiece focus settings and objective measures of their resulting visual acuity.

INTRODUCTION AND BACKGROUND

The panoramic night vision goggles (PNVG) produce an intensified field of view of approximately 100 degrees horizontal by 40 degrees vertical by combining the images from a total of 4 image intensifier tube channels[1]. Both eyes see the central part of the field of view through the two inboard channels, but only the right eye sees the right outboard channel and only the left eye sees the left outboard channel. The inboard and outboard channels are combined by using two eyepieces cemented together at an angle to produce two "windows" through which the image is seen (see Figure 1). Normally, eyepiece focus is obtained by installing the eyepiece lens in a movable lens cell that can be moved closer to or further from the output of the image intensifier tube. This adjustment moves the virtual image produced by the eyepiece closer to or further from the observer. However, the PNVG eyepiece arrangement makes it almost impossible to make an eyepiece that can be moved (i.e. focused). Therefore, it is desirable to select a single, fixed focus setting for the eyepiece that would be acceptable to all potential users of the PNVGs.

There are currently a dozen PNVGs that have been fabricated under a Phase 2 Small Business Innovative Research (SBIR) program primarily funded by the US Air Force Research Laboratory Helmet Mounted Sensory Technology (HMST) program office. These PNVGs were specified to have a fixed focus eyepiece of -0.75 diopters which means the virtual image produced by the eyepieces would be located about 1.33 meters from the observer (1/0.75). Four of these PNVGs were measured using a handheld dioptometer (see Figure 2) that showed the actual settings ranged from -0.2 to -1.0 diopters[6]. These PNVGs have been flown by several aircrew members without any complaints regarding image quality and focus that could be attributed to the diopter setting indicating that a fixed diopter setting within this range should be acceptable.

The US Navy adopted the Cat's Eyes NVGs over a decade ago and only recently has converted to the newer, higher resolution AN/AVS-9 NVGs. The Cat's Eyes NVGs have a fixed-focus eyepiece, reportedly specified to be about -1.0 diopters, because of the unique "see-through" beamsplitter design. During the 10 years or so that the US Navy flew with these NVGs there was no documented indications that the pilots had any problems with the fixed focus eyepiece.

The US Air Force currently flies F4949 (AN/AVS-9) NVGs which have adjustable eyepieces with a range of about +2 to -4 diopters. These eyepieces are adjusted by the aircrew members themselves for "best focus." One approach to determining what eyepiece focus would be appropriate is to measure the settings that crewmembers are selecting for themselves currently using the adjustable eyepieces.

All rated aircrew members must pass a flying physical before they are permitted to fly. This physical includes an eye test that measures the individual's visual acuity for both far (infinity - 0 diopters) and near (about 16 inches - about 2.5 diopters). Therefore anyone passing a flight physical should be able to focus on an image produced anywhere from 16 inches (-2.5 diopters) to infinity (0 diopters) implying that the eyepiece fixed focus lens could be set anywhere within this range (0 to -2.5 diopters). However, if the individual had to be fitted with bifocal lenses in order to see this range (near and far) this indicates the individual's accommodative range was less than 2.5 diopters. Since the upper lenses are set for the "far" vision, and this is the part of the eyeglasses the individual would be looking through to see the NVGs, it would be inadvisable to have the NVG image produced too close to the individual.

In order to obtain more information that might facilitate a selection of a fixed eyepiece focus for the new integrated panoramic night vision goggles (IPNVG), three activities were undertaken: a controlled in-house pilot study of eyepiece focus preference and repeatability, eyepiece measurement of a dozen US Navy Cat's Eyes NVGs, and measurement of USAF aircrew members' eyepiece settings using AN/AVS-9. This paper provides a summary of these efforts and the results.

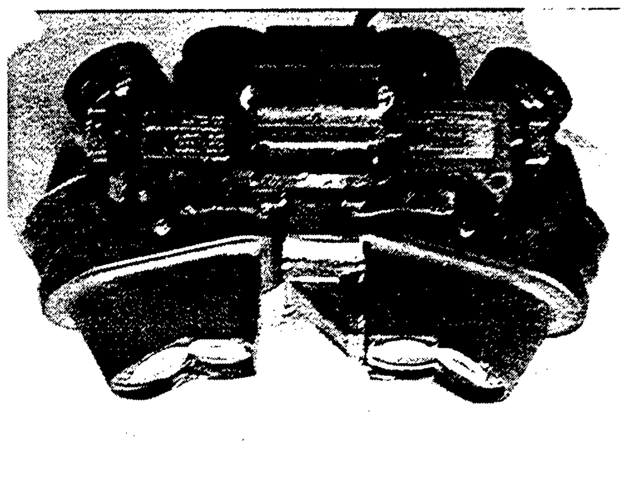

Figure 1. Panoramic night vision goggles

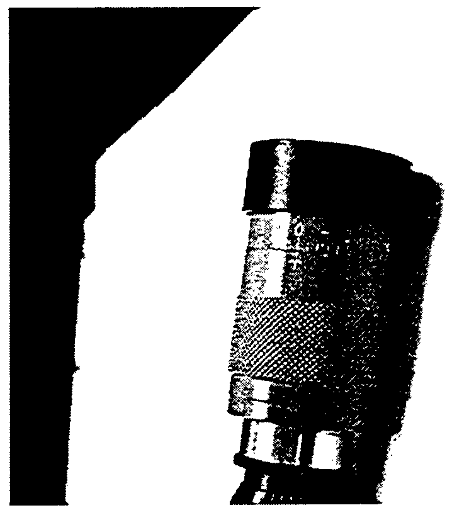

Figure 2. Dioptometer used to measure eyepiece settings

IN-HOUSE STUDY OF EYEPIECE FOCUS SETTING

Method

A brief pilot study was conduct using AN/AVS-9 NVGs with adjustable eyepiece focus. A total of 6 observers participated. The observers ranged in age from 31 years to 47 years with a mean of 38.8 years and a standard deviation of 5.6 years (3 male, 3 female). All observers had 20/20 distance vision and wore either contacts or eyeglasses. There were two parts to this study. In the first part the NVG eyepieces were set to -0.5 diopters and -1.5 diopters and the visual acuity of the observers was measured using the "walk-back" method [2]. For the second part, observers were asked to adjust the two oculars of the NVG until they were comfortable with the result. The observer's visual acuity and eyepiece focus setting were then measured and recorded. This was done on three consecutive days for a total of three trials for each observer. All viewing was done at an "optimum" illuminance level of about 1/4 moonlight illumination.

Results

For the first part, there was no statistically significant difference in visual acuity between the two diopter eyepiece settings (-0.5 and -1.5) . The average visual acuity at -0.5 was 20/24.2 and the average for -1.5 was 20/25.0. Four of the six observers did slightly better with the -0.5 setting and two did slightly better with the -1.5 setting.

The results of the second part of the study are best represented in Figure 3. Each observer set the right and left oculars of an NVG a total of three times. The graph in Figure 3 shows the observer/ocular combination (1L through 6R) at the bottom of the chart. For each of these observer/ocular combinations, the observer set the eyepiece focus 3 times as depicted by the diamond, square, and triangle symbols shown in the legend. A line was drawn from the two extreme eyepiece settings done by each observer for each eyepiece indicating the range of settings that a particular observer set for that eyepiece. Presumably, this line is representative of the range of values for which the observer was satisfied with the setting. The horizontal line at -0.75 diopters is a potential eyepiece value to be selected for the IPNVG. Note that this -0.75 line goes through the range of 9 of the 12 observer/eyepiece combinations. For the 3 combinations it misses (noted by a circle around the combinations - 1L, 2L, 1R), the amount it misses by is not very much. The maximum "miss" is 1L which misses by -.25 diopters. The average for the 36 readings (2 oculars, 6 observers, and 3 trials each) was -0.74 diopters; very close to the -0.75 under consideration for the IPNVG focus. The two heavy, horizontal lines show the average plus one standard deviation and the average minus one standard deviation for reference.

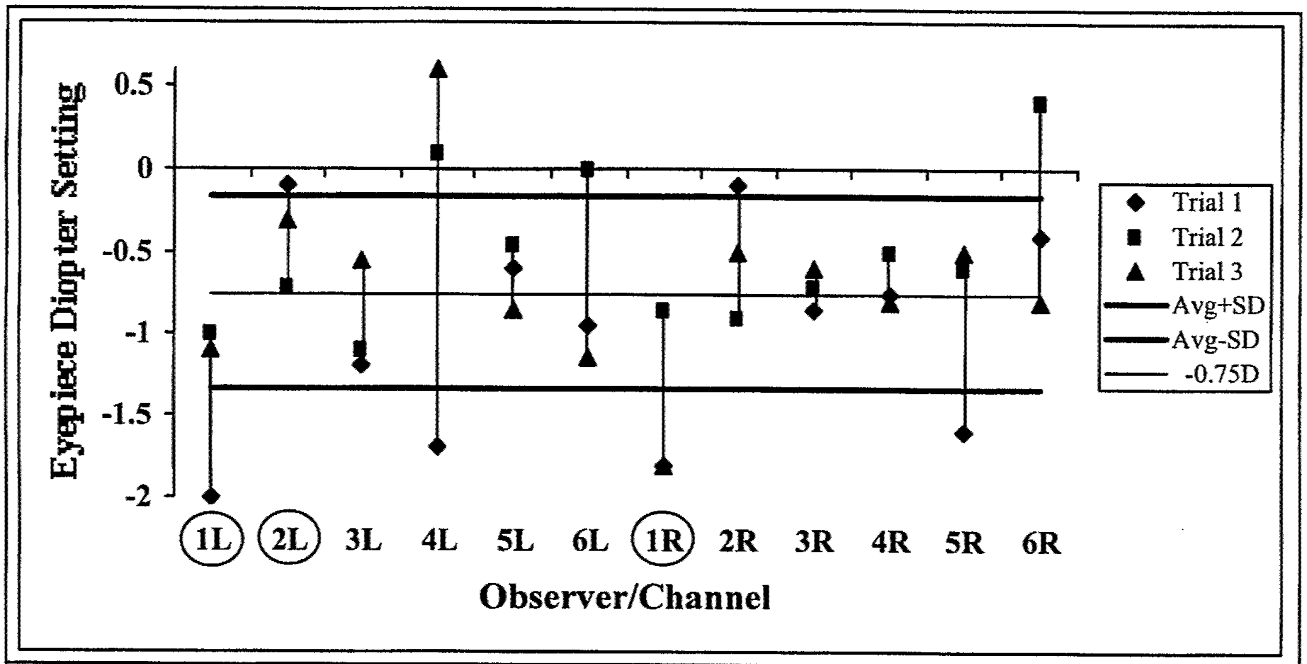

Figure 3. Summary of results of eyepiece focus setting. The average of all readings was -0.74 diopters.

FIELD STUDY OF EYEPIECE SETTINGS

An unpublished Air Force study conducted in the early 1990's surveyed ANVIS night vision goggle users on a number of characteristics[7]. One of the elements of the survey was for the aviators to set the eyepiece focus on the NVGs as they were trained to do. Some of the aviators had been taught to just set the eyepiece focus to zero diopters. The remaining 109 aviators adjusted the eyepiece focus for "best focus." This resulted in an average eyepiece setting of -1.1 diopters with a standard deviation of about 1.2 diopters. One problem with this survey is that the eyepiece settings were determined from the diopter scale on the NVGs. Even though the particular ANVIS night vision goggle that was used had been calibrated at the lab to insure correctness of the scale, the scale was rather course with an estimated "least count" of 1/4 diopter. To validate this data a field study was conducted at Nellis AFB, NV with experienced NVG aviators.

Method

One problem with collecting field data is the lack of control. NVG qualified pilots adjusted their NVGs as they had been trained and then were asked to let us check the eyepiece focus setting on their NVGs. Since the diopter scales on the NVGs are not always valid indicators of actual diopter setting, each ocular was measured using a dioptometer (see figure 2). Prior to measurement the dioptometer had to be adjusted for the investigator's eye by adjusting the eyepiece of the dioptometer. This was done by setting the dioptometer to zero diopters (see figure 2) and then adjusting the eyepiece for best focus while viewing a distant object (greater than 200 feet - see figure 3). Once this adjustment was done, the investigator could use the device to determine the eyepiece focus setting of the NVGs. The dioptometer was positioned at the eyepiece of the NVG (see figure 4) and then it was adjusted (using the scale portion, NOT the eyepiece adjustment) until the image in the NVG eyepiece was in good focus. Best (most repeatable) measurements were obtained by blocking light coming into the NVGs and using the scintillation pattern,as a focusing target. After the dioptometer was adjusted to obtain best focus, the diopter reading was obtained directly from the scale on the dioptometer (see figure 2). The scale was marked every 0.2 diopters and could easily be interpolated to the nearest 0.05 diopters.

Data was collected from 11 aviators that flew during the data collection period. In addition, eyepiece focus settings made by 5 other aviators were also measured with 2 of the 5 participating twice to obtain an indication of repeatability.

Figure 3. Adjusting the dioptometer for investigator's eye

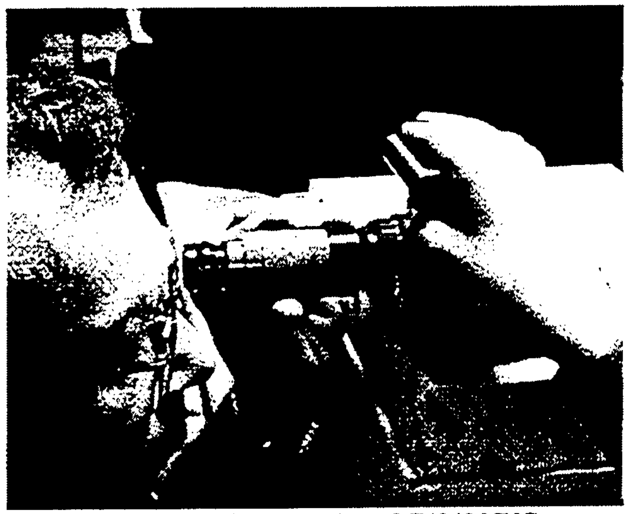

Figure 4. Measuring diopter setting of F4949 NVGs.

Results

The average for the 16 pilots (2 with repeated measures) for the 2 oculars (36 data points) was -0.96 diopters with a standard deviation of 0.78 diopters. This is relatively close to the -1.1 diopters obtained in the unpublished Air Force survey. The average setting for the 11 pilots that flew actual missions with the NVGs that they had adjusted during our measurement visit was -0.63 diopters with a standard deviation of 0.63.

One individual in particular had a relatively high reading of -2.5 diopters in each eye. In an effort to determine the significance of this relatively high setting, we adjusted an NVG to -0.75 diopters in each eye and asked the individual to look through the NVGs at the Hoffman 20/20 NVG tester to see if he found this setting acceptable. His response was that he could probably adapt to this setting but that when he just quickly looked into the tester (which provides a series of bar patterns of different levels of resolution), he could only see about 20/35 Snellen acuity whereas with the setting he had adjusted to (-2.5 diopters) he could readily see something better than 20/25 Snellen acuity. Whether this is a dark focus affect, an instrument myopia effect, or something else remains to be seen. However, if there are individuals within the NVG flying population that have difficulty accommodating to a fixed focus eyepiece setting of about -.75 diopters then we need to address this issue.

CAT'S EYES NVG MEASUREMENTS

Method

A total of 12 Cat's Eyes NVGs were obtained from the US Navy to measure their fixed focus eyepiece diopter setting. Since there was an indication that the Cat's Eyes might have astigmatism, a slightly different measurement strategy was used.

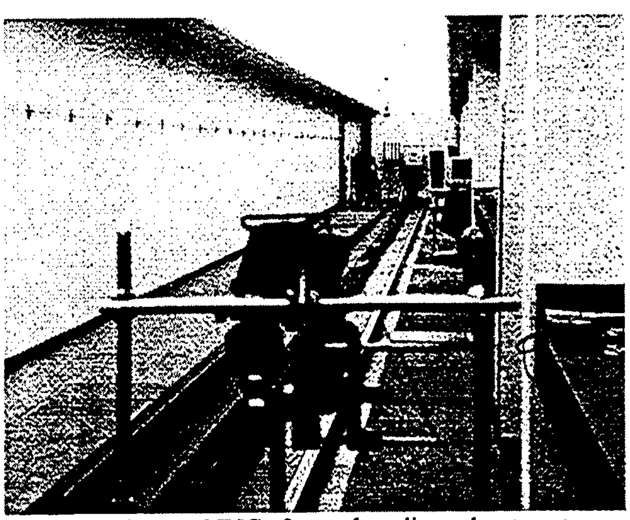

Figure 5. Cat's Eyes NVGs focused on distant bar target

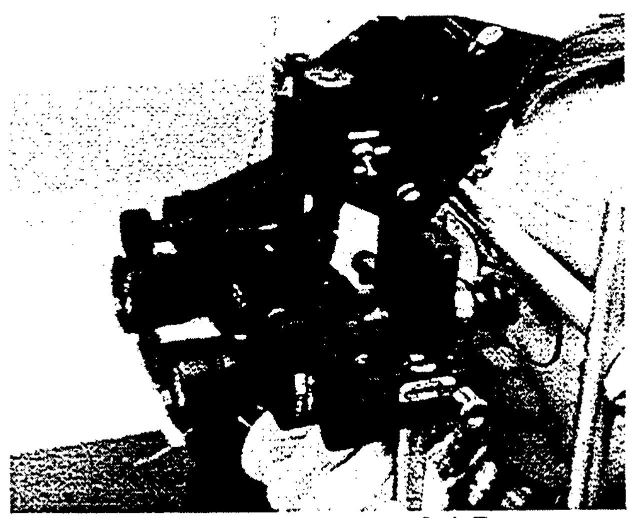

Figure 6. Using dioptometer to measure Cat's Eyes

A grating pattern was set up at the end of a long room (150 feet away- see figure 5) and the NVG objective lens was adjusted for best focus. The dioptometer was then adjusted for the investigator's eye as before and focused to produce the best image of the vertical bars. This diopter reading was recorded and the grating was then turned 90 degrees to produce horizontal bars. Again, the dioptometer was adjusted for best focus of the horizontal bars. If astigmatism was present the horizontal and vertical bars would be in focus at different diopter settings on the dioptometer. No consistent astigmatism effect was found. A total of four observers made measurements of each of the 24 oculars.

Results

A total of 6 measurements were made for each Cat's Eye ocular: 3 measurements from one observer and 1 measurement each from 3 more observers. There was no significant difference between observer measurements. These 6 readings were averaged to obtain a single diopter value for each of the 24 oculars. The average diopter value for the 24 oculars was -0.24 diopters with a standard deviation (for the 6 readings) of 0.07 diopters. The optical power of the 24 oculars ranged from -0.07 diopters to -0.42 diopters. This is significantly different than the reported specified value of -1.0 diopters.

DISCUSSION and CONCLUSIONS

From the results of the different sections presented above, it is apparent that there is no obvious eyepiece diopter value that should be selected. The in-house study points to a -0.75 diopters as a reasonable choice, the Nellis field data suggests something between -0.6 and -1.0 diopters, and the Cat's Eyes data suggests that -0.25 was an acceptable value for Naval aviators. In addition, the unpublished Air Force survey effort noted earlier had an average eyepiece setting of -1.1 diopters with a standard deviation of about the same size[7]. The unpublished manuscript by Gleason[5] concluded with several options that all involved a fixed setting with "snap-on" auxiliary lenses. In the Gleason study, they found the best visual acuity was at -0.75 diopters, with -0.5 diopters a close second. In addition, in their "long-term" wear study they found subjects commented (unsolicited) on discomfort for the fixed -1.5 diopter setting (long-term was for a 4 hour period)[3,4]. Based on these results, it appears that a fixed focus value somewhere between -0.25 and -1.0 diopters should be reasonable. The concern with selecting too high of a minus value (e.g. -1.0) is that hyperopes (far-sighted folks) might have difficulties. On the other hand, there are some individuals that are adamant that they need a high minus value (e.g. the Nellis anecdote related previously).

Another factor that needs to be considered is the visual capability of the individual if he/she needs to remove the NVGs and just use unaided vision. If the individual is presbyopic (focus ability about gone due to age), and he/she needs glasses in order to see the NVG image set for -1.0 diopters, then that person's vision will be adversely affected if the NVGs are removed.

It is apparent that further work needs to be done in this area. However, it appears the current best solution to the fixed focus problem is probably to select either -0.5 or -0.75 diopters for a setting and provide selected "snap-on" lenses, at least for the current program of the IPNVG, to achieve other settings (to be determined). This will allow for an actual field evaluation of the IPNVG with different eyepiece focus settings and may lead to an acceptable, single value for eyepiece focus.

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BIOGRAPHY

H. Lee Task has been employed as a research scientist for the US Air Force since 1971. He has served as chief scientist for the Armstrong Aerospace Medical Research Laboratory and in March of 1997 was selected as the Senior Scientist for Human-Systems Interface of the new Air Force Research Laboratory at Wright-Patterson AFB, Ohio. He is currently involved in research and development in the areas of helmet-mounted displays, vision through night vision goggles, optical characteristics of aircraft windscreens, vision, and display systems. He has a BS Degree in Physics (Ohio University), MS degrees in Solid State Physics (Purdue, 1971), Optical Sciences (University of Arizona, 1978), and Management of Technology (MIT, 1985) and a Ph.D. in Optical Sciences from the University of Arizona Optical Sciences Center (1978). During his career he has earned 42 patents and has published more than 90 journal articles, proceedings papers, technical reports, and other technical publications.

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NVG eyepiece focus (diopter) study

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Abstract

Technology is advancing to the point where night vision goggle designs being developed have wider fields of view to help achieve an increase in situational awareness. The appropriate diopter setting for the eyepiece of these goggles needed to be determined. Aircrew members were surveyed to determine the range of diopter settings they were using. In order to determine what fixed setting would work the best, two diopter settings were chosen (-1.0 and –0.5) to preset aircrew members' goggles. The aircrew flew with these presettings and then filled out a 14-question survey about the diopter settings.

Keywords

Diopter, dioptometer, field of view, night vision goggles, AN/AVS-9, Panoramic Night Vision Goggle (PNVG), Integrated Panoramic Night Vision Goggle (IPNVG), eyepiece diopter setting.

1. Introduction

Night vision goggles (NVGs) were developed by the US Army, but the US Air Force first used them for flying, in the early 1970's, as a temporary aid for helicopter pilots.[1] The majority of currently fielded U.S. Air Force aircrew goggles are the AN/AVS-9 (Figure 1), which have a 40-degree field of view (FOV) and adjustable eyepieces. A large survey of U.S Air Force NVG users in 1992 and 1993 revealed that an increased FOV was the number one enhancement desired by aircrew, with increased resolution a close second.[2] The current prototype goggle, the panoramic night vision goggle (PNVG) (Figure 1) has 100-degree horizontal by 40- degree vertical FOV, but it has a fixed-focus eyepiece. Currently in development, the Integrated Panoramic Night Vision Goggle (IPNVG) will have a 95-degree horizontal by 38-degree vertical FOV, and it may also have a fixed-focus eyepiece.

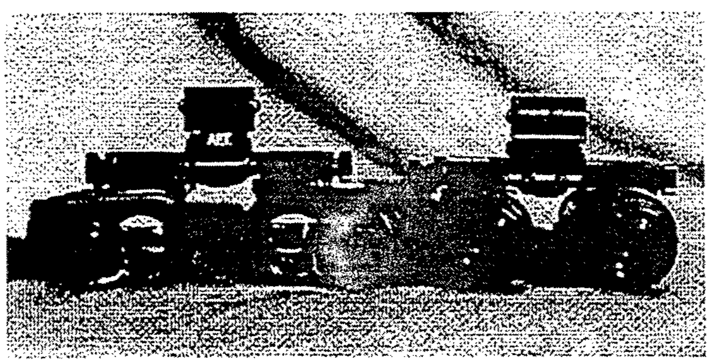

Figure 1. PNVG and AN/AVS-9

Three studies were performed to help determine what fixed diopter setting of the eyepiece will work for most aircrew. These studies were conducted at several Special Operations Squadrons in Ft. Walton Beach, Florida. This location was selected because of the large number of highly experienced night vision goggle trained aircrew in the Special Operations community. The first study investigated the diopter setting to which aircrew were adjusting their own goggles just prior to their missions. A second study addressed how repeatable aircrew were at setting their eyepieces following current NVG preflight protocol. The third study addressed how aircrew would tolerate a fixed-focus eyepiece.

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2. Study I

Study I was conducted at 5 US Air Force Special Operations Squadrons in the Ft Walton Beach, Florida area. It occurred in August 2000 over the course of a week. The purpose was to measure and record as many eyepiece settings from qualified NVG aircrew as possible.

2.1 Methodology

2.1.1 Participants: Ninety-five aircrew participated in the diopter setting study. There were 94 males and 1 female. Ages ranged from 21 to 59, with a median of 33. The 4th, 5th, 8th, 9th, and 711th Special Operations Squadrons participated. These squadrons were selected for their large numbers of highly NVG qualified aircrew. There were 32 pilots, 12 navigators, 20 loadmasters, 14 flight engineers, 8 gunners, 8 radio operators, and 1 life support technician.

2.1.2 Apparatus: The aircrew used their squadron's own goggles for this study. There are three power source mounts for the goggles and three types of power sources/goggle attachments: hand-held battery pack, opera mount, and the helmet battery pack. The helmet mount has a battery pack in the back of the helmet to power the goggles. The hand-held battery pack is small and lightweight. The opera mount is also a handheld power source, but much bulkier and looks like a helmet battery pack on a stick. The pilots and loadmasters use the helmet mounts. The remainder of the aircrew would typically use either the hand-held battery pack or the opera mount. These goggles are pre-flighted by aircrew members using the ANV-20/20 (Hoffman 20/20). The ANV-20/20 (Figure 2) is a portable case containing optics with a resolution chart, which allows aircrews to adjust their goggles to infinity focus.[3] An investigator used a hand-held dioptometer (Figure 3) to read the diopter settings off the eyepieces of the NVGs after they were set by the aircrew member. A diopter is an expression of the eyepiece focus described as the reciprocal of the image distance.[4]

Figure 2. ANV-20/20.

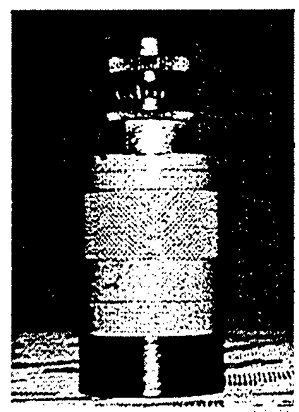
Figure 3. Dioptometer.

2.1.3 Procedure: The aircrew preflighted their own goggles as they normally did for their night missions. Preflighting is a term aircrew use to describe the focusing of the night vision goggle, typically done shortly before departing on their flying mission. After the crewmember adjusts the goggles for the distance between the crewmember's eyes, the crewmember looks into the ANV-20/20, sees a resolution chart, grossly adjusts the objective lenses by focusing on the coarser lines on the resolution chart, then adjusts one eyepiece at a time. The crewmember focuses the eyepiece by first turning the eyepiece counterclockwise which will blur the image in the positive diopter direction. Next, the crewmember turns the eyepiece clockwise until the image is clear. For that ocular, the crewmember then returns to the objective lens and "fine tunes" the objective lens so that the image of the fine lines on the resolution chart come into clarity. There are several procedures for recording visual acuity. Some aircrew members use the high-light level acuity/low-light level acuity of both eyes, and some aircrew record the visual acuity of each eye individually. We specified only that the aircrew record the acuity, as they would normally do in their squadron's logs. The goggles were then handed to the investigator, who read the left ocular diopter setting to the nearest 0.05 diopter (D) and recorded it on a data sheet. This method was repeated for the right ocular.

The eyepiece of the dioptometer was calibrated for the investigator. The investigator first sets the objective lens to 0 D. Next the investigator must find an object greater than 200 feet away (Figure 4). Looking through the dioptometer, the investigator rotates the eyepiece counterclockwise to blur the image and then rotates the eyepiece clockwise until the image is crisp and clear.

Figure 4. Focusing the dioptometer.

To read the diopter setting of the goggles, the investigator, in a darkened room, keeps the eyepiece of the dioptometer fixed. The investigator puts the objective piece of the dioptometer close to the eyepiece of the goggle. While focusing on the scintillations, the investigator rotates the objective lens of the dioptometer, counterclockwise (to blur the scintillations), and then clockwise to bring the scintillations into the best possible focus. Scintillations are the "noise" of the image intensifier tubes, which appeared as sparkles.[5] The diopter value was then recorded. All goggles were read from left ocular to right ocular. The aircrew member determined a visual acuity value by looking at the resolution chart in side the ANV-20/20. The visual acuity of the aircrew member was recorded on the data sheet.

2.2 Results

There were 95 aircrew participants who preflighted their goggles. The diopter settings of the 190 oculars (95 aircrew X 2 oculars) ranged from –3.9 to +0.5 D with a median of –1.05 D. Figure 5 shows the estimated Weibull distribution (see Appendix for a description of Weibull distribution) for the 190 oculars.

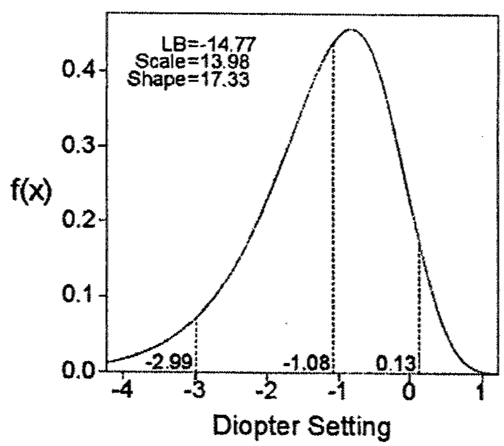

Figure 5. Estimated Weibull distribution for 95 aircrew. Referenced values are 5th, 50th and 95th percentiles.

3. Study II

Study II was conducted at the same time as Study I. The purpose was to see how consistent these highly trained aircrew were at preflighting their goggles.

3.1 Methodology

3.1.1 Participants: Eighteen aircrew members participated in the second study. There were 8 pilots, 3 loadmasters, 2 flight engineers, 3 gunners, and 2 radio operators. Ages ranged from 21 to 45 years, with a median of 32 years.

3.1.2 Apparatus: The apparatus in this study was the same as that used for Study I.

3.1.3 Procedure: The same procedure was used as in Study I, except each crewmember preflighted his/her goggles a total of five times. After the goggle was handed to the investigator, who read the settings of both oculars with the hand-held dioptometer, the investigator reset the eyepiece ocular to zero and handed the goggle back to the aircrew member.

3.2 Results

Figure 6 contains the diopter settings per aircrew individual for each of the five repetitions. The repeatability limit (rL) was defined as: approximately 95% of all pairs of adjustments from the same aircrew individual and same ocular should differ in absolute value by less than the rL. There were some individuals, such as number 15, who were much more variable than other individuals. Since some of the non-pilots appear to be less experienced than the pilots in adjusting their goggles, it was decided to utilize just the pilots (numbers 1-8) in computing the rL. The rL of the pilots was 1.2 D.

The pooled standard deviation of the left and right oculars for Figure 6 was determined for each aircrew number. There was not a significant correlation between the age and pooled standard deviation of the 18 aircrew ($R = 0.30$, $p = 0.2574$). This implies that there was not a relationship between an individual's age and the spread of his/her five settings.

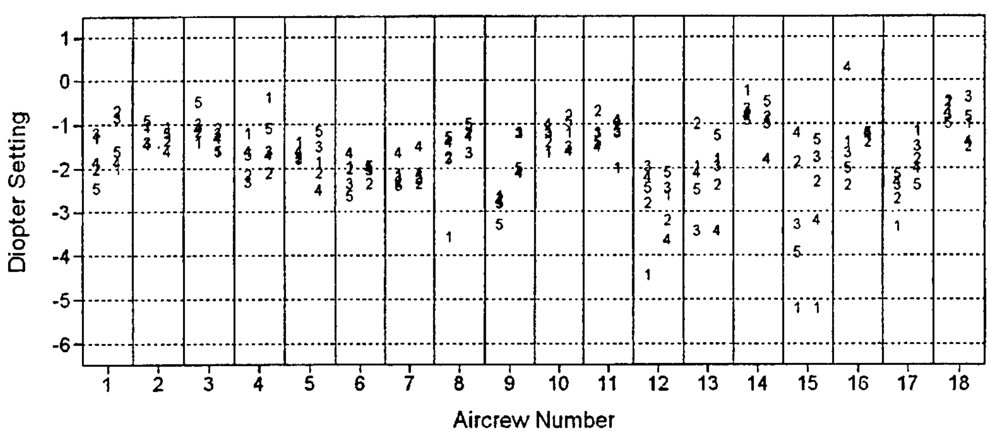

Figure 6. Diopter values for each crewmember, ocular, and adjustment are in the above figure. Within each aircrew number's window, the left ocular values are on the left and the right ocular values are on the right. The legend is the value of the adjustment (1-5). Aircrew numbers represent aircrew positions as follows: 1-8 pilot, 9-11 loadmaster, 12-13 flight engineer, 14-16 gunner, 17-18 radio operator.

4. Study III

The main purpose of Study III was to find out how aircrew liked certain fixed diopter settings. Since the median diopter setting from the first study was –1.05 D, it was decided to use –1.0 D as a starting eyepiece setting. When many of the aircrew felt that –1.0D was unacceptable, a diopter setting of –0.5 D was selected as a second setting to test.

4.1.1 Participants: Ninety aircrew participated in the November 2000 eye focus part of Study III. There were 41 pilots, 17 navigators, 12 loadmasters, 12 flight engineers, 4 gunners, 2 radio operators, and 2 flight surgeons. These crewmembers came from the 4th, 5th, 8th, 9th, 20th, and 711th Special Operations Squadrons.

Seventy-seven crewmembers filled out the questionnaire. There were 34 pilots and 43 non-pilots, consisting of 2 women and 75 men with ages ranging from 24 to 57 years and a median of 36 years. Forty-three aircrew flew with the –1.0 D setting and 34 aircrew flew with the –0.5 D setting. There were 4 individuals who responded to both the –0.5 and –1.0 D setting questionnaires. The NVG flying hours of all aircrew ranged from 15 to 3000 hours with a median of 500 hours.

4.1.2 Apparatus: The equipment was the same as in Study I, except there was a questionnaire. A logbook was used instead of data sheets and the eye focus aircrew settings were performed on a calibrated pair of goggles from AFRL. The questionnaire included background information such as name, sex, squadron, age, aircrew position, and NVG flying hours. Further questions focused on their flight with a fixed eyepiece. These questions included: (1) whether they adjusted the preset goggles in flight, and if they adjusted the preset goggles and why, (2) how long they wore the goggles continuously in-flight, and if they looked away from their goggles for an extended period, why, and for what duration, (3) whether they preferred their current goggle with the adjustable eyepiece focus or a fixed-focus goggle with a wider FOV, (4) six questions with rating scales for finding their opinions on the chosen fixed settings, and (5) a comments section at the end. Although the questionnaire had 14 questions, only a couple are considered for analysis here. We have analyzed an abridged version covering the sex of the aircrew member, the age, the aircrew member's NVG hours, briefly covering whether they preferred their own setting or the preset eyepiece, which was better with regard to eyestrain, blurriness, situational awareness, and threat detection.

4.1.3 Procedure: For this study, aircrew preflighted a pair of laboratory-owned and eyepiece-calibrated AN/AVS-9. This goggle was handed to the investigator who read the settings to the nearest 0.25 D and recorded it in the logbook. The aircrew member's flight goggles were previously preset to either –1.0 or –0.5 D using the hand-held dioptometer. The aircrew member used the ANV-20/20 to ensure that their visual acuity was acceptable by the aircrew member's own standards for flying. The specific visual acuity that is acceptable depends on the particular goggle. They recorded their visual acuity in our logbook. They flew their scheduled night sortie. When they returned to the squadron, they filled out the questionnaire.

4.2 Results

There were 185 aircrew total from (Study I and Study III) that were used for diopter setting analysis.
Their ages ranged from 20 to 59 years, with a median of 34 years. Seventy-three pilots and 112 non-pilots participated, including 7 women and 178 men.

The settings of the 370 oculars (185 aircrew x 2 oculars) ranged from –3.9 to +0.5 D with a median of –0.90 D. Figure 7 shows the estimated Weibull distribution for the 370 oculars.

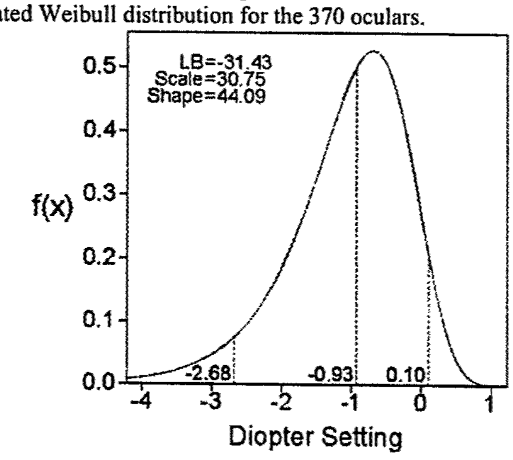

Figure7. Estimated Weibull distribution for all aircrew (referenced values are 5th, 50th, and 95th percentiles).

Figure 8 shows separate estimated distributions for the pilots and non-pilots. The parameter estimates for pilots only were: LB=-13.91, Scale=13.06, and Shape=18.11. The average of the left and right diopter settings was determined for each aircrew individual. There was a significant difference in these averages (p = 0.0216) between the pilots (N = 73) and other aircrew (N = 112) using the Wilcoxon rank sum test.

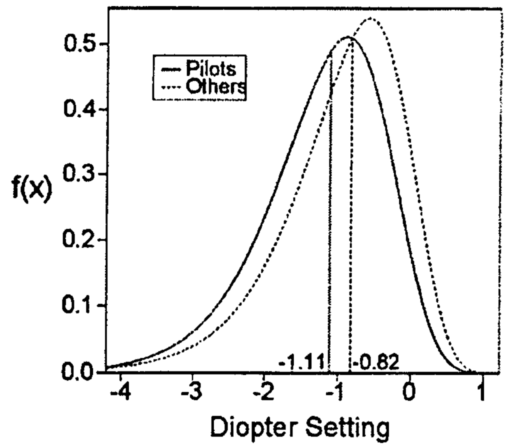

Figure 8. Estimated Weibull distributions for pilots versus others (reference values are 50th percentiles).

Ocular disparity is the difference in diopter settings between the right and left eyepiece. The absolute difference in ocular disparity ranged from 0 to 2.5 D with a median of 0.4 D. Of the185 aircrew, approximately 29% had ocular disparity greater than 0.5 D.

Table 1. This table shows a summary of the comparison of fixed settings vs. the aircrew member's personal settings. We compared fixed focus of either –1.0 D or –0.5 D to adjustable focus. The fixed settings were compared to the aircrew member's personal setting, and how it affected: the mission, reducing eyestrain, situational awareness, reducing blurriness, and threat detection.

Table 1. Percent of aircrew rating effect of fixed eyepiece setting the same, somewhat better, or much better compared to personal setting.

Effect of Fixed Eyepiece Setting	Percent Same or Better	
	-1.0 D (N=43)	-0.5 D (N=34)
compared to personal	60	47
mission accomplishment	86	71
reducing eyestrain	76	53
reducing blurriness	51	38
situational awareness	86	67
threat detection	85	67

5. Discussion/Analysis

The Study I excursion was a data gathering mission to determine to what diopter values aircrew were setting their goggle eyepieces. The data were examined to determine the best possible single diopter setting which might work for the NVG using community. The median setting of –1.05 D resulted in a starting fixed setting of –1.0 D. We were also able to see that the settings ranged from –3.9 to +0.5 D. How variable the aircrew were in adjusting their oculars was another concern, since with a fixed-focus aircrew would not have an option of different diopter settings in each ocular. Twenty-nine percent of setting disparities were over 0.5 D, possibly indicating that refresher courses in NVG focusing could be helpful. This is important because a person's eyes do not accommodation sufficiently to differential stimuli greater than 0.5 D.[6] Suppression does not occur when the diopter difference between the two eyes is less than about 0.5 D.[6] While people may have different diopter requirements in each eye, they should have been corrected to 20/20 Snellen acuity, and most people do not have large differences in their eye prescriptions. This brings up the concern that a significant percentage of the aircrew were likely adding eyestrain and accommodating with both eyes inappropriately. Of course, a fixed-focus eyepiece would alleviate this issue for most aircrew.

Looking at the 18 aircrew that performed the repeatability study, there are several issues to be discussed. The repeatability was calculated for the pilots. The pilots had a repeatability limit of 1.2 D; so for an individual pilot, focusing one eye could be 1.2 D different from one preflight to another. This raises several potential issues. It is possible that individuals are not truly sensitive to the eyepiece adjustment of their goggles. If we were to take an aircrew member and set his goggles within 1.2 D of his personal eyepiece setting, this should be tolerable. The aircrew member did not wear these setting for more than the time required to focus in the ANV-20/20. While they may have been able to achieve an acceptable level of visual acuity, it is possible that some of these settings may have caused the aircrew eyestrain during flight.

It was observed that the pilots and loadmasters were able to focus their goggles with a narrower range compared to the other aircrew members. Their use of a helmet mount for the goggle may play a role in their ability to set eyepieces within a tighter range. With goggles anchored at a fixed distance from the individual's eyes, their hands are not needed to support the weight of the goggles during the focusing procedure. For mission safety, both pilots and loadmasters must be able to see more clearly, with better visual acuity, and less eyestrain than other aircrew members. The other aircrew members do not usually use their helmets to mount their goggles; instead, they typically use the opera mount or the battery pack to power the goggles. Neither of these devices can offer the same stability as the helmet mount. If supporting the weight of the goggles, an aircrew member's hands may become less steady from one eye focusing to the next. In addition, the distance of their eyes to the goggle would likely differ from each eye focusing. Other members do not wear the goggles as much in flight, so they may not take the same time to ensure the most clear eye focus. It can be noted that some of the greatest differences in ocular disparity for goggles were from the gunners; this could be because, in the aircraft, they do not wear the goggles very often or for very long on their missions.

If one were forced to pick an acceptable diopter setting, one could draw a line through Figure 6 cutting through the adjustment range of most of the 18 aircrew. This would be done with the assumption that all settings within each individual's range would be acceptable for that aircrew member and not cause too much eyestrain. When we pass such a line through –1.0 D, it essentially passes through all but 3 aircrew members' settings. Pilot #6 and pilot #7 were within 0.5 D of this line, so they may be able to find this setting acceptable. If –0.5 D were selected, 10 aircrew would likely not find this setting acceptable. The Study I and Study II analyses helped us select –1.0 D as a starting setting for Study III.

The settings from Study III were combined with the Study I settings, yielding an even clearer picture of where aircrews were setting their goggles. The estimated Weibull distribution for all the aircrew combined showed the 50th percentile to be –0.93 D. It has been reported that the optimum power is between –1.0 and –0.5 D by Pearce et. al.[7] and between –2.25 and –1.0 D by Mouroulis and Woo.[8] The pilots had a left shift in their diopter setting plot. Pilots were approximately –0.3 D (50th percentile of –1.11 D) more minus from the rest of the aircrew (50th percentile of –0.82 D). This could be because they tried to achieve the sharpest visual acuity possible. These results are remarkably similar to an Air Force Research Laboratory technical report on an 1993 survey in which an average eyepiece setting of –1.1 D was observed.[4] This result, a setting around –1.0 D, has also been supported in the literature indicating that acuity is maximized for a target at a distance corresponding to about 1.0 D of accommodation.[9] In a short-term wear study conducted by Gleason and Riegler, it was found that the best eye focus was –1.0 D, with this setting yielding the best average visual acuity across all conditions and subjects.[4]

Examining the questionnaire data, it appears that the –1.0 D fixed setting was less distasteful to the aircrew than the –0.5 D fixed setting; however, both the –1.0 and –0.5 D fixed settings were worse than personal settings for many of the aircrew. The greatest concern of the aircrew with the fixed setting appeared to be blurriness.

6. Conclusion

Is fixed focus or adjustable focus best for night vision goggles? Single-focus eyepieces are simpler, lighter, and cheaper because focus mechanisms are not needed; shorter single-focus eyepieces would reduce a goggle's overall length, bringing the center-of-gravity closer to the head while maintaining eye relief.[4] It has not been possible to find a perfect setting for all users, but –1.0 D may be acceptable to a large number of aircrew. The aircrew have become used to the ability to set their own goggles. Since aircrew members desire as much control over their missions as possible, it is likely that they would prefer to maintain this if possible. The views of the aircrew have been positively supported in the literature, that visual acuity is always better with an adjustable-focus eyepiece, than with a fixed-focus eyepiece.[10] Recent developments <u>may</u> permit a limited range of eyepiece adjustable focus for the integrated panoramic night vision goggle. This would likely be a 2 D range. Based on modeling, an eyepiece having a –0.25 to –2.25 D range is probably best. According to the Weibull distribution, this range would not cover approximately 25% of aircrew. Approximately 9% would want more negative adjustment, and approximately 16 percent would want more positive adjustment.

However, given people's ability to accommodate, if we assumed aircrew could accommodate ±0.5 D, the relative range would span +0.25 to –2.75 D, which would exclude only about 7% of the aircrew. Approximately 5% of ocular settings would be more negative than –2.75 D and approximately 2% would be more positive than +0.25 D. Also, when designing an optical product there are certain production tolerances that are allowed. We would not want the margin of error to be shifted in the more positive direction. If the settings were more positive than 0 D in the most positive direction, and if there was only a 2 D span of settings, the crewmembers that required the more negative settings would not be satisfied.

If adjustable lenses do not come into production, we may need to provide "snap on lenses"on a fixed focus eyepiece. These "snap on lenses" would be additional lenses that would attach to the eyepiece and would have minus or plus power. If we had a fixed eyepiece, based on the data we would likely choose –1.0 D. We might also provide a –1.0 snap on lens that would provide a total –2.0 D, which would only have approximately 13% of aircrew requiring more negative power. A +0.75 D lens would be utilized to provide a net –0.25 D. This would leave only approximately 16%of people to the right of this range who would require a more positive setting. These people that would be out of the range may not be satisfied due to the possibility of eyestrain, fatigue and possibly blurriness.

If we must have a fixed eyepiece, we would likely select –1.0 D. This appears to be the best setting. Snap on lenses would help meet the needs of the aircrew that require it. If variable focus becomes available, it will likely be well received by the aircrews and other NVG users. It would be advisable to be able to have a range that would effectively include crewmembers that would require +0.25 to –2.75 D. If a limited adjustable eyepiece can be designed with future goggles, then this should be undertaken, since there is no one diopter setting that will best serve all of our goggle users.

Acknowledgments

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Appendix

Weibull Distribution

Following is a description of the Weibull distribution.[11] This distribution was used to model diopter settings.

$$f(x) = \left(\frac{\beta}{\alpha}\right)\left(\frac{x - x_o}{\alpha}\right)^{\beta-1} e^{-\left(\frac{x-x_o}{\alpha}\right)^{\beta}} \quad \text{where } 0 < \alpha \text{ and } 0 < \beta$$

α = scale parameter, β = shape parameter, x_o = lower bound (LB)

$$F(x) = 1 - e^{-\left(\frac{x-x_o}{\alpha}\right)^{\beta}} \quad \text{transforms to: } Ln\{-Ln[(1-F(x)]\} = -\beta * Ln(\alpha) + \beta * Ln(x - x_o)$$

regression equation: $Y' = Intercept + Slope * X'$

so: $\beta = slope$, and $\alpha = e^{-\left(\frac{Intercept}{\beta}\right)}$

Parameter estimates are obtained by transforming the cumulative distribution F(x) to a form that can be used in linear regression. In the transformed cumulative distribution, estimates of F(x) are the cumulative proportion at every level of X from the observed data. The lower bound is determined by using the X_O value that makes the transformed cumulative distribution the most linear (i.e., yields the highest correlation). The scale and shape parameter estimates are determined from the intercept and slope estimates of the linear regression.

It is possible for the lower bound (X_O) to be an unattainable value. For example, absolute differences must be non-negative yet X_O may be negative. This negative lower bound is necessary to obtain the best fit of the transformed cumulative proportions. A desired goal in fitting the Weibull distribution is for the percentiles of the estimated distribution to match closely with the percentiles of the data. What should occur is the area under the curve ≤ 0 should closely match the cumulative proportion at $X = 0$ from the data.

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Brief Biography

Share-Dawn Angel was commissioned into the US Air Force in 1993. Before coming to the Air Force Research Laboratory at Wright-Patterson AFB, OH, she was a flight surgeon attached to the 9th Special Operations Squadron, Eglin AFB, FL. She has over 50 hours of NVG time in MC-130P Combat Shadows. She has a BS degree in Biology from George Mason University, Fairfax, Virginia, in 1993, and is a 1993 graduate of AFROTC from College Park, University of Maryland in 1993. She earned her medical degree from the Uniformed Services University, Bethesda, MD in 1997. In 1998, she completed a General Surgery Internship at Keesler Medical Center, Keesler AFB, MS.

4. MEASUREMENT OF NIGHT VISION GOGGLES AND RELATED COMPONENTS

The articles in the present section describe techniques used to measure other NVG parameters, such as gain, field of view, dark spots, distortion, magnification, image rotation, etc. Pinkus & Task (1998) presents the results of an interlaboratory study designed to determine the level of repeatability and reproducibility that can be achieved for measuring the NVIS-weighted transmission coefficient of aircraft transparencies (windscreens and canopies). This article is not about measuring NVGs *per se* but describes a measurement procedure for a component that may significantly impact the performance of NVGs used in aviation.

These articles are reprinted to provide the reader with a reference and background to better understand the measurement of NVGs and related components.

Aleva, D. L., Task, H. L., & Goodyear, C. D. (1998). **Repeatability and reproducibility of NVG gain measurements using the Hoffman ANV-126 test device.** *SAFE Journal, 28(2),* 106-111.

Marasco, P. L., Pinkus, A. R., & Task, H. L. (1998). **Photographic assessment of dark spots in night vision device images.** *Proceedings of the 36th SAFE Association* (pp. 20-25).

Marasco, P. L., & Task, H. L. (1999). **Optical characterization of wide field-of-view night vision devices.** *Proceedings of the 37th SAFE Association,* http://www.safeassociation.com

Task, H. L., Hartman, R. T., Marasco, P. L. & Zobel, A. R. (1993). ***Methods for measuring characteristics of night vision goggles.*** (Report No. AL/CF-TR-1993-0177). Wright-Patterson AFB, Ohio, Armstrong Laboratory. (DTIC No. A277046)

Pinkus, A. R., & Task, H. L. (1998). ***Interlaboratory study (ILS) of the standard test method for measuring the night vision goggle-weighted transmissivity of transparent parts.*** (Report No. AFRL-HE-WP-TR-1998-0016). Wright-Patterson AFB OH: Air Force Research Laboratory.

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Aleva, D. L., Task, H. L., & Goodyear, C. D. (1998). Repeatability and reproducibility of NVG gain measurements using the Hoffman ANV-126 test device. *SAFE Journal, 28(2)*, 106-111.

Repeatability and Reproducibility of NVG Gain Measurements Using the Hoffman ANV-126 Test Device

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INTRODUCTION

Night vision goggles (NVGs) are being used extensively by our special operations forces for covert night operations. Often the individual operational units purchase the NVGs directly from the manufacturer. Upon delivery to the unit, the NVGs are tested to verify that they meet the gain specifications. The Hoffman Engineering ANV-126 portable test set is used for this purpose. However, the reproducibility of the NVG gain measurements obtained with the ANV-126 was unknown. Therefore, operators were uncertain as to whether to reject NVGs whose gain measurements were slightly below the criterion value. In addition, there was concern among NVG researchers and operators that the intensifier tubes in some NVGs might be greatly mismatched for gain, resulting in the luminance seen by the operator being significantly higher in one eye than the other.

Two specific objectives which are addressed herein were:

- Objective 1: Determine the accuracy (repeatability and reproducibility) expected when measuring NVG gain using the Hoffman 126 test device.
- Objective 2: Determine the distribution of Binocular Gain Ratios for fielded NVGs in both the linear gain radiance region and in the automatic brilliance control (ABC) radiance region of operation.

These objectives were addressed by an NVG gain data collection effort conducted at HQ AFSOC/LGMA NVG maintenance facility at Hurlburt Field, Florida. The testing took place during the period 18-20 November, 1996.

OBJECTIVE 1

If a test device is going to be used to make acquisition or acceptance decisions then it is necessary to determine the accuracy of the device to insure the validity of any resulting decision. The Air Force has acquired a number of ANV-126 NVG test devices but the reproducibility of the NVG gain measurements obtained with the device is unknown. Sources of variance expected are changes in gain of the NVGs themselves, the operators making the measurements, the test device itself and differences between test devices.

Method

In order to establish an estimate of the reproducibility of NVG gain measurements using the ANV-126 test device it was necessary to collect data on several NVG oculars using several test devices and operators. It was desirable to include as many test devices as possible to obtain a good estimate of the variance between devices. The test plan was designed in accordance with ASTM Publication E-691 (1992) which outlines procedures for testing repeatability and reproducibility.

Operators. The operators were five scientists from Armstrong Laboratory (Aircrew Training Research Division [AL/HEA], Mesa Arizona and Human Engineering Division [AL/HEC], Wright-Patterson Air Force Base, Ohio) and one representative from Hoffman Engineering. All had previous experience using the ANV-126 to measure NVG gain.

Test Sets. The test sets were nine Model ANV-126 Night Vision Device Test Sets for Ground Support Maintenance.

The ANV-126 is produced by Hoffman Engineering. It is a self-contained portable test set designed for field operational checks and depot-level NVG maintenance. Four of the test sets were resident at the Hurlburt facility, two were brought from Eglin Air Force Base, one from Hoffman Engineering, and one each from AL/HRA and AL/CFH. All test sets had been calibrated within one year of the test (range from 1 day to 8.5 months).

NVGs. The NVGs utilized in this testing were all F4949 D model. These NVGs were currently in use at Hurlburt Field by the SOF and were in the repair facility for periodic maintenance.

Procedure. Ten NVGs (20 oculars) were tested using 9 test sets and 6 operators (measurement personnel). NVG gain was measured using the standard procedures in the ANV-126 users' manual (1996) which include exposing the ocular to the maximum ANV-126 test level radiance input for 60 seconds prior to measurement. All gain measurements were made at the 0.1 X 10^{-3} fL radiance level.

Each operator tested 10 NVGs on each of 9 test sets. Six measurements were made of each NVG (3 for each ocular). Operators did not reset input level between measurements (i.e., the procedure was to exercise goggle, measure Left ocular, measure Right ocular, measure Left ocular, measure Right ocular, measure Left ocular, measure Right ocular, go to next NVG). It took an operator 30 - 45 minutes to measure all 10 NVGs with one test set. Operators by test set order was counterbalanced in case of learning or fatigue effects.

The day to day repeatability issue was addressed on Day 2. In this case we were concerned about the variability of the individual test sets over time. The procedure on Day 2 was the same as on Day 1, with the exception that 3 operators (Operators A, B, and F) tested each of 5 NVGs (all odd-numbered NVGs from Day 1) on each of 8 test sets (test set 9 was found to be defective). This, along with corresponding data from Day 1, allowed the assessment of repeatability of individual test sets over a 2-day period.

Results

Repeatability. Repeatability refers to the consistency of test results obtained by a single operator with a single test set. A repeatability limit was calculated for each of the 20 oculars. The repeatability limit tells us that for any pair of measurements by the same operator using the same test set and in a short time period, there is a probability of 0.95 that the second measurement will be within +/- the repeatability limit of the first measurement. The repeatability limit is given by $Repeatability = 2.77\sqrt{\sigma_e^2}$ where σ_e^2 is the error variance. The average repeatability limit for the Day 1 measurements was 138 or 2.4 percent of the mean gain (overall mean gain = 5786. Repeatability was not found to increase or decrease significantly as a function of gain value (p = 0.67). Therefore, the repeatability of an individual gain measurement may be calculated by using the average repeatability value:

$$Repeatability\ limit = 138.$$

On Day 2, three operators measured 5 NVGs (10 oculars) using 8 test sets. Repeatability (same ocular, same operator, same test set) over Days 1 and 2 averaged 4.1 percent of the mean gain for all oculars. Again, repeatability was not found to increase or decrease significantly with gain value (p = 0.46); the calculated repeatability over the two-day period is given by:

$$Repeatability\ limit = 240.$$

Reproducibility. Reproducibility refers to the consistency of test results obtained by various operators using different test sets. A reproducibility limit was calculated in a manner similar to the procedure used to calculate the repeatability limit. However, the reproducibility limit is based on comparisons across all operators and test sets. The calculation of the reproducibility limit takes into account both operator and test set variances as well as the error variance for a single operator and test set. The reproducibility limit is represented by:

$$Reproducibility = 2.77\sqrt{\left(\sigma_s^2 + \sigma_o^2 + \sigma_{sXo}^2 + \sigma_e^2\right)}$$

where σ_s^2 is the test set variance, σ_o^2 is the operator variance, σ_{sXo}^2 is the variance of the test set by operator interaction and σ_e^2 is the error variance. Unlike the repeatability limit, which remained fairly constant across the range of gain values measured, the reproducibility limit was found to increase significantly with increased gain value (p = 0.0013); reproducibility limits for the 20 oculars ranged between 7.5% and 10.5% of the measured gain average. The reproducibility limit of an individual gain measurement is represented by:

Reproducibility limit
= 186 + 5.6% of the gain measurement.

Discussion

While the repeatability and reproducibility limits do not give us an estimate of the accuracy of the gain measurement, they do allow us to calculate a range within which 95% of all differences between pairs of measurements can be expected to fall. For example, if our first measurement of an NVG ocular indicates a gain of 5800, then we can calculate the repeatability limit by: 5800 + 240 and 5800 - 240. This tells us that 95% of all second readings of that ocular by the same operator using the same test set within a 24 hour period can be expected to fall between 5560 and 6040. Likewise, we can calculate a reproducibility limit by: 186 + 0.056 * 5800 = 510.8. This tells us that 95% of all second readings by a different operator using a different test set can be expected to fall between 5289 and 6311.

Differences due to operators were much smaller than differences due to test sets. The gain values for test sets varied between an average of 5512 for test set 8 to an average of 5967 for test set 7. This is a range of 455. The average gain values for operators varied between 5765 for operator A and 5806 for operator C; this is a range of only 41. Thus, the range of values due to test sets is an order of magnitude greater than that due to operators. The highly trained operators appear to be responsible for relatively little of the variability in the gain measurements.

Difficulties encountered with test set 9 indicate that the test sets should be checked for proper functioning between routine calibrations. The ANV-126 users' manual should be consulted for the probe check procedure.

OBJECTIVE 2

There has been concern expressed by NVG researchers and operators that a large gain ratio (higher gain/lower gain) between the left and right NVG oculars may cause problems during NVG operations. Some evidence suggests that large gain ratios (greater that 1.5) may cause binocular rivalry and illusions of depth perception related to the Pulfrich Phenomenon (Pulfrich, 1922). There is currently no specification regarding gain ratio for NVGs. The purpose of this phase of the gain testing was to assess the extent of the problem. Gain ratios for a large population of NVGs were measured at Hurlburt Field, FL on 19 November 1996.

It is assumed that the binocular gain ratio (the gain of the NVG ocular with the highest gain to the gain of the other ocular) in the linear gain region is a reasonably accurate estimate of the binocular luminance ratio one might expect from an NVG. With this assumption, it is desirable to establish a maximum allowed binocular gain ratio to ensure that the luminance difference in the two channels of the NVGs will not be objectionable to the NVG user. In addition, it is desirable to measure the binocular luminance ratio of the NVGs when the tubes are in the ABC mode since this may be significantly different from the ratio obtained in the linear region. Again, the reason for this is to ensure binocular luminance compatibility. A separate study will determine what maximum allowed binocular gain ratio and ABC mode luminance ratio should be established. The purpose of this activity was to determine what levels of binocular luminance disparity exist in currently fielded NVGs. This activity had already been partially accomplished by Air Force Special Operations Command (AFSOC) which had collected gain data on 252 NVGs operating in the linear gain region. Table 1 is a summary of these data reduced to show binocular gain ratios: More than 97% of these NVGs had a gain ratio of 1.28 or less indicating the NVGs are reasonably well balanced in gain between right and left channels. These same data are shown in graphic form in Figure 1.

Table 1. Summary of AFSOC data for 252 NVGs showing percentage of NVGs achieving different levels of binocular gain ratios.

Gain Ratio	% of NVGs
1.04	19.4
1.08	37.7
1.12	55.6
1.16	77.8
1.20	89.3
1.24	92.9
1.28	97.2
1.32	97.6
1.36	98.8
1.40	99.2
1.44	99.6

Operators. The operators were three of the five scientists from Armstrong Laboratory (AL/HRA) who took part in the Objective 1 testing.

Test Sets. The test sets were 3 of the 9 Model ANV-126 Night Vision Device Test Sets for Ground Support Maintenance that were used for Objective 1. These test sets were identified as test sets 1, 2 and 3.

NVGs. Fifty-nine Model F-4949D NVGs were tested. These included the 10 NVGs used for the Objective 1 testing.

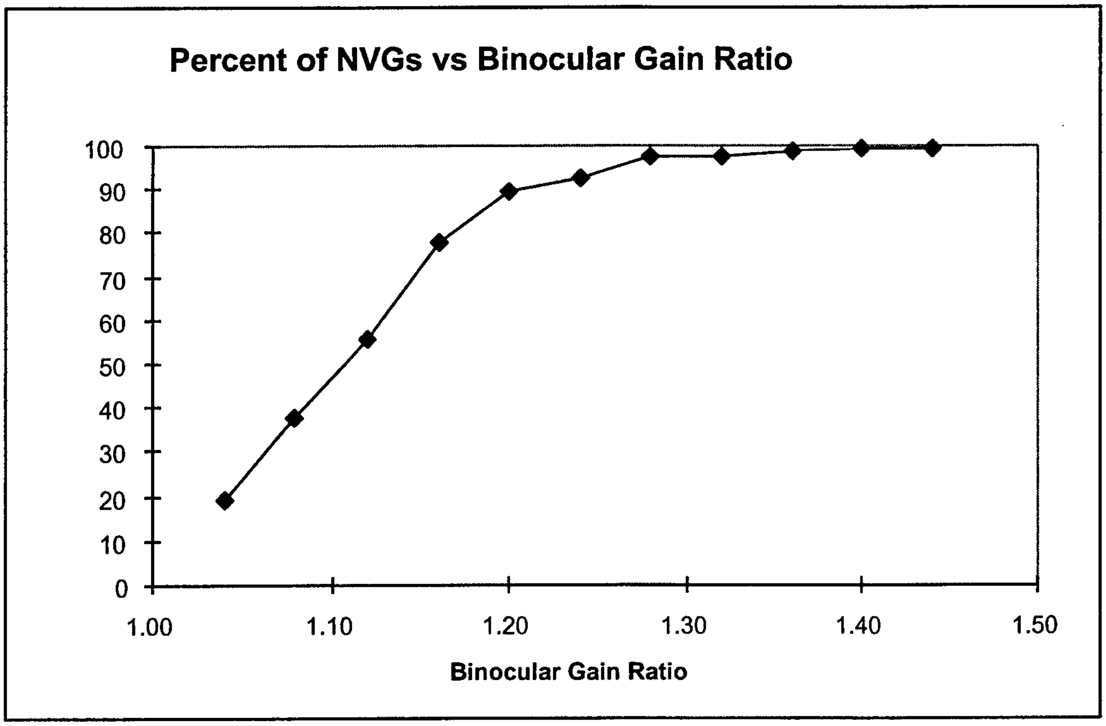

Figure 1. AFSOC gain data showing percent of NVGs achieving various levels of binocular gain ratio. Only one NVG exceeded a ratio of 1.50 (it was 1.57).

Procedure. Each NVG was measured according to the procedures used to measure gain from the phase I testing. However, after gain was measured at an input illumination of 0.1 X 10^{-3} fL, the input level was increased to the maximum provided by the test set (approximately 1.4 X 10^{-3} fL). The illumination level placed the NVG in the automatic brilliance control (ABC) operating mode. Gain then was measured from each ocular under ABC conditions.

Results

The data were analyzed in a fashion similar to that shown in Table 1 and Figure 1. The results of the ratio measurements are shown in Table 2 and Figure 2 for the linear region and the ABC region. The results, in the linear region, revealed that only one NVG (s/n 3781 gain ratio = 1.72) had a gain ratio higher than 1.5. The average gain ratio was 1.11. In the ABC region, no NVGs had a gain ratio higher than 1.5, with the highest being 1.22 and the average being 1.06.

Repeatability and Reproducibility of Ratios. In a similar manner as described above, the repeatability and reproducibility of the NVG gain ratio between oculars was calculated. The repeatability limits (same operator, same test set) for gain ratio measurement can be calculated by:

Repeatability limit
= -0.037 +6.4% of the gain ratio.

Similarly, the reproducibility limits (different operator, different test set) can be calculated by:

Reproducibility limit
= -0.064 + 13.4% of the gain ratio.

Discussion

These data permit a practical decision on establishing an acceptable level of binocular luminance disparity until data is available from other studies to determine if the interim binocular ratio should be changed (increased or decreased) based on visual performance and acceptance. Given the fact that many thousands of NVGs are currently fielded without significant user complaints regarding luminance disparity it is probable that the vast majority of these NVGs are in an acceptable binocular disparity range. The AFSOC data indicates that more than 97 percent of the NVGs they tested were at or below the binocular gain ratio of 1.3 which was the maximum level of disparity recommended in the Boeing Handbook for Equipment Design (Farrell and Booth, 1984). More than 93 percent of those tested in the current evaluation were at or below 1.3 in the linear region and all were below 1.3 in the ABC region.

Table 2. Results of Gain Ratio Measurements of 59 NVGs in theLinear and ABC Regions.

Gain Ratio	Linear - #NVGs	Linear - Cum %	ABC - #NVGs	ABC - Cum %
1.00	0	0	0	0
1.04	15	25.4	30	50.8
1.08	32	54.2	48	81.4
1.12	44	74.6	52	88.1
1.16	49	83.1	53	89.8
1.20	51	86.4	56	94.9
1.24	54	91.5	59	100
1.28	55	93.2	59	100
1.32	56	94.9	59	100
1.36	56	94.9	59	100
1.40	56	94.9	59	100
1.44	57	96.6	59	100

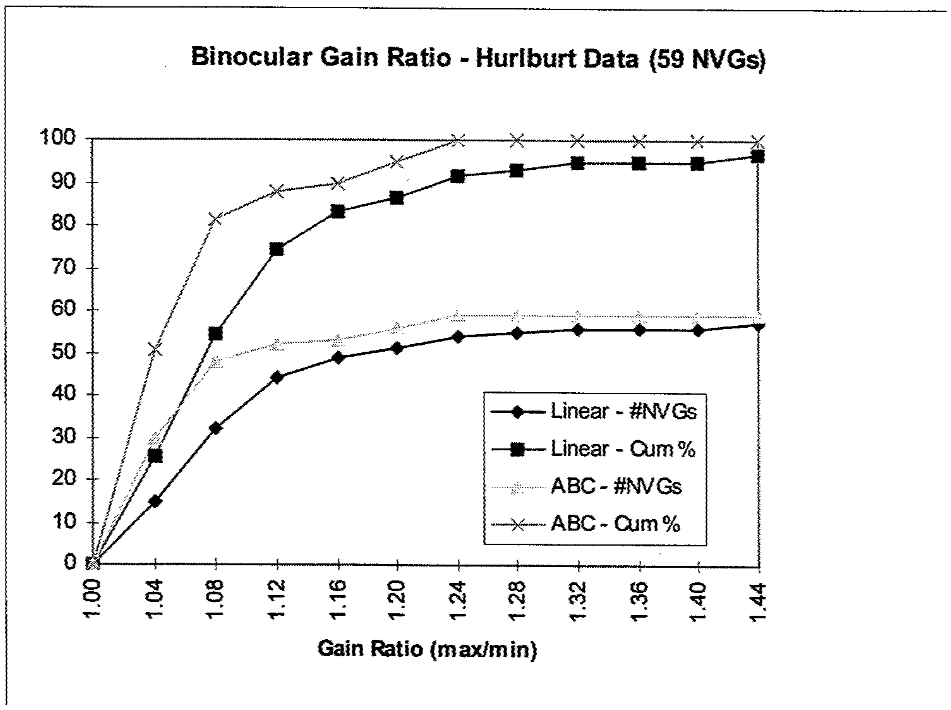

Figure 2. Results of gain ratio measurements of 59 NVGs in the linear and ABC regions.

As was discussed above for gain measurements, repeatability and reproducibility can be calculated for the measured gain ratio of a particular NVG. If, for example the measured gain ratio is 1.11, the repeatability can be calculated by: $-0.037 + 0.064 * 1.11 = 0.034$. Therefore, 95% of all differences between measurements of this NVG by the same operator using the same test set within a short period of time could be expected to fall between 1.076 and 1.144. Similarly, the reproducibility can be calculated by: $-0.064 + .134 * 1.11 = 0.085$. Therefore, 95% of all differences in the ratio measurement of this NVG by a different operator using a different test set could be expected to fall between 1.025 and 1.195.

CONCLUSIONS

The repeatability (same test set, same operator) and reproducibility (different test set, different operator) of gain measurements using the Hoffman 126 test device have been quantified. These values should be useful to the operational units in setting limits for the acceptance/rejection of NVGs. However, this does not erase all uncertainty from the NVG acceptance/rejection question. Assume, for example, that the criterion for acceptance were gain equal to or greater than 5000. Table 3 gives the reproducibility limit and reproducibility range for several gain values around 5000. As we can see from the table, gain values between 4600 and 5400 result in uncertainty, as the reproducibility range spans both the unacceptable and acceptable regions. NVGs which test in this range may require further evaluation. However, we can feel confident that, for a criterion of 5000, NVGs which test below 4500 should be rejected and those which test above 5500 should be accepted.

Table 3. Reproducibility Limits and Ranges for a Selected Set of Gain Values

Gain Meas	Repro Limit	Repro Range
5500	494	5006 - 5994
5400	488	4912 - 5888
5000	466	4534 - 5466
4600	443	4157 - 5043
4500	498	4062 - 4938

It was determined that the gain ratio between oculars for most of the NVGs tested did not exceed 1.5 in either the linear or the ABC region of operation. This finding was consistent with the fact that no NVGs were identified at Hurlburt Field as being regularly shunned by aircrew.

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Photographic Assessment of Dark Spots in Night Vision Device Images

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ABSTRACT

Visible defects in night vision device (NVD) images, arising from image intensifier (I^2) tube defects and dirt on the device's optics, can become more than cosmetic blemishes. They can act as visual distractions and may be large enough to mask critical information pilots need to conduct normal night vision operations. This paper is concerned with the assessment of NVD dark spots. Current methods of assessing dark spots examine only the image intensifier tube, ignoring spots due to dirt and dust introduced during night vision device assembly. Current methods are limited in the size of spot that can be counted and do not address the issue of spot contrast. This paper discusses a photographic method for classifying, locating, and counting dark spots in an assembled night vision device.

Also documented in this paper is an experiment to determine an observer's ability to classify round dark spots, conducted as part of an effort to determine the accuracy of the photographic test procedure. To quantify the defects, they were classified by size and then counted. Inspectors used a comparison key as an aid in categorizing dots by size. The defect specification should not exceed the classifiers' visual discrimination capabilities. This study directly examined the dot size classification performance of observers using dots of 3, 4, and 6 minutes of arc (MOA) in diameter.

INTRODUCTION

A dark spot is anything appearing dark to an observer viewing the output of an I^2 tube with the input illuminated by a uniform light. Dark spot defects can be caused by photocathode burns, broken or contaminated (blocked) fibers in the fiber optic twister, bad channels in the microchannel plate, phosphor burns, or dust on the outside surfaces of the I^2 tube. These defects manifest themselves as black spots of varying sizes and can be located anywhere in the field of view. Centrally located black spots may have a greater deleterious affect on the observer's visual performance than do those located in the periphery due to the importance of foveal vision [Ronchi, 1957].

Not all blemishes appear perfectly black. An obstruction inside the I^2 tube's fiber optic twister might appear gray but could still obscure valuable visual information, especially in dim light. For the purposes of these tests, a minimum contrast, C (as defined by Equation 1), of 30 percent was adopted. Blemishes exceeding a contrast of 30 percent were counted as a dark spot [MIL-I-49428(CR)]. In Equation 1, L_1 and L_2 are the luminance of the bright background and the luminance of the dark spot respectively.

$$C = \frac{L_1 - L_2}{L_1 + L_2} \qquad (1)$$

For years, pilots and aircrew members experienced in NVD operations have known that dark spots in the NVD field of view were distracting. In response, as part of a program to develop an ejection compatible NVD for the U.S. Air Force, an effort was started to improve NVD image quality by significantly reducing the number and size of blemishes, or dark spots, in the NVD field of view. Available dark spot specifications, such as those for the Army's Aviator's Night Vision Imaging System (ANVIS) and the Navy's Cat's Eyes NVD were considered too loose. Older specifications called for 10.3 MOA spots as the smallest to be graded [MIL-I-49428(CR)]. New requirements necessitated the measurement of spots as small as 3 MOA [F33657-91-R-0045].

Classifying and counting dark spots of this size is difficult using current methods. The diameters of countable spots were considerably smaller than previously required for any NVD. Initial efforts at spot measurements used a ten-power (10X) microscope to directly view the image intensifier tube output [MIL-I-49428(CR)]. The magnification was low enough to allow an observer to view the entire tube output all at once and made for quick tube examinations. Unfortunately, it was difficult to use this method to quantify the small blemishes countable under the new dark spot requirement nor could it account for dark spots due to dirt introduced during NVD assembly. Increasing the microscope magnification improved the sensitivity of the procedure, but this approach was limited by the luminance output of the I^2 tube. Also, the observer could no longer view the entire tube output, significantly slowing the process and reducing their ability to accurately catalogue a spot's location.

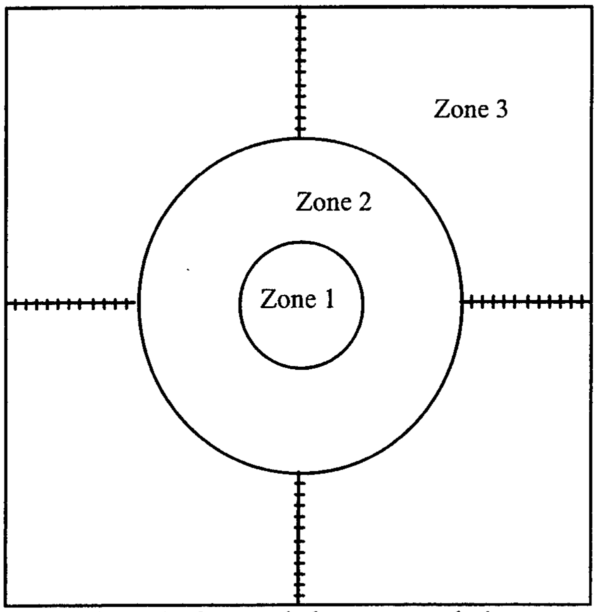

Figure 1. Current dark spot target design.

To overcome the disadvantages of current dark spot tests, a new procedure was developed, involving photographing the NVD output under lighting controlled to yield the best photographs. Then, a trained observer would examine the photographs to catalogue the size and zone of tube blemishes.

Dark Spot Photography
This experiment was conducted in a room with light control capable of complete darkness. Before attempting the assembly and positioning of the required equipment, the eyepiece lenses of the NVD and the data acquisition camera were focused to optical infinity. The camera lens was also set to infinity by focusing on a sufficiently distant object.

With the room lights on, the Dark Spot Target (see Figure 1) was positioned against a wall, perpendicular to the optical axis of the NVD under test. The minimum target dimensions were calculated using trigonometry and based on testing a 40-degree field-of-view NVD at a testing distance of 5 feet (60 inches) from the NVD objective lens. Zone diameters were also calculated using trigonometry. Zone 1 was a 5 degree radius circle centered in the NVD field of view. Zone 2 was an annulus having an inner radius of 5 degrees and an outer radius of 13 degrees. Zone 3 encompassed everything outside of the 13 degree radius circle. The target was plotted on white paper with lines one eighth of an inch thick, subtending about 7 MOA (Figure 1) and mounted to white foam-core board. Small marks were added to horizontal and vertical lines through the outer zone at 1 degree intervals, to aid NVD alignment.

The test NVD was then positioned using its helmet mount and other optomechanical parts on a tripod such that the test ocular was five feet from the target and roughly centered on the target at the same height as the target center. A Nikon 35 mm single lens reflex camera with a 28 mm focal length wide-field-of-view Nikon lens was then mounted to another tripod and placed in position behind the test NVD.

Next, a lamp was fitted with a 7.5 Watt frosted incandescent light bulb and attached to an aluminum rail, which was bolted to a photographic tripod. A mask was placed over the lamp housing to reduce the lamp to a 31 mm diameter source. An 8 X 10 inch, one quarter inch thick Plexiglas piece was fixed to the end of the rail, perpendicular to a line from the lamp to the center of the target. Light shaping filters were held by their edges to the Plexiglas sheet with cellophane tape. Then, the distance between the lamp and the filter was adjusted to closely match the filter's design distance. The lamp and filter were positioned slightly behind, above and off to one side of the camera such that the camera did not cast a shadow into the test NVD's field of view.

Light Shaping Filter
Several characteristics of the NVD output make photography difficult. The I^2 tube itself inherently has a three to one center to edge luminance falloff (see Figure 2) making the center of the NVD image much brighter than the edge. This effect is not very noticeable to an observer due to the human eye's logarithmic luminance response [Cornsweet, 1970]. However, it is much easier to capture this luminance falloff on film. This undesirable phenomenon can mask the desired information printed on a photograph.

Another phenomenon that hinders NVD photography is the illumination of the target. Theoretically, if a Lambertian extended light source is used to illuminate the entire target, a "Cosine-to-the-Fourth" luminance falloff would be seen on the target [Dereniak, 1984]. This is noticeable because of the size of target required to fill the entire NVD field of view.

To overcome the effects of these phenomena, a filter exhibiting non-uniform absorption was used to alter the illumination falling on the target. To design the lamp filter, the two falloffs were normalized and multiplied together as a function of angle, labeled "Total Falloff" in Figure 2. Filter transmissivity would have to have the inverse profile with large attenuation in the center and gradually decreasing towards the edges of the target, as shown in Figure 3. The scale in Figure 3 was normalized based on the light passed through the center equaling unity. Filters were generated using a computer drawing package and printed onto overhead transparency material using a laser printer.

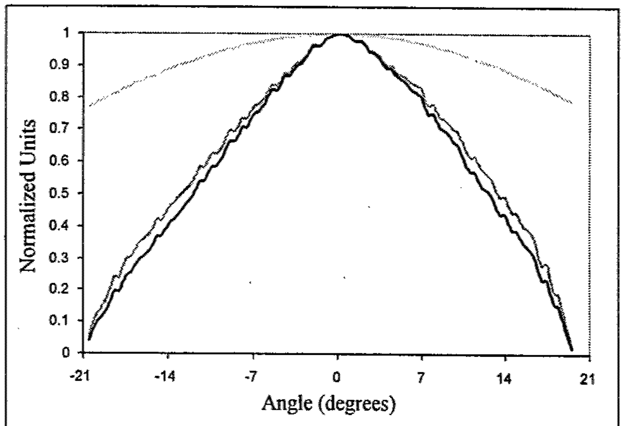

Figure 2. NVD luminance falloff.

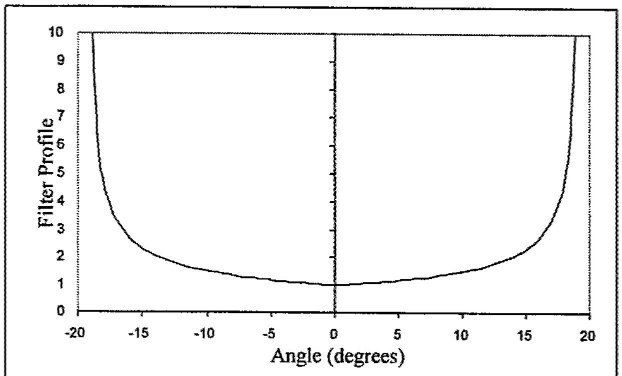

Figure 3. Theoretical lamp filter profile.

The next step was to illuminate the target with the non-uniform light source. After alignment of the NVD and camera, the luminance profile on the target was measured using a low light photometer. Overall luminance could be adjusted by changing the distance separating the lamp and the filter. Normally, data photos were taken with a target luminance profile of approximately full moon (2.0X10-2 foot-Lamberts(fL)) in the center and approximately three times full moon (6.5X10-2 fL) near the edge of the field of view. While this was not the profile required for perfectly uniform photographs, it did, however, prove adequate.

Fine alignment began with the room lights turned off and the filtered lamp turned on, illuminating the target. The NVD was turned on and focused on the target using the NVD objective lens. Next, the target was centered in the field of view by adjusting the height and tilt of the NVD/camera combination. Final alignment and centering were performed by counting the hash marks between the Zone 2 circle and the edge of the NVD field of view. The NVD and camera were centered on the target when an equal number of marks were counted to left and right, above and below the Zone 2 circle.

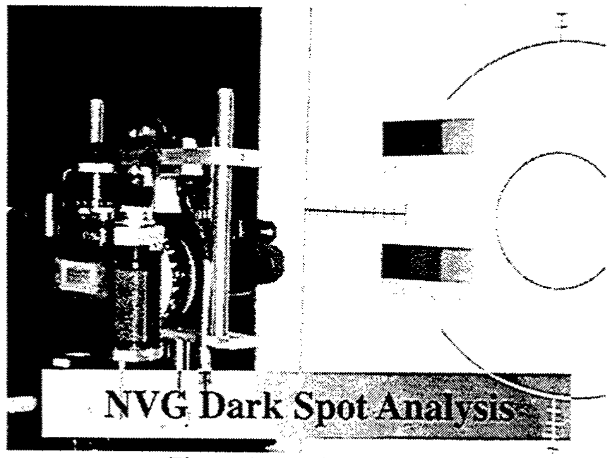

Figure 4. Equipment setup.

Photography and Processing

The film used was Kodak Technical Pan 2415, black and white, fine-grain with an ASA of 25. It was well suited for NVD dark spot photography because it was capable of very high-resolution photographs due to its fine grain size. The photos were then taken using a series of exposure times ranging from 0.25 to 8 seconds at f/5.6. Exposure times of one or two seconds yielded the best data. Computer generated contrast templates (see Figure 4) were then placed on the wall target in four places and photographed at the same f-number and exposure times as the dark spot data. These contrast reference photos were used later to determine if a spot in a data photo can be counted, exceeding the 30 percent contrast limit, or ignored. The film developing procedure required 1 to 1.5 minutes in Dektol developer, 4 minutes in fixer solution, and then rinsed for 8 minutes.

Data photographs were then enlarged and printed using a common printing process. To review the data, full 8 X 10 inch prints were made first. The best frames were chosen for the left and right oculars and then reprinted on 11 X 14 inch paper for analysis.

Template Design

To analyze the 11 X 14 inch photos, a transparency overlay was created based on large target details easily processed by the combination of test NVD, the camera, and the developing and printing processes. First, the diameters of the circles dividing Zone 1 from Zone 2 and Zone 2 from Zone 3 on the data photograph under analysis were measured. A conversion factor, in MOA per inch, was then calculated by dividing the number of arc minutes the zone subtended by the zone diameter.

This yielded two conversion factors per photograph, which were averaged to get a single conversion factor for the entire photograph. This factor was then used to determine the diameter of the spots on the spot template for the corresponding categories of spot sizes.

Spots of the appropriate diameters were printed using a laser printer, reduced on a photocopier, and then printed on overhead transparency film. The spots on the completed overlay transparency were then measured under a microscope to verify their size.

Figure 5 shows an example of the spot reference template. The template used pairs of spots to define the different categories into which dark spots may fall. Sets of spot pairs were grouped for use in the different zones, speeding the data reduction process by eliminating the need to hunt for the proper spot sizes of a given classification and a given zone.

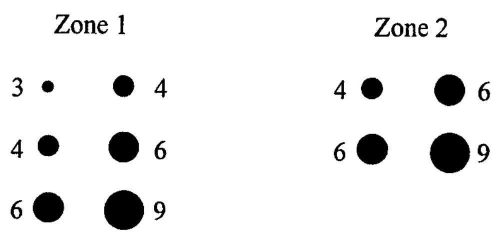

Figure 5. Spot pairs for dark spot classification.

Data and Analysis

After printing the reference spot overlay, analysis could begin. The photographic process yielded photos like Figure 6. The examination started in Zone 1 and gradually proceeded through the other zones, working clockwise. Only spots that were definitely large enough were examined further. Spots of marginal size were not counted. If a spot was considered large enough to count, its contrast was visually checked against the contrast reference photos. Spots that appeared grayer than the 30 percent contrast area on the reference photo were not counted. Spots near 30 percent but still of questionable contrast were also ignored. Only spots that were definitely large enough and dark enough to exceed the 30 percent contrast threshold were counted. Blemishes on the photos that were considered dark spots were then circled. Once the examination was completed, the examiner would have a photo with all the counted spots circled and a table of the number of spots that fell into each category in each zone.

SPOT CLASSIFICATION STUDY

Early dark spot specifications employed large classification ranges [MIL-I-49428(CR)]. This was primarily due to the belief that manufacturers could not fabricate I^2 tubes with smaller spots and that observers could not classify spot sizes with great precision. With the new set of image quality requirements [F33657-91-R-0045], allowable spots and bin sizes became smaller by about a factor of three, which raised a question about classification precision. A study was undertaken to help establish spot classification judgement criterion based on observers' visual capabilities. The results also can be applied to other spot size judgement tasks that use this range of size.

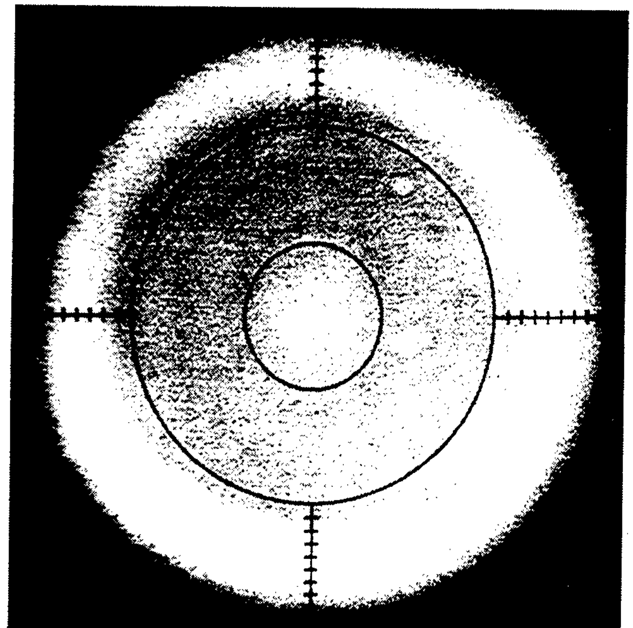

Figure 6. Example data photograph.

PROCEDURE

Ten trained observers (three women and seven men) participated in the spot classification study. All had normal distance vision correctable to 20/20 Snellen acuity without astigmatism. The observers were placed in a well-lighted room and were presented a series of high contrast targets, round, black spots on white backgrounds. Three, four, and six MOA dot sizes were used as references against which test dots were judged to be either larger or smaller. The test dots were mounted to white foam-core board to facilitate handling during the experiment. An 8 by 8 foot piece of white foam-core was used as the stimulus surround and a small ledge held the dots near the center. All targets were viewed at a distance of 100 feet. The white background was 11.6 fL and the contrast (Michelson, Equation 1) of all dots was 0.88.

Each trial consisted of the observer viewing a pair of dots; a reference standard dot and a test dot. The 48 dot pairs (a 3, 4, or 6 minute reference with one of 16 test dots), positions (reference on left or right), and repetitions (six per condition) were randomly presented in a within-subjects design. For ten observers, this yielded 2880 data points per reference dot size.

An observer was seated 100 feet from the dots. While their eyes were covered, a reference and a test dot were placed on the holder. The observer was then asked to view the pair and state which dot was smaller, then close their eyes while the next pair was set up for viewing.

RESULTS

This study showed that human evaluators could reasonably accurately classify small spots as being larger or smaller than a reference. Figures 7, 8, and 9 show the mean correct spot size classification as a function of the size difference (in tenths of a MOA) between a reference (center values 3, 4, and 6 MOA) and a test dot. Observers exhibited 100 percent accuracy in classifying test dots when the difference was at least 0.4 MOA for all spot standards tested. It should be noted that the data were asymmetrical about their respective standards. One would not expect any significant difference when comparing larger or smaller dot sizes to the standard. To further simplify analysis, the data were folded about the standard. From these combined data the ranges for 95 and 99 percent probability of correct classification were interpolated. Tables 1 & 2 show these interpolated range values for the three standards in MOA and as a percentage.

Table 1. Errors based on the 95 percent probability of a correct classification.

Reference (MOA)	Error Bounds (± MOA)	Error Bounds (± Percent)
3	0.182	6
4	0.190	5
6	0.194	3

Table 2. Errors based on the 99 percent probability of a correct classification.

Reference (MOA)	Error Bounds (± MOA)	Error Bounds (± Percent)
3	0.290	9
4	0.276	6
6	0.370	6

DISCUSSION AND CONCLUSIONS

Older dark spot test methods could not quantify the image quality of new I^2 tubes. The photographic method documented in this report achieved the required sensitivity and accuracy. Experimentation showed that human evaluation of photographic dark spot data was viable and reasonably accurate. Observers achieved a 99 percent classification accuracy for spots at least ± 9 percent different than a given standard size. For larger reference spots, error as a percentage of the reference decreased with spot size.

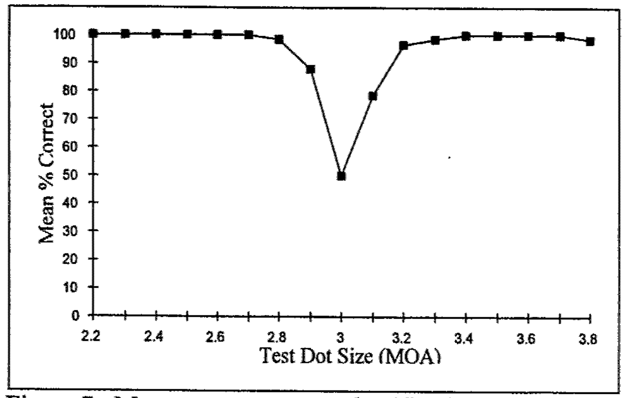

Figure 7. Mean percent correct classification for a 3 MOA reference.

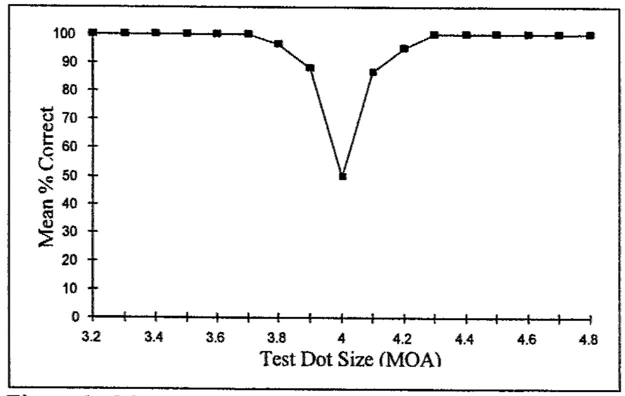

Figure 8. Mean percent correct classification for a 4 MOA reference.

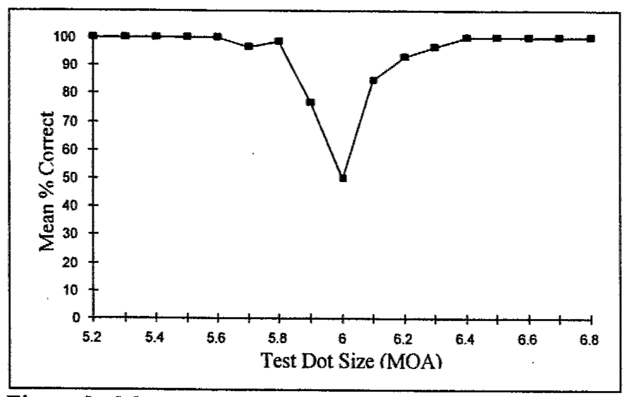

Figure 9. Mean percent correct classification for a 6 MOA reference.

This indicated several things. First, spot classification specifications could be more stringent that originally thought. Bin sizes could be made narrower due to relatively high precision in classification. Also, increasing the magnification in the printing process for Dark Spot Photos could decrease errors in photographic spot classification.

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BIOGRAPHY

Peter L. Marasco came to the U.S. Air Force in 1991 as a research physicist. His work as an optical engineer has been primarily in the areas of Night Vision and Aircraft Transparency Technology conducting basic research, guiding and executing optical and opto-mechanical design efforts, evaluating concepts and prototypes, and developing and improving optical test methods. Mr. Marasco received a BS degree from the University of Rochester in 1991 and an MS degree from the University of Arizona in 1993, both in Optical Engineering. Currently, he is working toward a Ph.D from the University of Dayton in Electro-Optical Engineering. He is a member of the SAFE Association and the Society of Photo-Optical Instrumentation Engineers (SPIE).

Alan R. Pinkus
H. Lee Task
(See earlier paper on NVG visual acuity.)

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Optical Characterization of Wide Field-Of-View Night Vision Devices

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ABSTRACT

An advanced night vision device, the Panoramic Night Vision Goggle (PNVG), presents the wearer with a large horizontal field of view (100 degrees) by combining the output from multiple image intensifier tubes. This significantly complicates the testing and evaluation of this state-of-the-art device. Current tests were considered insufficient and required modification to fully characterize conventional night vision device parameters. In addition, new tests were required to characterize parameters unique to the current PNVG design. This paper discusses the optical performance testing of the PNVG, concentrating primarily on four night-vision-device parameters: field of view, visual acuity, eyepiece diopter setting, and image discontinuity.

INTRODUCTION AND BACKGROUND

Night vision goggles (NVGs) have become a key technology for covert military and law enforcement operations at night in both fixed wing and rotary wing aircraft. With the success of NVG technology came a flood of NVGs in different configurations designed to improve their characteristics and usefulness. In order to evaluate these different NVG designs it was seen as desirable to have a collection of measurement procedures capable of characterizing new systems and acquiring data necessary for critical comparisons. Much work was done in the early 1990's to design and document tests used to characterize conventional NVGs. However, depending on the design of the NVG (folded optics, offset input/output axes, eyepiece combiners, etc.) some of the procedures become more difficult to apply.

One such system that required unique tests to fully characterize its capabilities was the Panoramic Night Vision Goggle, or PNVG. This design combines the outputs from four image intensifier tubes into one continuous image, providing the wearer an unusually large (100 degrees horizontal, 40 degrees vertical) field of view. The PNVG comes in two basic designs, the PNVG I and PNVG II. The first and more exotic PNVG I liberally incorporates folds into the imaging optics to achieve a design that fits close to the wearer's face and is ejection compatible. PNVG II is a more conventional, less folded design, intended to be less expensive and to interface with existing AN/AVS-6 NVG hardware for use on platforms that do not require ejection compatibility.

While many of the procedures documented earlier could be applied to the PNVG, some could not. This paper documents the procedures specifically designed for the PNVG to measure field of view, halo diameter, visual acuity, eyepiece diopter setting, and image discontinuity. In addition this paper documents some of the results of these and other optical tests conducted on several PNVG prototypes.

MEASUREMENT PROCEDURES

Field of View

The most significant parameter associated with the PNVGs is probably the total field of view (TFOV) since the objective of the PNVG program was to provide the pilot with significantly more TFOV than existing fielded systems. However, the field of view of PNVG is somewhat complicated because of the way it is achieved.

There are a total of 4 oculars that are aimed in 3 different directions. The center two oculars are pointed directly ahead. The left and right outboard channels have their optical axes pointing 30 degrees to the left and right of the center channels respectively. Each ocular is designed to provide a 40 degree circular field of view; although the full 40 degree FOV of each ocular may not be visible to the observer because of eye position. This combination of ocular axes and the interaction of visible FOV with eye position makes it somewhat difficult to easily characterize field of view.

Two approaches were taken to characterize the PNVG's total field of view. The first method was simply to verify that the PNVG's total field of view was at least 100 degrees (all except one of the PNVGs demonstrated this total field of view) and the other method was designed to directly measure the individual ocular FOVs and the angular locations of their FOVs with respect to the right, in-board ocular, which was used as a reference channel.

To conduct the first test, the PNVG was fixed to a bench and placed a known distance from a wall. Two small marks were made on the wall a distance from each other that subtended 100 degrees from the position of the PNVG on the bench, 50 degrees off to each side of the test goggle (see Figure 1). If both marks were visible, then the PNVG field of view was at least 100 degrees. This test was sufficient to determine if the requirement of the wide, 100-degree, field of view was met.

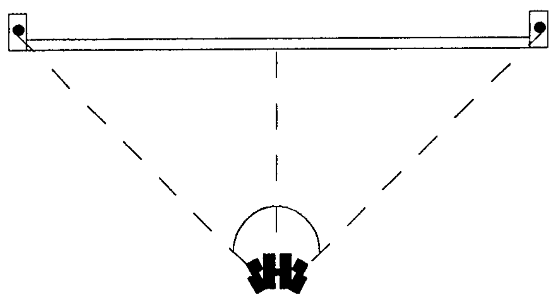

Figure 1. Relative position of LEDs for the assessment of field of view.

Table 1. Field angles for center, left edge, and right edge of PNVG oculars.

Ocular	Left Edge	Center	Right Edge
Right In-board	-20 deg	0 deg	+20 deg
Left In-board	-20	0	+20
Right Out-board	+10	+30	+50
Left Out-board	-10	-30	-50

A similar approach was used for the second FOV test in that the right channel objective lens of the PNVG was positioned a known distance from a long horizontal rail. Two red LEDs were positioned a distance to either side of the center point corresponding to ± 20 degrees. The observer then viewed through the right central channel only and adjusted the position of the PNVG until the two red LEDs were visible at the right and left edges of the FOV. The PNVG was then kept in this position for all of the following measurements. While observing through the left ocular only, and moving the eye if necessary, the LEDs were then positioned at the left and right boundaries of the left ocular field of view. If the PNVG was perfectly aligned and the oculars were exactly 40 degrees, the position of the LEDs would shift to the left by the observer's inter-pupillary distance. By knowing the edges of the left ocular field of view, it is possible to determine where the center of the left ocular FOV is directed. The edges of the left and right outboard ocular FOVs were measured in a similar fashion and their field angles with respect to the right ocular axis were determined and compared to what they should be. If the PNVG were perfectly assembled the field angles for the different oculars should be as shown in Table 1.

Visual Acuity

This procedure was designed to measure how well a human observer could see high contrast targets at a specified light level through the PNVG.

High contrast, square-wave acuity targets were used as the visual acuity opto-types. These square-wave targets were in steps of one Snellen acuity point (e.g. 20/24, 20/25, 20/26, etc). The test PNVG was fixed to a bench at a distance of 30 feet from the acuity targets. The observer was then allowed to dark adapt for about 10 minutes. An illuminator with a color temperature of 2856K was used to light the target acuity targets to a luminance level corresponding to quarter moon illumination ($5x10^{-3}$ foot-Lamberts (fL) and starlight only illumination ($5x10^{-4}$ fL). The observer then focused the test PNVG objective lenses (central only; outboard objective lenses were fixed focus for these PNVGs) on the square wave acuity target. A technician then prompted the observer to read the chart, first through each channel of the NVG using their dominant eye, and then through both oculars using both eyes (binocular vision). The target with the highest spatial frequency the subject could clearly see was then recorded. This procedure was repeated three times per observer.

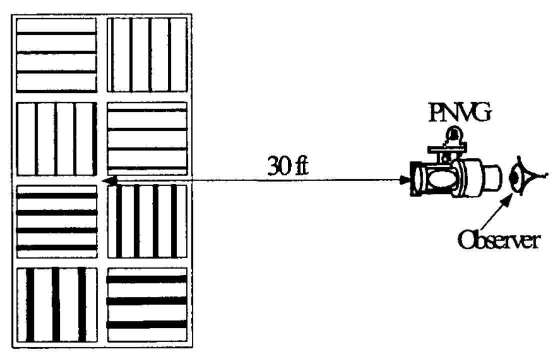

Figure 2. Relative position of equipment for visual acuity measurements.

Three trained observers familiar with the operation of the test PNVG having 20/20 vision or vision corrected to 20/20 and no astigmatism were used. Each observer viewed through each ocular 3 times selecting the highest spatial frequency pattern that could be resolved. These three readings were averaged across the three observers for each ocular of each of the PNVGs measured to obtain a final "visual acuity" value through the PNVG oculars.

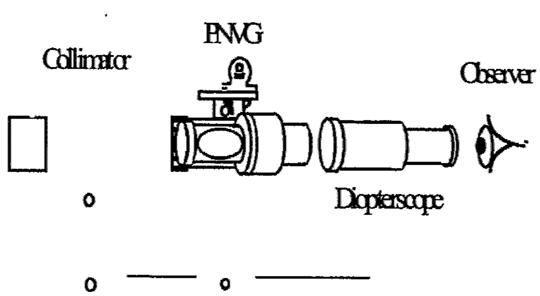

Figure 3. Measurement of eyepiece focus.

Eyepiece Focus

The current PNVG design features a fixed focus eyepiece. In order to improve observer visual performance, the manufacturer set the eyepiece to –0.75 diopters. Due to the optical complexity of the PNVG, it was considered necessary to verify this using a diopterscope. To do this, an activated PNVG was fixed to a bench and focused into collimated light source that projected an image of a grid. Once acceptable image of the grid was achieved, a calibrated, eight power diopterscope was used to measure eyepiece diopter setting by focusing the scope through the NVG eyepiece onto the grid. The diopter setting was then read directly from the diopterscope. This was repeated three times for each eyepiece and averaged.

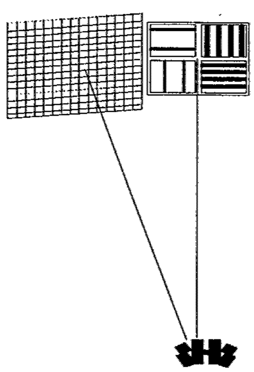

Figure 4. Relative positions of charts used in the assessment of image discontinuity

Image Discontinuity

Extending a night vision device's horizontal field of view by combining the output of multiple image intensifier tubes creates the possibility of image overlap errors arising from poor alignment of the optical system. These errors can be the result of excessive overlap of the adjacent fields of view, gaps in coverage in the observer's field of view, image discontinuities, or shifts, as objects move between the adjacent fields of view. This procedure is designed to visually assess and measure these defects by imaging a grid through a night vision device and comparing the defects to the size of grid features.

To start, the test NVG was placed in a mount that was firmly fixed to a test bench a known distance in front of a focusing target. A large grid was then position at the edge of the central ocular's field of view and oriented such that the plane of the grid was perpendicular to a line from the grid to the test NVG. Then the grid was observed through the NVG from the proper eye position. The technician would then describe the grid in terms of grid features that would appear or not appear in the field of view of the central and outboard ocular and determine the magnitude of the continuity errors.

This technique can be used to quantify image discontinuities if the angular size of the grid elements is known. The size of one grid square could be calculated using trigonometry once the separation between the lines of the grid and the distance between the test goggle and the grid were measured.

An alternative method of capturing the image discontinuities between central and outboard channels was developed using photography. The PNVGs were mounted and positioned a known distance from a large (8 ft by 8 ft.), back-illuminated grid board with lines spaced 8 inches apart. With the room lights off and the grid board lighting set to a very low level both the in-board and out-board ocular FOVs were photographed using a camera with a wide angle lens (see Figure 5).

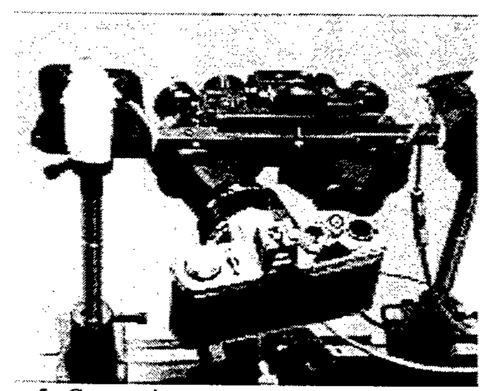

Figure 5. Geometric arrangement to photograph both the left central and outboard oculars of a PNVG II.

From the distance to the grid board and the grid board line spacing it was possible to calculate the angular subtense of each of the 8-inch grid squares. Using this information and the photograph obtained using the Figure 5 set-up it was possible to quantitatively assess image discontinuity.

Ideally, the angular size of a grid square should be small, on the order of a few milliradians. However, it is important to choose a grid size and grid line thickness that the NVG under test can image. This test should be conducted using distances of 30 feet or longer if any of the NVG objective lenses are fixed and focused at infinity in order to minimize errors due to the inherent misfocus common in infinity focused NVG lenses when tested at distances shorter than "infinity."

Gain
The gain of an NVG is an assessment of its ability to amplify available light. For the PNVG, gain was measured using a Hoffman ANV-120. This device was used to implement a test outlined in earlier documents [Task, 1993] in which the luminance output of the NVG is measured and compared to the luminance input to the NVG from a spatially large, Lambertian, 2856K black body source. Gain is calculated simply by dividing the luminance output by the luminance input.

Maximum Output Luminance
The maximum output luminance of an NVG is an assessment of the maximum brightness an NVG can produce when presented with a uniformly bright input. For the PNVG, this was measured by using a Hoffman ANV-120 to implement a test outlined in earlier documents [Task, 1993] in which the luminance from a Lambertian, 2856K black body source is increased to a level where the NVG output cannot become brighter.

Eye Relief
This procedure is to measure the physical distance separating the last optical surface of the NVG eyepiece and the front surface of the user's cornea. For the PNVG, eye relief was measured using a test outlined in earlier documents [Task, 1993] in which a video camera was used to monitor the collapse of field of view as a function of distance. This method normally required the technician to monitor all edges of the collapsing field of view. However, only the top and bottom of the PNVG oculars were monitored since the individual fields of view were not perfectly round.

RESULTS
Over the course of several months, eleven PNVG systems were characterized to some degree at AFRL/HECV. Unfortunately, due to the limited availability of the PNVG prototypes, not all tests were performed on all systems. Far more data were collected than presented here. The following is a summary of the data collected between January and May 1999 on four systems. Only a representative sample of data from some of what are considered the more important tests and the tests documented in this paper appears below. For comparison purposes, similar data collected from an AN/AVS-9, F4949 D in 1995, when the goggle was new, was also provided.

Field of View Results
Table 2. Field of view PNVG I and PNVG II.

PNVG I	Left Edge	Center	Right Edge
Right Central	-17.6 deg	0.3 deg	18.2 deg
Left Central	-23.3	-4.5	14.3
Right Outboard	14.2	33.2	52.1
Left Outboard	-13.1	-32.7	-52.3
PNVG II			
Right Central	-18.2	2.0	22.2
Left Central	-20.1	0.0	20.1
Right Outboard	12.5	32.3	52.2
Left Outboard	-11.9	-32.3	-52.7

One should note that while that each of the F 4949 oculars is as large or larger that any individual PNVG ocular, the total PNVG field of view (105 degrees) is far larger than that of the F 4949 (40 degrees). This is the benefit of the PNVG's additional, non-overlapping outboard channels.

Visual Acuity Results
Table 3. Acuity _ Moon.

Conf., S/N	Left Out.	Left Cent.	Both	Right Cent.	Right Out.
1, 05	20/33	20/30	20/29	20/34	20/30
2, 01	20/33	20/33	20/32	20/31	20/32
4, 02	20/36	20/27	20/26	20/27	20/34
5, 01	20/42	20/28	20/27	20/29	20/34
F4949		20/26	20/26	20/26	

Table 4. Acuity Starlight.

Conf., S/N	Left Out.	Left Cent.	Both	Right Cent.	Right Out.
1, 05	20/37	20/37	20/33	20/40	20/35
2, 01	20/38	20/36	20/34	20/36	20/36
4, 02	20/41	20/31	20/29	20/30	20/36
5, 01	20/50	20/33	20/35	20/33	20/41
F4949		20/35	20/36	20/36	

Tables 3 and 4 above show that the PNVG performs approximately as well as the F 4949 at _ moon and starlight illumination on target. While obscured somewhat by the variability in the PNVG data, one might argue that at starlight, the PNVG actually outperforms the F 4949. This is not entirely unexpected. The PNVG's faster f/# objective lenses allow it to make better use of available light than the F4949, improving low light acuity.

Eyepiece Focus Results
Table 5 indicates that the original PNVG feature of a

fixed focus eyepiece, set to –0.75 Diopters was not easy to achieve. This could be due to two reasons. Either manufacturing techniques are not quite capable of setting this parameter repeatability or the mechanics are not capable of holding the eyepiece elements in place for long periods of time. More effort is required to optimize this PNVG parameter.

Table 5. Eyepiece Diopter Setting.

PNVG, Conf., S/N	Left Out (D)	Left Cent (D)	Right Cent (D)	Right Out (D)
I, 1, 05	-1.0	-0.5	-0.8	-0.8
I, 2, 01	-0.4	-0.4	-0.3	-0.2
II, 4, 02	-0.2	-0.5	-0.5	-0.5
II, 5, 01	-0.6	-0.8	-0.8	-1.0

Image Discontinuity Results

The data listed in Table 6 was collected using the first Image Discontinuity procedure described above. One should remember that the sign of the Shear measurements between channels is with respect to the central image. Outboard images which appear lower than the central image are considered to have negative shear. Also, the image flaw labeled "Holes" is an assessment of the lack of overlap between central and outboard oculars, or holes in the field of view. A negative sign in the "Holes" category overlap in adjacent fields of view. One should also note that due to the way these measurements were made, there is a measurement threshold, below which the defect is noticeable but not measurable. Noticeable image flaws smaller than 3 minutes of arc were listed in Table 5 as "Minor."

Table 6. Discontinuity.

PNVG,	**Shear**	(MOA)	**Holes**	(MOA)
Conf., S/N	Left	Right	Left	Right
I, 1, 0005	Minor	-4.8	Minor	Minor
I, 2, 0001	Minor	Minor	23.9	28.6
II, 4, 0002	7	14	-7	9
II, 5, 0001	-4.8	-9.5	Minor	Minor

Although the photographic procedure (the second Image Discontinuity procedure described above) has not yet been fully developed, it is apparent from the few photos taken so far that we should be able to use it to estimate the errors of interest. The following photo (Figure 6) were taken through the left oculars and right oculars respectively. In each of these photos it is apparent that there is some discontinuity between the pair of oculars captured in the photo. For example, in Figure 6 the horizontal lines are almost matched at the top of the interface between the oculars but they are very clearly separated at the bottom of the photo indicating that there may be a slight magnification difference between the two oculars (note: magnification of oculars was not measured in this series of tests but this photo indicates it should be). In addition, the horizontal lines of the two oculars in Figure 6 are not co-linear indicating the one of the ocular channels has an image rotation compared to the other.

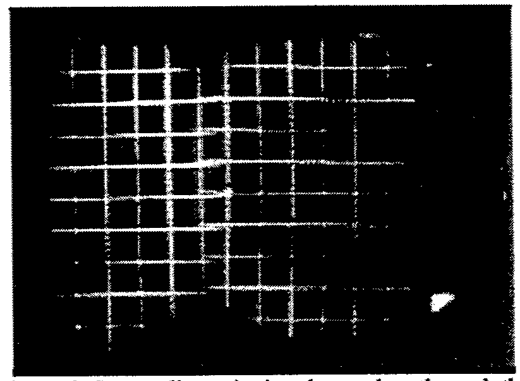

Figure 6. Image discontinuity photo taken through the left central and outboard oculars simultaneously.

In Figure 6 the faint double line in the center of the photo indicates the two ocular channels do not have their input and output optical axes properly aligned (this has been termed "collimation" in test procedures for earlier NVGs). This results in a minor "double image" at the interface of the two ocular channels. All of these effects are not readily apparent when viewing through these PNVGs at natural outdoor scenes. It is expected that further work will be done on this measurement procedure to provide quantitative results instead of just qualitative insight.

Gain Results

Table 7. Gain.

PNVG, Conf., S/N	Left Out	Left Cent	Right Cent	Right Out
I, 1, 05	5158	3579	4579	4316
I, 2, 01	3850	4400	4297	3082
II, 4, 02	4758	5569	5888	4978
II, 5, 01	4743	5595	4368	6270
F4949 D		8427	7837	

The data in Table 7 indicate that the tested PNVG systems did not exhibit gain as high as the F 4949. It should be noted that the newness of the PNVG tube and optical design created difficulties for the manufacturer in setting system gain. This should be overcome in later versions. Also, the comparison F 4949 was a prototype high gain design.

Maximum Output Luminance Results

Table 8 shows that the tested PNVGs exhibited maximum output luminance between 2.15 and 4.9 fL. This wide spread in the data is most likely due to the newness of the PNVG image intensifier tube and the lack of experience on the part of the manufacturer in setting this parameter. This should be overcome in later versions.

Table 8. Maximum Luminance Output.

PMVG, Conf., S/N	Left Out (fL)	Left Cent (fL)	Right Cent (fL)	Right Out (fL)
I, 1, 05	2.95	2.40	3.24	3.22
I, 2, 01	3.01	2.49	2.63	2.15
II, 4, 02	2.90	2.56	2.29	3.07
II, 5, 01	2.21	3.92	2.15	4.92
F4949 D		2.77	2.82	

Eye Relief Results

Table 9. Eye relief.

PNVG, Conf., S/N	Left Out (mm)	Left Cen (mm)	Right Cen(mm)	Right Out(mm)
I, 1, 05	24.5	25.8	24.8	24.5
I, 2, 01	24.8	24.7	24.3	25.0
II, 4, 02	30.4	29.9	31.4	31.3
II, 5, 01	29.9	27.7	28.8	27.4
F4949 D		23.7	23.0	

One should note from the data listed in Table 9 that the PNVG I was able to exhibit eye relief on par with the F 4949 in spite of its folded optical design, which tends to reduce eye relief. Eye relief performance of the optically simpler PNVG II well exceeded both the PNVG I and the F 4949 due in part to its simpler optical design and faster f/# optics.

DISCUSSION AND CONCLUSIONS

The procedures documented in this paper and in Task, et al, 1993 still stand incomplete. Little is known about the repeatability and reproducibility limits of these tests, as defined by ASTM E 177-90a and ASTM E 691-92. Some attention has been paid to determining the repeatability of the AFRL NVG test procedures. But, at this time only work on gain measurement repeatability has been published (Aleva, 1998). Unfortunately, the results of this work were less than encouraging. Future work is clearly required to resolve this issue.

However, even after considering all this, one can still draw relevant comparisons between PNVG systems. PNVG II tends to have better visual acuity performance and longer eye relief than PNVG I due in part to the simpler optical design. It is also possible to draw relevant comparisons between the PNVG and the F4949 since both sets of data presented here were collected using the same equipment, experimental conditions, laboratory, and technicians. One can conclude, from the data provided here, that the PNVG is capable of performing at least as well as the F4949 D NVG.

Some of the inconsistency in the PNVG data can be attributed to the fact that the systems examined were prototypes and not production quality models. The newness of the PNVG image intensifier tube and optical design created difficulties for the manufacturer in setting certain parameters. This should be overcome in later versions. Much improvement is expected as the manufacturer becomes more familiar with this complex imaging system.

It should also be pointed out that the PNVG is clearly superior to the F4949 in one category in particular, field of view. And, the operational benefit of this much-needed improvement is just now becoming known.

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ARMSTRONG LABORATORY

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METHODS FOR MEASURING CHARACTERISTICS OF NIGHT VISION GOGGLES (U)

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There are many parameters that are used to describe and specify night vision goggles (NVGs) such as resolution, field of view, brightness gain, distortion, etc. However, standardized test procedures for determining the value of these parameters have not been established. Informal comparison studies have shown that measurements of some of these parameters may vary considerably (as much as a factor of two) depending on the method, equipment, and procedures used to make the measurements. The purpose of this technical report is to document specific procedures for measuring most of the major parameters used to specify NVGs to help standardize methodology and improve accuracy and comparability between measuring organizations.

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PREFACE

The work described in this technical report was funded under Program Element 62202F Project 7184-18-07 entitled "Night Vision Devices" and Program Element 63231F Project 3257 entitled "Helmet-Mounted Systems Technology" (HMST). The primary purpose of this report is to document the night vision goggle (NVG) measurement methods that have been developed to quantify the performance of the NVGs. The motivation was to develop standardized procedures that could be used for any NVG without dissecting the NVG and measuring the component parts. These methods were used to evaluate the I-NIGHTS night vision goggles/helmet-mounted displays developed under the HMST program. These procedures are still being developed and the reader should understand that some of these procedures may be modified in the future to improve their accuracy, repeatability, and/or utility.

INTRODUCTION

Night vision goggles (NVGs) have become a key technology for fighting and flying at night in both fixed wing and rotary wing aircraft. With the success of NVG technology came a flood of NVGs in different configurations designed to improve their characteristics. In order to evaluate these different NVG designs it is highly desirable to have a collection of standardized measurement procedures to permit critical comparisons between devices. The purpose of this report is to document some of the measurement procedures that have been developed to assess the characteristics of night vision goggles. In each case it is assumed that the NVG cannot be disassembled, which would permit the measurement of individual components, but instead must be measured as a whole. It should be further noted that the procedures described herein are still subject to further revision as more experience is gained from their application. Depending on the design of the NVGs (folded optics, off-set input/output axes, eyepiece combiners, etc.) some of the procedures are more difficult to apply than others.

Prior to evaluation of any NVG it is critical that the NVG be properly prepared to insure fair and accurate measurement of its characteristics. The optics should be carefully cleaned and adjusted. If the NVG has adjustable objective lenses and/or eyepiece lenses, these need to be set for infinity and zero diopters respectively. For measurements involving brightness and brightness gain the NVG should have fresh batteries to insure optimum results. During testing the NVGs should be checked periodically to make sure the optics are still clean (no fingerprints!).

BRIGHTNESS AND BRIGHTNESS GAIN

1.1 Introduction

Brightness and brightness gain are measurements of the luminance output of NVGs as a function of luminous input. In strictest terms, these parameters should really be called *luminance* and *luminance gain*, because the measurements conducted for this part of the evaluation are photometric. Brightness implies visual perception, an unmeasurable quantity. However, since brightness and brightness gain have been the terms used traditionally, we will conform to this convention.

Night vision goggles cannot work in complete darkness. They are essentially amplifiers of visible and near-infrared radiation. The measurement of brightness and brightness gain give some indication of how well a night vision system amplifies natural ambient light. Brightness is a measurement of the limit imposed on the maximum goggle output by the automatic gain control and gives an indication of how easily a user could see the intensified image of a well lighted area. The NVG's brightness gain is the ratio of the output luminance from the goggle to the input luminance to the goggle.

NVGs have an unusual spectral sensitivity, which makes the concept of brightness gain difficult to define. Gain involves a ratio of similar quantities, in this case, luminances, which are only defined for the spectral sensitivity of the human eye. Unfortunately, the eye and the NVG's image intensifier tube are sensitive to slightly different regions of the spectrum. Problems arise because the NVGs can "see" sources which are undetectable by the human eye and, therefore, have zero luminance. This allows a condition in which infinite gain could be calculated. For example, a source emitting light with a wavelength of 900 nanometers would have zero luminance because the eye is relatively insensitive to infrared radiation. But when viewed through an NVG, which is very sensitive to this wavelength, the system will produce a non-zero output luminance. A non-zero output luminance divided by a zero input luminance will produce an infinite value for gain.

To overcome this problem, it is necessary to define a specific spectral distribution for an input light source which emits radiation in both the visible and near infrared spectral region. The visible portion of the emitted radiation provides a measurable, non-zero input luminance. A light source simulating a 2856 degree Kelvin (K) black body

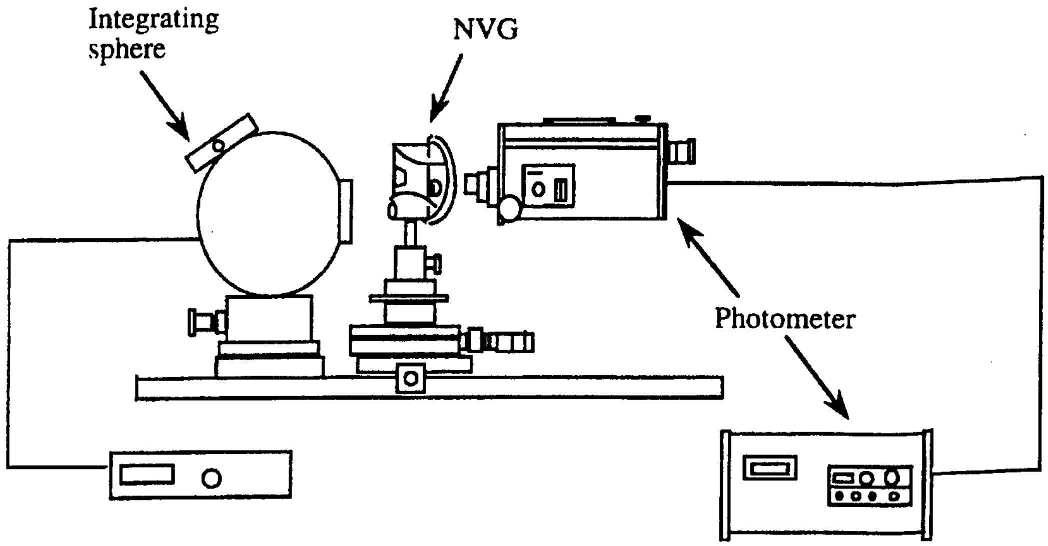

Figure 1. Test setup for the brightness gain procedure.

radiator was selected because it is a standard lamp, is easily approximated using halogen bulbs, and is specified as a light source for testing image intensifier tubes in the ANVIS image intensifier assembly specification (6).

1.2 Approach

The input light source may be any device that approximates the spectral distribution of a 2856 K blackbody radiator, emits very uniform luminance across its field, and can fill the entire field of view (FOV) of the NVG under test. Either an integrating sphere or a uniform, wide field of view collimator is a good choice.

The equipment arrangement for the brightness and brightness gain measurement using an integrating sphere is shown in Figure 1. The arrangement for use with a collimator is the same, except the collimator replaces the sphere. This procedure requires a light source with a desired luminance range of 10^{-6} footlamberts (fL) to 0.02 fL and a photometer which must be sensitive down to 10^{-5} fL.

Controlling the output from the light source while maintaining the correct color temperature and uniformity of its luminance across the output field is essential for accurate results. This is best accomplished by using a variable slit or aperture between the bulb and the integrating chamber of the light source. Altering the bulb voltage to change the output level will alter the source's color temperature. All these factors must be carefully considered when choosing a light source because of their significant impact on the results.

The photometer used was modified with a 7 mm limiting aperture over its objective lens for this procedure only. The 7 mm aperture was chosen because it is the same diameter as the widest eye pupil in low luminance conditions. Its presence required the photometer to be recalibrated to compensate for the reduced light gathering capacity. However, the aperture was necessary to ensure accurate luminance readings from NVGs with exit pupil forming optical systems. If the photometer objective lens is larger than the NVG exit pupil, erroneously low readings will be obtained.

The photometer is positioned in front of the light source to check its calibration and ensure that the emitted luminance values are correct for the corresponding aperture settings. The NVG to be tested is positioned with the objective lens of one ocular as close to the light source as possible. The limiting aperture of the photometer is placed at the expected eye position of the NVG and pointed toward the approximate center of the NVG's field of view. The measuring field of view of the photometer should be no greater than 2° as stated in the ANVIS image intensifier assembly specification.

Once all components have been positioned, the light source is adjusted to produce an input to the NVG objective lens of 10^{-5} fL. The output luminance from the NVG is measured by the photometer and recorded. The aperture in the light source is then adjusted to produce a higher luminance and the photometer reading is again recorded. This is repeated until the lamp reaches its maximum luminance capability, 0.02 fL.

The step sizes between luminance levels should be spaced more closely at lower levels and further apart at higher levels. Changing values by a factor of two is a good compromise between limiting the procedure to a reasonable number of data points and providing sufficiently fine interval spacing so as not to miss any interesting effects (see Table 1).

1.3 Results

The results from this measurement procedure can be displayed in tabular form (see Table 1) with three columns of data: input luminance, output luminance, and the ratio of output to input labeled brightness gain. The raw data can also be displayed in

Table 1. Example of brightness gain tabular data.

Input luminance (fL)	Output luminance (fL)	Brightness gain (unitless)
1.10×10^{-5}	0.0200	1820
2.30×10^{-5}	0.0400	1740
4.60×10^{-5}	0.0800	1740
9.20×10^{-5}	0.170	1850
1.84×10^{-4}	0.350	1900
3.67×10^{-4}	0.720	1960
7.34×10^{-4}	1.23	1680
1.47×10^{-3}	1.24	849
2.94×10^{-3}	1.25	425
5.88×10^{-3}	1.26	214
1.18×10^{-2}	1.27	107
2.35×10^{-2}	1.27	54.0

graphical form (Figure 2) with output luminance plotted against input luminance. The maximum output luminance value obtained is then recorded as the maximum brightness of the NVG.

As noted from Table 1, brightness gain is a unitless fraction describing the ratio of light out of the system to light into the system at specific input light levels, while brightness is the luminance output at the same input light levels, expressed in ft-Lamberts. Brightness gain is determined by dividing the output luminance by the input luminance (column three in Table 1). This can also be graphed as the brightness gain as a function of input luminance (Figure 3). The gain at $3.67 * 10^{-4}$ fL input is recorded as the brightness gain. This value is somewhat arbitrary and was chosen because most NVGs, tested in this fashion, reach their maximum brightness gain value at or near this luminance input level.

1.4 Comments

It must be kept in mind that the results are for a specific standard lamp color temperature. When spectral distribution or color temperature of the light source is different, different results will be obtained.

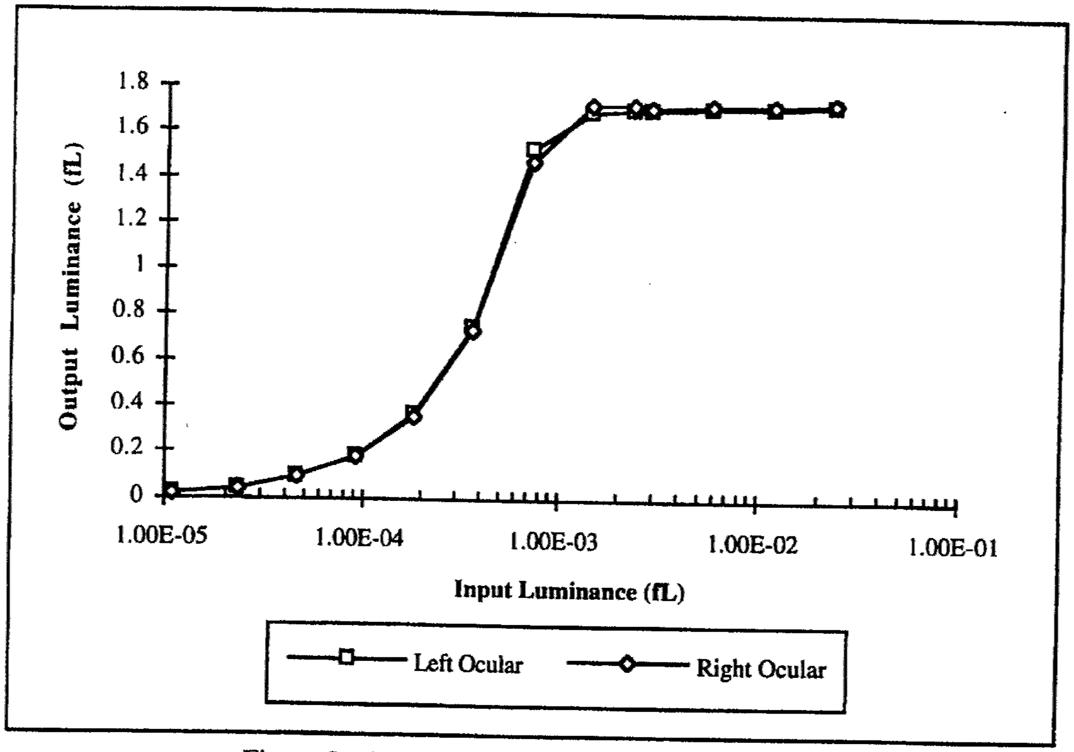

Figure 2. Output luminance vs. input luminance

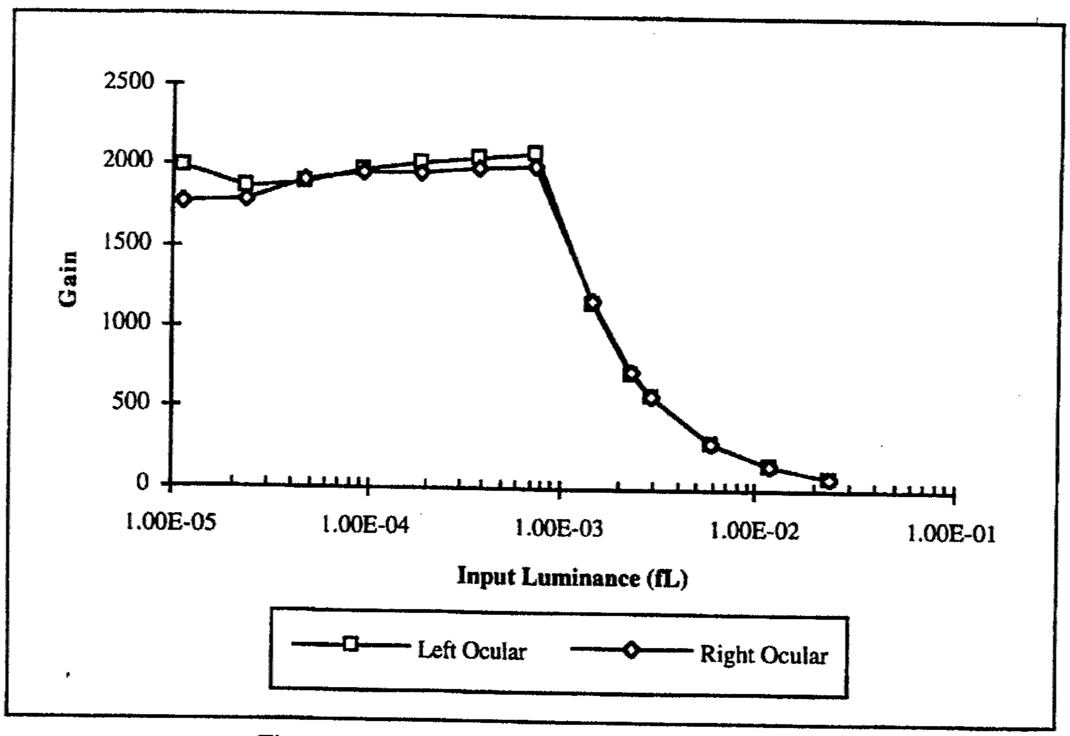

Figure 3. Brightness gain vs. input luminance

The brightness gain graph, such as Figure 3, provides some information on how well the NVG amplifies light. However, the luminance output curve shown in Figure 2, which is also obtained from this procedure, provides an indication of how much light the observer has to see in the NVG image. Since visual acuity of the observer varies considerably with light level (4) the latter curve provides some information as to the visual capacity of the observer to extract key information from the scene as displayed by the NVG.

Table 1 and Figures 2, and 3 indicate that brightness and brightness gain are affected by the level of input luminance, although they are typically only recorded at specific values, brightness at its maximum value and brightness gain at an input luminance of about $3.67 * 10^{-4}$ fL. This can be misleading, since the NVGs are often operated at light levels other than those at which these maximum brightness and brightness gain values occur.

All NVGs are equipped with an automatic gain control to protect the goggles from damage. The graphs of brightness and brightness gain are heavily influenced by the gain control circuit. It limits the maximum brightness leaving an NVG and determines at what input light level the slope of the brightness and brightness gain curves begin to change.

This procedure requires that the light source fills the full field of view of the NVG. If this is not the case, it is possible to obtain drastically different brightness and brightness gain results. The automatic gain control limits the total current flow within the image intensifier tube. The same current may be generated from a considerable amount of light on a small area of the NVG or by a small amount of light on a large area. In the first case, the output luminance will be much higher than in the latter. Figure 4 shows several brightness curves that were generated by filling up different fractions of the field of view. Note that, as the area of the light source is reduced at the input, much higher maximum output luminances are obtained.

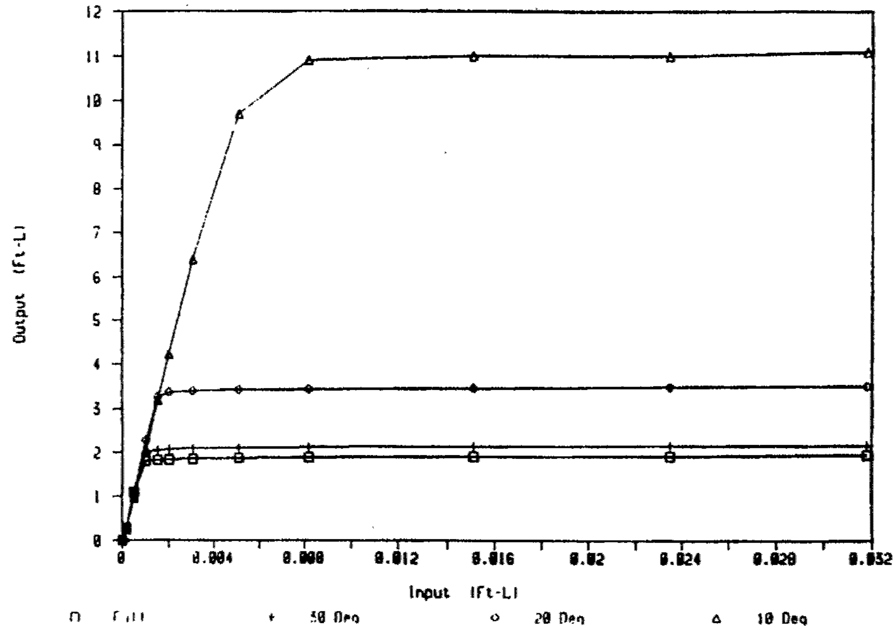

Figure 4. Output luminance vs. input luminance for various illuminated fields of view.

GEOMETRIC IMAGE PARAMETERS

2.1 Introduction

The four parameters addressed in this section: 1) distortion, 2) image rotation, 3) magnification, and 4) optical axis misalignment, all deal with geometric aspects of the image produced by the night vision goggles. Thus, a single measurement procedure was developed to capture all four parameters simultaneously.

Distortion, the non-linear mapping of the outside scene to the output image plane, is probably the most difficult parameter to characterize, because there are several types of distortion that may occur in NVGs. The optical system may cause barrel or pincushion distortion. The fiber optic twist, which is used in many, but not all NVG designs, may produce both shear effects and "S" distortion. Of all of these, the procedure herein described is primarily directed at characterizing the "S" distortion, although evidence of shear, barrel, and pincushion distortion may also be detected. "S" distortion originates in the fiber optic plug, which is used to invert the image intensifier's output image, when it is manufactured by heating and twisting approximately 180°. The "S" distortion is so named because there is usually a small amount of residual effect due to the twist that produces an "S" shaped curve from a straight line input. The more the output image departs from a straight line, the worse the distortion.

Another problem encountered with NVGs is image rotation. For NVGs incorporating fiber optics, the fiber optic plug may be twisted somewhat more or less than 180°, resulting in the output image being rotated compared to either the input image or the other ocular. This effect may also be exaggerated by inaccurate alignment of the mirrors in a folded optical system.

Magnification is another geometric image parameter that must be addressed. Most NVGs are designed to have unity magnification. However, if there is a mismatch between the objective lens and the eyepiece lens, it is possible to have a small amount of magnification (or minification). The procedure can determine the amount of image size increase or decrease produced by the NVG lens and image intensifier tube system compared to the unity magnification of the unaided eye.

An additional problem area is optical axis alignment. Since the combination of objective lenses, folding optics, image intensifier and eyepiece lenses is relatively complex, it is possible to have a mismatch between the input optical axis and the output optical axis. Thus, objects that are at a particular point in object space may appear to be at a different point when viewed with NVGs. The parameter measured is the relative angular difference between the objective lens optical axis and the eye lens optical axis for NVGs.

2.2 Approach

The equipment required for this measurement includes a rotary table, on which to mount the NVGs, a collimator with single small point image, a small, CCD array video camera, and a video monitor. It is also necessary to have digital calipers to accurately measure distance on the face of the video monitor. Figure 5 depicts the arrangement of the equipment for this measurement procedure.

To conduct this measurement correctly, the CCD camera must be fitted with a comparatively long focal length lens, on the order of 100 mm to 120 mm. This makes the camera more sensitive to optical defect phenomena by creating a larger spot size and

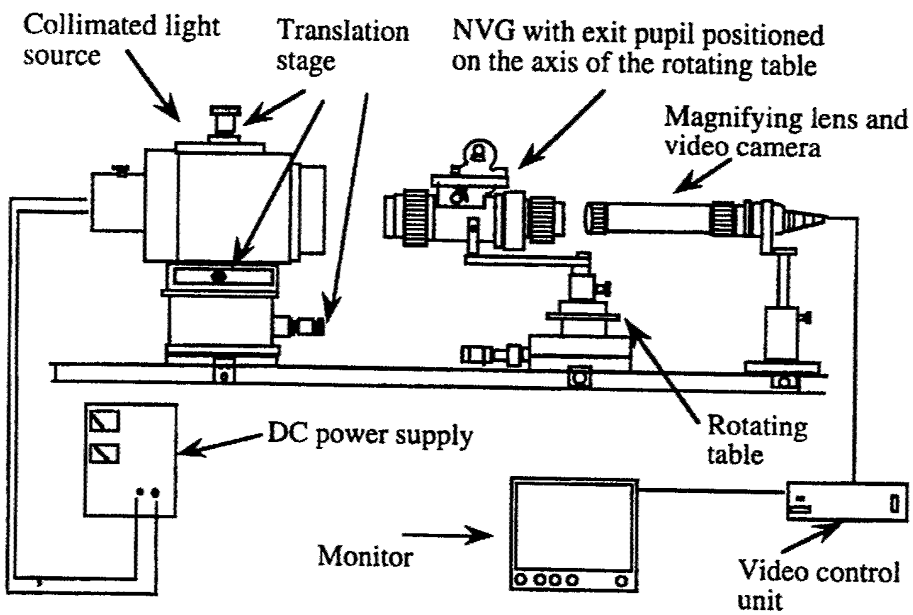

Figure 5. Test setup for the distortion procedure.

larger movements on the video monitor which are easier to measure accurately. The camera field of view must also be known in order to convert linear distance on the monitor into units of angular deviation.

The video camera is adjusted in front of the collimator, without the NVG in the system, until the small point image appears in the center of the video monitor. This aligns the optical axis of the video camera with the collimator. The NVG is then mounted on the rotary table between the video camera and the collimator such that the axis of rotation of the table is directly below the eye position of the NVG. The camera is then adjusted to position its objective lens directly over the table's axis of rotation. The spot of light within the collimator should now be visible on the monitor when viewed through the NVG. If the spot is no longer in the center of the video monitor, then the input and output optical axes of the NVG are not in alignment. By knowing the angular field of view of the video camera and the linear vertical and horizontal distance that the spot of light has moved from the center of the video monitor, the elevation (vertical) and azimuth (horizontal) angular misalignment value can be calculated.

After the on-axis misalignment has been recorded, the rotary table is then turned both clockwise and counter-clockwise, until a line across the full field of view has been scanned. At each field angle the vertical and horizontal position of the spot of light on the video monitor is measured and recorded.

2.3 Results

At the end of the above procedure, one has a table of results that consists of three columns: 1) horizontal angular position, 2) vertical angular offset, and 3) horizontal angular offset. Table 2 shows results for a typical NVG. These data points can be graphed and analyzed in different ways to obtain information on each of the four geometric parameters discussed. To determine the presence of unusual distortion phenomena, the vertical and horizontal offset data was plotted against angular position in Figure 6. Curved, symmetric edges of the graph indicate barrel or pincushion distortion. Jagged discontinuities indicate areas of shear effects.

Optical Axes Misalignment Analysis

The misalignment from the input to the output optical axis can be determined from the zero position angular offset. The offset in both vertical and horizontal

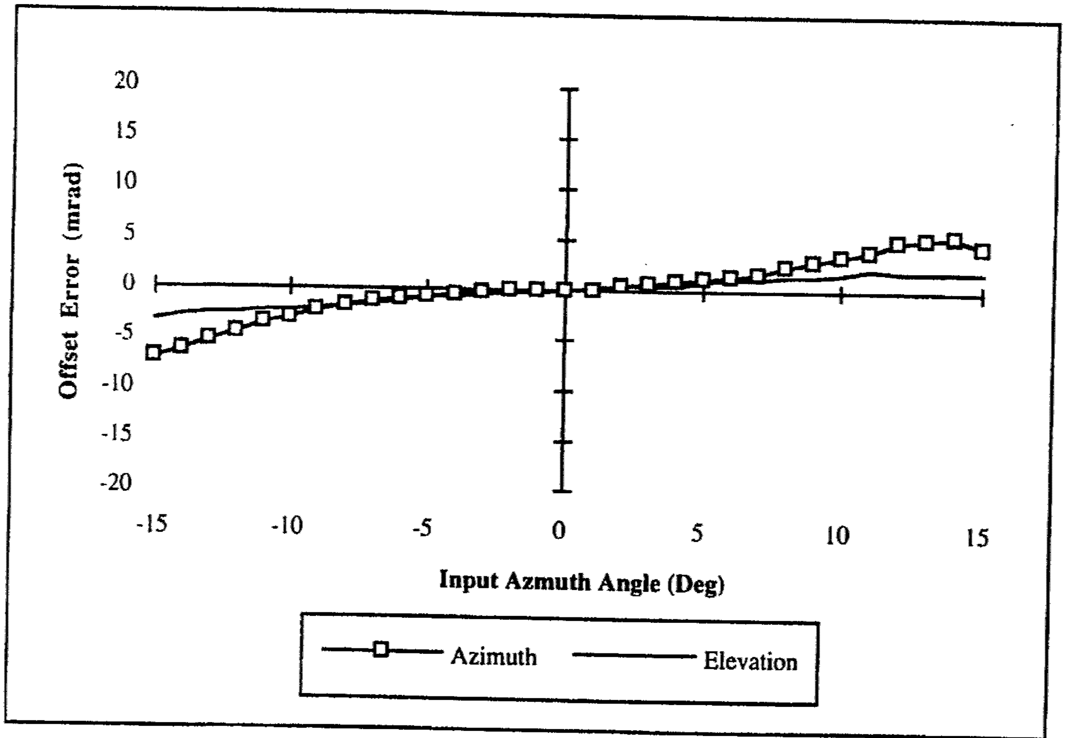

Figure 6. Distortion: offset data plotted vs. angular position.

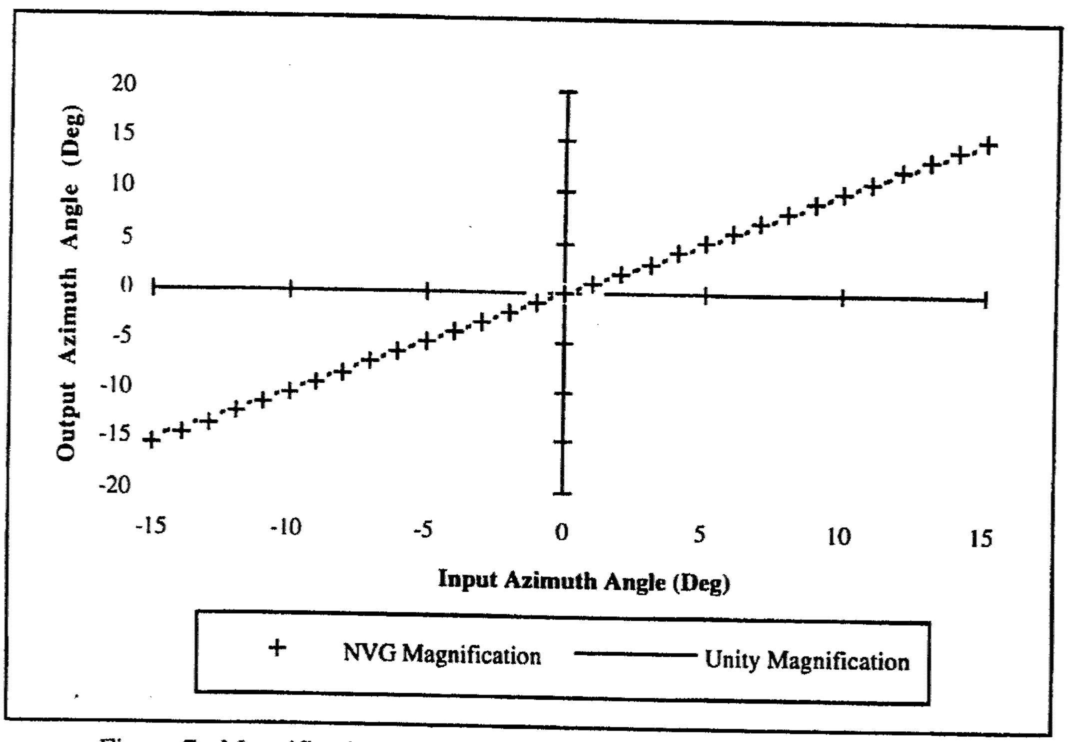

Figure 7. Magnification: output azimuth angle vs. input azimuth angle.

Table 2. Geometric measurement procedure tabular data.

Horizontal Position degrees	Vertical Offset milliradians	Horizontal Offset milliradians
-15	-6.977	-3.189
-14	-6.284	-2.903
-13	-5.365	-2.549
-12	-4.625	-2.580
-11	-3.575	-2.331
-10	-3.170	-2.357
-9	-2.370	-2.057
-8	-1.775	-1.686
-7	-1.324	-1.643
-6	-1.025	-1.177
-5	-0.765	-0.917
-4	-0.559	-0.700
-3	-0.339	-0.426
-2	-0.165	-0.286
-1	-0.015	-0.197
0	0.0	0.0
1	0.068	0.166
2	0.570	0.354
3	0.823	0.466
4	0.904	0.523
5	1.134	0.889
6	1.466	1.174
7	1.800	1.143
8	2.362	1.383
9	2.863	1.394
10	3.491	1.783
11	3.922	2.154
12	4.929	1.866
13	5.137	1.880
14	5.395	1.871
15	4.559	2.040

dimensions from the zero degree field angle position in Table 2 is the amount of vertical and horizontal misalignment. A single quantity representing the angular misalignment between the two viewing axes, O, of the NVG is also determined by taking the square root of the sum of the squares of the vertical and horizontal offset (equation 2.1),

$$O = \sqrt{X^2 + Y^2} \tag{2.1}$$

where Y is the vertical angular offset in degrees and X is the horizontal angular offset in degrees. This measurement can be recorded in milliradians, degrees, or minutes of arc.

Magnification Analysis

If magnification other than unity magnification is present in the system, then the horizontal angular offset would increase at a uniform rate with respect to the horizontal field angle as the horizontal angular scan is produced. This can be graphed as the horizontal field angle plus horizontal angular offset versus actual input field angle. Since there is also typically some distortion present, this line may not be perfectly straight. To circumvent this problem, a linear, least-squares fit is made to the data to provide a best fit line with slope and intercept. The slope of the least-squares fit straight line is the magnification of the system. A reference slope of one, representing unity magnification, is also graphed for comparison with the measured value (see Figure 7). Note that this analysis can easily be modified to examine data from a smaller portion of the total system. If there is significant distortion at the outer edges, for example, the data reduction can be restricted to the central 80% of the field of view.

Image Rotation Analysis

Image rotation analysis is very similar to that done for the magnification, except the vertical (elevation) angular offset is graphed as a function of horizontal field angle. Again, a linear, least-squares fit line is computed and graphed along with the data (see Figure 8). The amount of image rotation, Θ, is the arctangent of the slope, $\pm m$, of the best fit line (see Equation 2.2).

$$\theta = \tan^{-1}(\pm m) \tag{2.2}$$

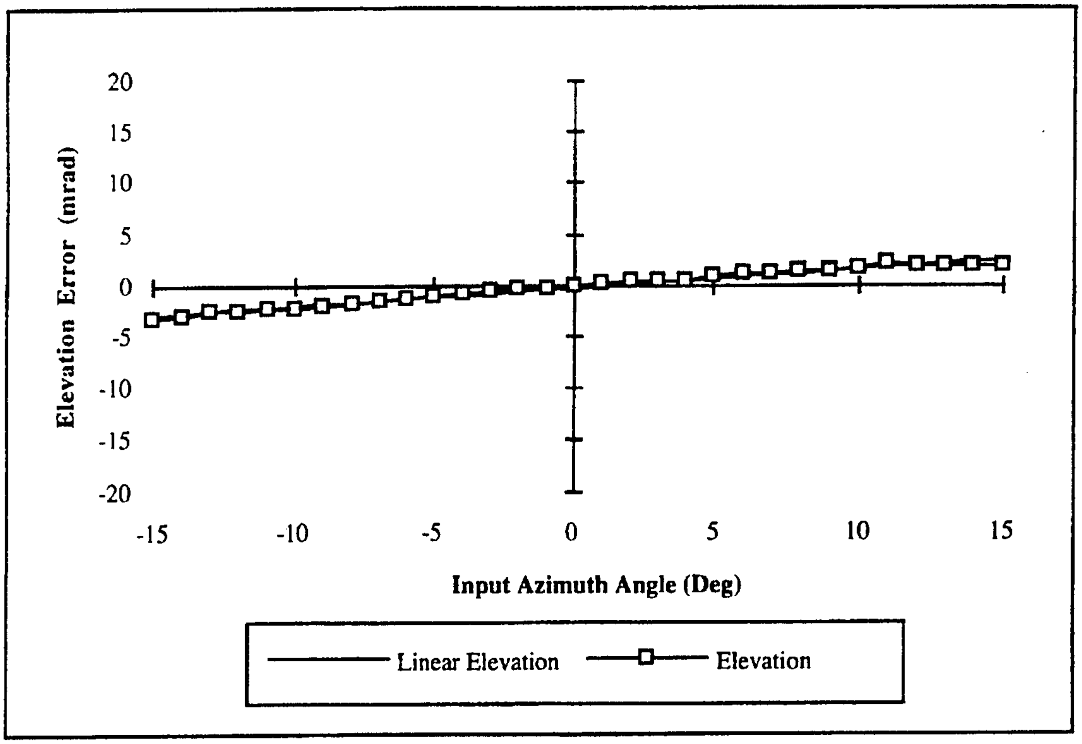

Figure 8. Image rotation: vertical angular offset vs. input azimuth angle.

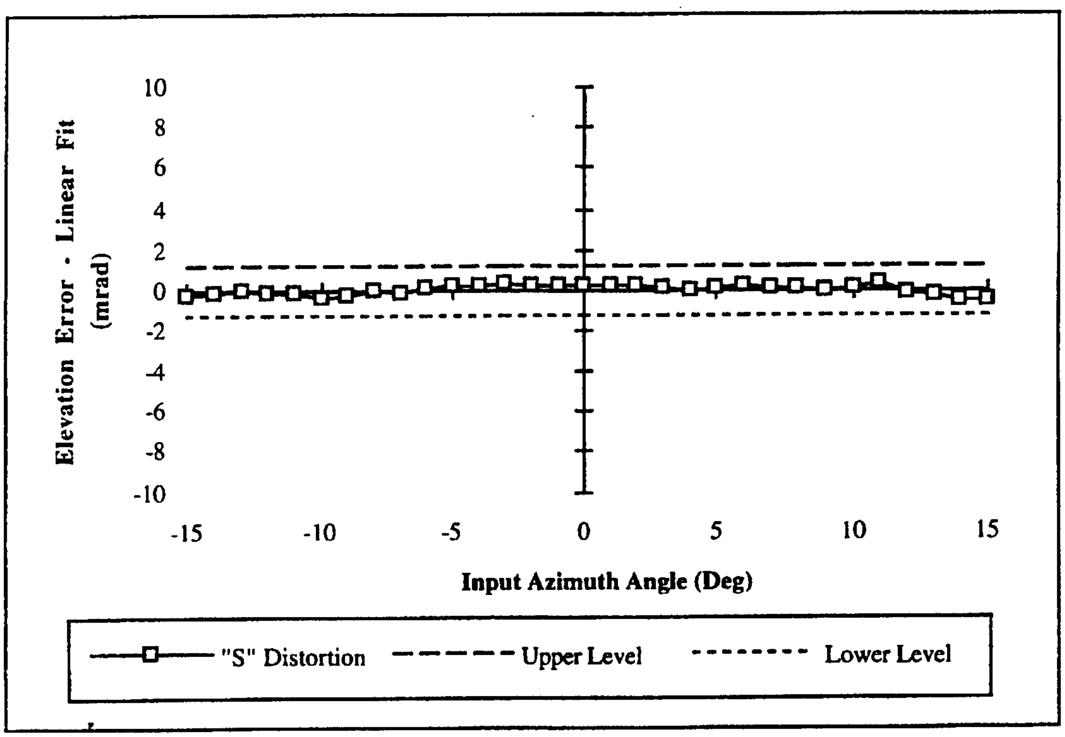

Figure 9. "S" Distortion: vertical offset minus rotation curve fit error vs. input azimuth angle.

Distortion Analysis

The "S" distortion can be displayed on the same graph as image rotation. However, to obtain a clearer picture of the "S" distortion by itself, the linear best fit curve for image rotation can be subtracted from the vertical angular offset data. This difference can then be graphed against horizontal field angle. Current specifications require that the "S" pattern fit between two horizontal lines, such as those on the graph in Figure 9, that are spaced ±1.22 milliradians from the origin, corresponding to a ±30 microns maximum allowed by the ANVIS image intensifier assembly specification. This value is for the fiber optic plug only and comes from the ANVIS image intensifier assembly specification. It can, however, be generalized to the NVG as a whole. For a quantitative measure of the "S" distortion, the maximum value is subtracted from the minimum value to obtain the peak to valley amplitude of the curve.

2.4 Comments

The angular offset in both the vertical and horizontal dimensions from the zero degree field position (Table 2) demonstrates the amount of vertical and horizontal optical axis misalignment. Ideally, the collimator output is used to define the optical axis of the video camera and the input optical axis of the NVG system. With exaggerated offset optical systems where the separation between the camera axis and the NVG input axis is greater than the collimator lens diameter, a slight modification of this procedure is needed. The measurement is then accomplished by translating the collimated light source from the eyepiece position to the objective lens position, measuring the change in position of the point light source on the video monitor.

The evaluator must be careful not to introduce tip or yaw of the collimator into the system as the collimator is translated. Doing so would destroy the axis reference with the video camera and render the results meaningless. Strong, precision machined mounts are required to prevent this.

Magnification other than unity magnification along the edges of the image is an indication of either pincushion or barrel distortion. These aberrations can be caused by either the relay or imaging optics, the fiber optics, or by some combination.

EXIT PUPIL SIZE (DIAMETER)

3.1 Introduction

NVG optics can be either non-pupil forming or pupil forming. The measurement of exit pupil size is a procedure performed on real pupil forming systems only. A pupil forming system, such as a telescope, has an area where the entire image can be seen as long as the eye is anywhere within it. However, as the eye begins to move out of the exit pupil the image first begins to dim and finally disappears when the eye entrance pupil is completely outside of this area (7). In pupil forming NVG optical systems, the exit pupil is the image of the aperture stop as viewed from image space.

3.2 Approach

The equipment arrangement for the exit pupil measurement using a collimator is shown in Figure 10. An integrating sphere can also be used, provided the NVG field of view is filled. This procedure requires a translational target stand with a mounted screen of thin diffusing material.

The objective lens of the NVG is placed close to the exit aperture of the collimator, ensuring the NVG's field of view is fully illuminated. The translation stage with the diffusing screen is then placed behind the NVG eyepiece. With the NVGs on and the room completely dark, the real image (circle of light with the smallest diameter) formed by the eyepiece is brought into focus on the diffuser by moving the translation stand toward or away from the NVG. The diameter of the image, or exit pupil diameter, is then measured with digital calipers and recorded. This procedure is repeated five times to obtain an average value.

3.3 Results

The results from this measurement procedure can be displayed in tabular form (see Table 3). Due to the subjectivity of the measurement, the data is statistically analyzed so that the confidence interval (C.I.) of the measurements can be determined.

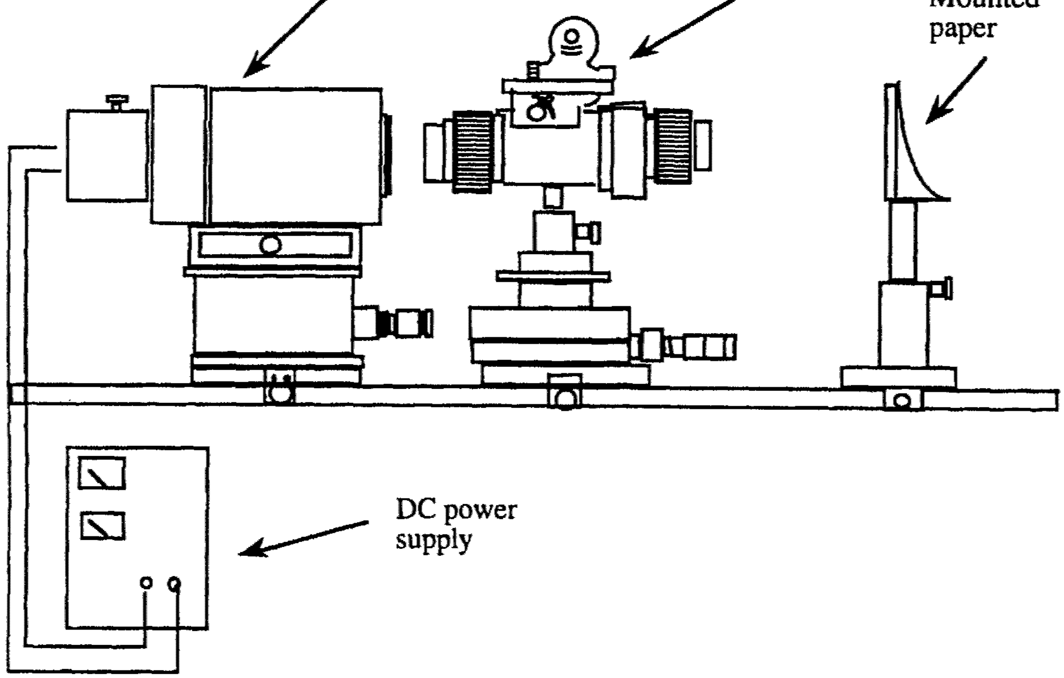

Figure 10. Test setup for the exit pupil diameter procedure.

Table 3. Example of exit pupil diameter tabular data.

Measurement Number	Exit Pupil Diameter (mm)
1	9.5
2	9.5
3	9.0
4	9.3
5	9.0
Average	9.26
Variance	0.25
95% C.I.	9.26 ± 0.35

3.4 Comments

It may be noted that different materials can be used for the screen. Anything that is translucent and scatters light relatively uniformly could be used. Unfortunately, the thickness of the diffuser limits the precision of the measurement. When trying to determine the exact location of an image plane to a tenth of a millimeter, it becomes the limiting factor. Therefore, a thin diffusing material, such as cellophane tape, produces the best results.

EYE RELIEF

4.1 Introduction

As already noted, some NVGs are pupil forming and some are non-pupil forming systems. The procedure for measuring eye relief changes somewhat depending on which of the two types is being tested, but the basic definition remains the same. In this report, eye relief is defined as the physical distance separating the last optical surface of the NVG eyepiece from the front surface of the eye, the cornea.

A non-pupil forming system is similar to a simple magnifying lens in that, as you move your eye away from it, the edge of the field may be cut off (vignetted) (7). Therefore, the maximum eye relief for such a system is defined as the maximum distance between the last optical element in the NVG eyepiece and the cornea, such that the NVG user can still see the system's full, unvignetted field of view, minus 3 mm. For a pupil forming NVG, eye relief is the distance from the NVG's last optical element and the plane of the exit pupil minus 3 mm. Since the entrance pupil of the human eye must fall at the system's exit pupil for ideal viewing, the distance from the cornea to the eye's entrance pupil must be subtracted.

These definitions do not conform to the ANVIS specification for eye relief, which has more to do with the diameter of the eyepiece lenses than the actual distance separating the NVG and the eye. The results from this procedure give a real distance which is useful in determining things such as system compatibility with protective equipment and eye glasses.

4.2 Approach

Figure 11 shows the equipment arrangement for the eye relief measurement. The procedure to measure non-exit pupil forming NVGs requires a collimator with a square grid insert with numbered vertical and horizontal axes to identify position, a micro CCD array camera with a 5 mm aperture, and a video monitor

The CCD video camera's field of view must exceed the FOV of the goggle under test. To achieve this, a short focal length lens is used to image the goggle output onto the CCD array. In this case, a lens with a focal length of 8.9 mm was used. As mentioned

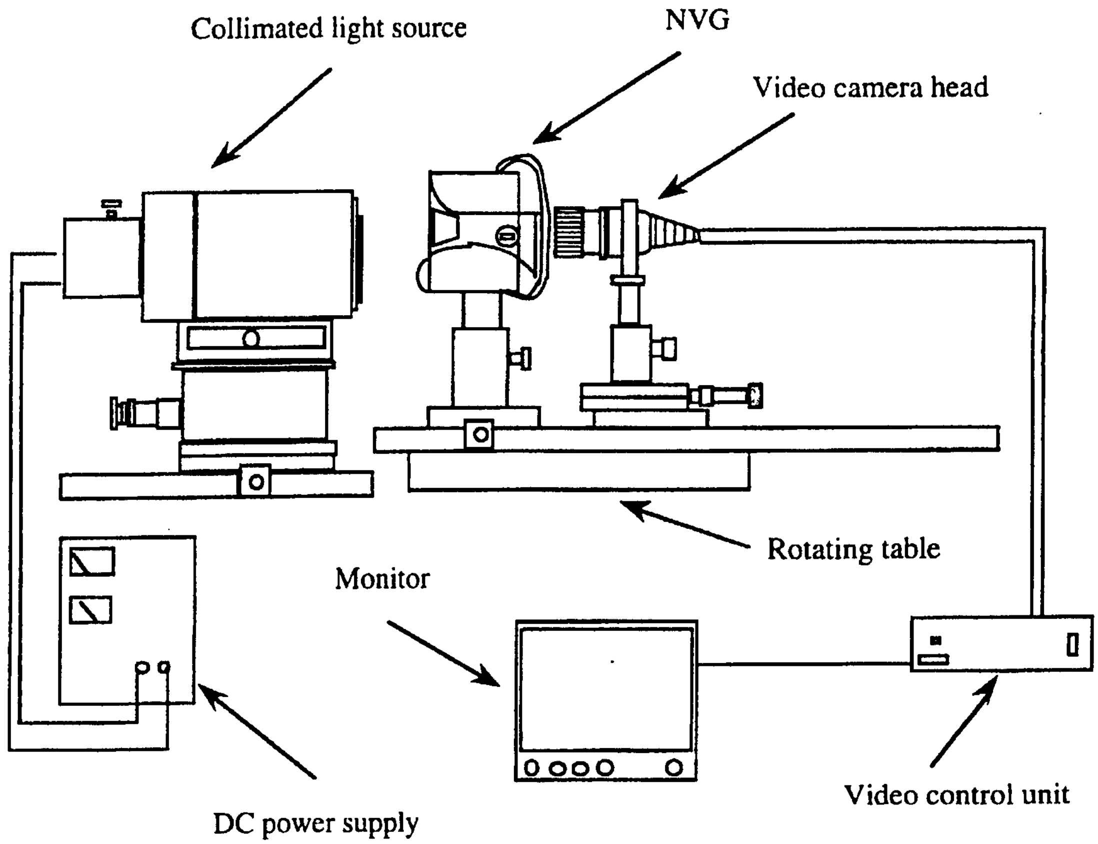

Figure 11. Test setup for the eye relief procedure

earlier, the ideal aperture size for night vision applications to simulate the human eye pupil is 7 mm. Due to equipment restrictions, a 5 mm aperture is used in conjunction with the video camera. This has only a marginal affect on the results.

The video camera is adjusted in front of the collimator without an NVG in the system, such that the origin of the grid pattern appears in the center of the video monitor. This will align the optical axis of the collimator with that of the video camera. The NVG is then mounted between the collimator and the video camera such that the entire FOV is filled with the grid image. In this procedure, both the NVG and the collimator remain stationary while the miniature video camera is translated along the optical axis. Then the video camera and translational stage are positioned such that the camera lens is almost touching the surface of the NVG eye lens. With the room lights turned off and the goggle turned on, the grid pattern should be visible on the monitor as viewed through the NVG. The location of the micropositioner is then recorded as the initial value, x_i. The camera is then moved away from the NVG eyepiece lens until vignetting occurs. The micropositioner location is then recorded as a final value, x_f. This procedure is repeated five times for each ocular to achieve an average value.

Eye relief measurements on exit pupil forming systems follow a similar procedure but require slightly different equipment. The CCD camera is replaced by a strip of thin diffusing material. Setup remains the same except the square grid insert for the collimator becomes optional.

With the goggles positioned in front of the collimator, the thin diffusing screen is placed in contact with the NVG eyepiece lens and its initial position is read from the translational stage and recorded as x_i. Like the procedure for non-exit pupil forming systems, the diffuser is moved away until the intensified image emerging from the goggles reaches its smallest diameter, or achieves best focus if the square grid insert is used. Both should yield equivalent results. The position of the stage is then recorded as x_f. Like the procedure for non-exit pupil forming systems, five measurements are taken on each ocular to calculate an average value.

4.3 Results

At the end of the measurement procedure, the eye relief can be calculated using the following equations. It is often helpful to display the raw data in a table before making the necessary calculations (see Table 4). For non-exit pupil forming systems, eye relief, $E\,R$, is calculated with Equation 4.1

Table 4. Example of eye relief tabular data

Measurement Number	Eye Relief (mm)
1	21.2
2	20.9
3	19.9
4	20.5
5	21.1
Average	20.7
Variance	0.53
95% C.I.	20.7 ± 0.74

$$ER = (x_f - x_i) + pp - 3mm \qquad (4.1)$$

where *pp* is the distance from the vertex of the lens to the first principal plane of the video camera and 3 mm is the distance from the cornea to the entrance pupil of the eye.

The eye relief calculation for exit pupil forming NVGs is conducted with Equation 4.2

$$ER = (x_f - x_i) - 3mm \qquad (4.2)$$

Due to the inherent subjectivity in the procedure, the data is statistically analyzed so that the confidence interval (C.I.) of the measurements can be determined.

4.4 Comments

For proper results, the micro CCD camera must provide a field of view greater than that of the NVG. If this is not the case, longer eye relief measurements will be obtained because the camera will not see the goggle's field starting to collapse until its own field starts to collapse. Overfilling the goggle's field of view is also critical to obtain reliable measurements. Vignetting will go undetected unless the goggle objective lens is completely filled. This will also result in longer eye relief measurements.

Vignetting may not occur evenly throughout the entire field of view. Often, part of the field collapses followed by the remaining FOV. To account for this phenomenon, a grid target with divisions representing angular units was used. The skill of the evaluator also adds some uncertainty to this procedure.

When organizing a test sequence to evaluate night vision equipment, this parameter should be measured first. Several other goggle evaluation procedures mentioned in this report depend on knowledge of the proper eye position for the alignment of equipment and accurate results.

VISUAL ACUITY

5.1 Introduction

Resolution is the ability of an imaging system to reproduce an image in fine detail. This procedure is actually a measurement of the human dependent analog to resolution, visual acuity. The method described herein relies on a subjective observation, in which a test observer views a USAF 1951 tri-bar resolution test chart through the NVG and determines the smallest discernible pattern. The average limiting acuity of the system as seen by several observers can be extracted from this observation.

5.2 Approach

The equipment required for this procedure includes a collimator with an aperture larger in diameter than the NVG objective lens aperture and a positive 1951 USAF tri-bar resolution pattern, one that produces an image of dark bars on a white background, positioned at the collimator's focal plane. Three experienced observers with vision corrected to 20/20 visual acuity or better are needed. Figure 12 shows the arrangement of the equipment for this measurement procedure.

The NVG objective lens is aligned to look into the collimator and is focused on the 1951 tri-bar pattern such that a minimum of 50% of the intensified FOV is filled with the tri-bar pattern image in order to prevent degradation of the resolution due to high output luminances (see Figure 4). The input light level for this measurement is approximately equivalent to full moon, $2.35 * 10^{-2}$ fL from a 2856 K light source.

Once the initial conditions are met, an observer places his/her eye in the proper eye position of the NVG. The observer looks through one ocular and is then asked to determine the smallest horizontal and vertical elements of the 1951 tri-bar resolution chart they can resolve. This procedure is repeated for each ocular and each observer.

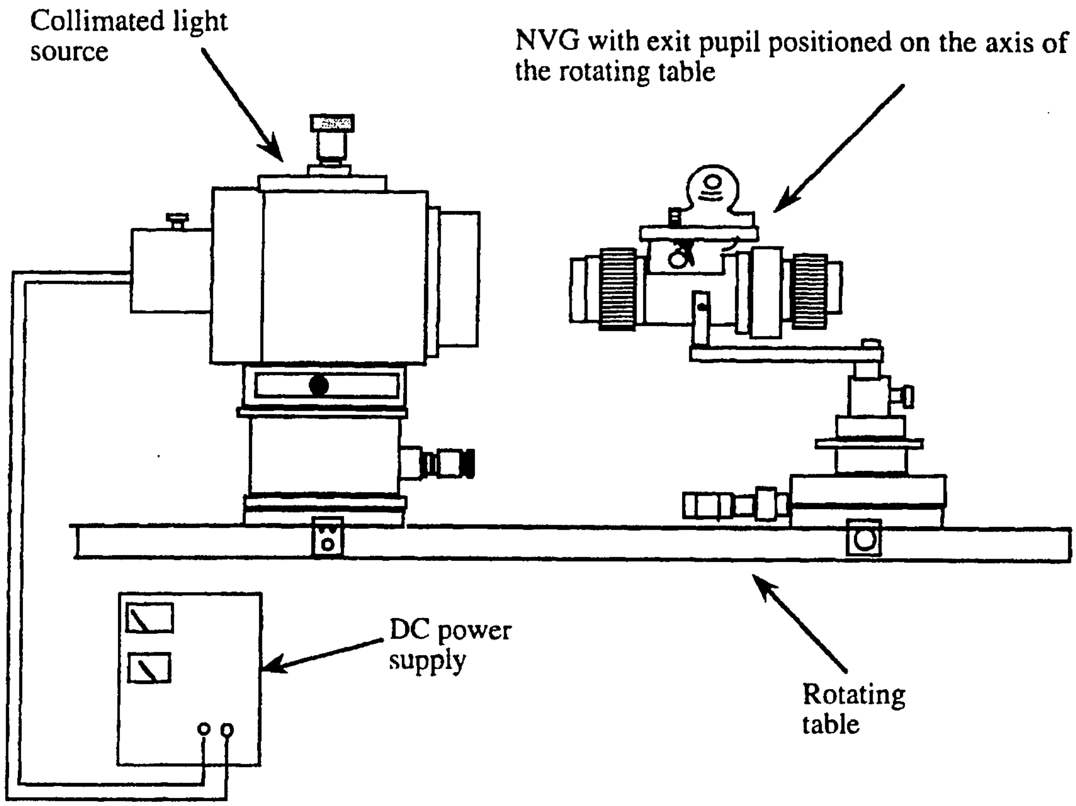

Figure 12. Test setup for the visual acuity procedure for center NVG FOV only.

5.3 Results

A table of raw data similar to Table 5 can be constructed. The smallest resolvable horizontal and vertical elements of the USAF tri-bar chart are then converted to either Snellen acuity or cycles per milliradian using Equations 5.1, 5.2, and 5.3.

Table 5. Example of resolution raw data, one ocular.

Observer	Group/ Element Horizontal	Group/ Element Vertical	Bar Width (mm) Horizontal	Bar Width (mm) Vertical
1	2/6	2/5	0.0710	0.0783
2	2/5	2/4	0.0783	0.0875
3	3/1	2/6	0.0625	0.0710

To convert group/element values to arc minutes use Equation 5.1,

$$\Theta = 60 \tan^{-1}\left(\frac{w}{fl}\right) \tag{5.1}$$

where θ is the subtended angle in arc minutes, fl is the focal length of the collimator in millimeters and w is the width of each bar of the chosen group/element in millimeters.

To calculate Snellen acuity use Equation 5.2,

$$X = \theta * 20 \tag{5.2}$$

where X is the denominator of the Snellen acuity ratio (i.e., $20/X$).

To convert from Snellen acuity to cycles per milliradian use Equation 5.3,

$$Y = 1.719 * 20/X \tag{5.3}$$

where Y is in units of cycles per milliradian and 1.719 is a conversion factor in cycles/milliradian.

The following example steps through each calculation. In this example, the observer's limiting resolution was recorded as group 2 element 5. The focal length of the collimator used was 100 mm and the bar width in the observed element was 0.0783 mm. First the subtended angle is calculated using Equation 5.4.

$$\Theta = 60 \tan^{-1}\left(\frac{0.0783}{100}\right) = 2.69 \textit{ arcminutes} \tag{5.4}$$

Knowing that the subtended angle is 2.69 arcminutes, Snellen acuity can be calculated with Equation 5.5.

$$X = 2.69 * 20 = 53.8 \tag{5.5}$$

So in this example, the observer resolved the target with 20/54 Snellen acuity. If the result is required to be reported in cycles/milliradian use Equation 5.6 for the conversion,

$$Y = 1.719 * 20/54 \tag{5.6}$$

which results in 0.64 cycles/milliradians.

After the raw data is collected, it is then converted to either Snellen acuity or cycles per milliradian and a table of final results can be constructed (see Table 6). The average acuity of the three observers is recorded as the resolution of the night vision goggle.

Table 6. Example of resolution tabular data, one ocular.

Observer	Horizontal Acuity	Vertical Acuity
1	20/48	20/54
2	20/54	20/60
3	20/43	20/48
Average Acuity	20/48.3	20/54

5.4 Comments

Once the collimator system has been fabricated and the focal length is known, it is recommended to make a conversion chart from milliradians to Snellen acuity for the USAF 1951 tri-bar chart. This will make data collection and reduction easier.

This is a subjective method, which relies on the experience of the 3 observers, so that an average may be calculated with some certainty. Note that both horizontal and vertical elements are recorded and analyzed to test the system for astigmatism.

RESOLUTION

6.1 Introduction

Measuring visual acuity can be a long and tedious process. The use of human subjects is a complication because they must be trained in the use of NVGs and must be relatively familiar with the system under test and the evaluation procedure. Because of this, the need for a quicker, more objective evaluation procedure appeared. In response, a photographic resolution procedure was developed based on the visual acuity test.

6.2 Approach

The equipment and test assembly are very similar to those used to measure visual acuity. A collimator with a negative 1951 USAF tri-bar resolution pattern, one that produces an image of white bars on a dark background, positioned in its focal plane is used as an image source and a 35 mm camera to record the resolution data.

The collimator must emit light which approximates the spectral distribution of a 2856 K blackbody radiator and emit full moon illumination, $2.35 * 10^{-2}$ fL. Its output must overfill the tested NVG's field of view and project an image of the 1951 USAF tri-bar chart that fills at least 50% of that goggle's field of view. This is required to avoid degradation of the resolution due to high output luminances. A negative 1951 tri-bar chart is used because it is easier to photograph through the goggles than the positive chart.

The camera used in this evaluation is a standard 35 mm camera with a 150 mm focal length lens well corrected for the third order aberrations and chromatic aberration. Like in other procedures mentioned in this report, the input aperture of the camera is limited to a 5 mm diameter to simulate the eye's entrance pupil at the correct light level. Photos are taken with Kodak 2415 technical pan film. Another equivalent film can also be used.

Once the collimator is properly adjusted, the goggles to be tested are aligned to the collimator's output. The goggles are then checked to see if the negative tri-bar chart image is damaging the image intensifier tube. As noted earlier in this report, small illuminated areas, such as the individual bars of the 1951 USAF chart, will cause greater localized gain than a fully illuminated goggle FOV because of the image intensifier tube's current control. This could leave minor burns on the NVG's phosphor screen. If the image seems to be overwhelming the goggle, the collimator's output luminance level is turned down slowly until the goggle is in no danger. This is to assure that the resolution photographs are taken at a high light level.

Once a non-damaging goggle output level is obtained, the camera is placed in the eye position of the NVG and the entire system is adjusted to achieve best focus through the goggle. Several photos are taken for different exposure times, ASA and F-stop settings. The photos are then developed and enlarged eight by ten inch prints are made. The best photo is selected for each ocular as its resolution data.

6.3 Results

The smallest resolvable group and element in both the horizontal and vertical

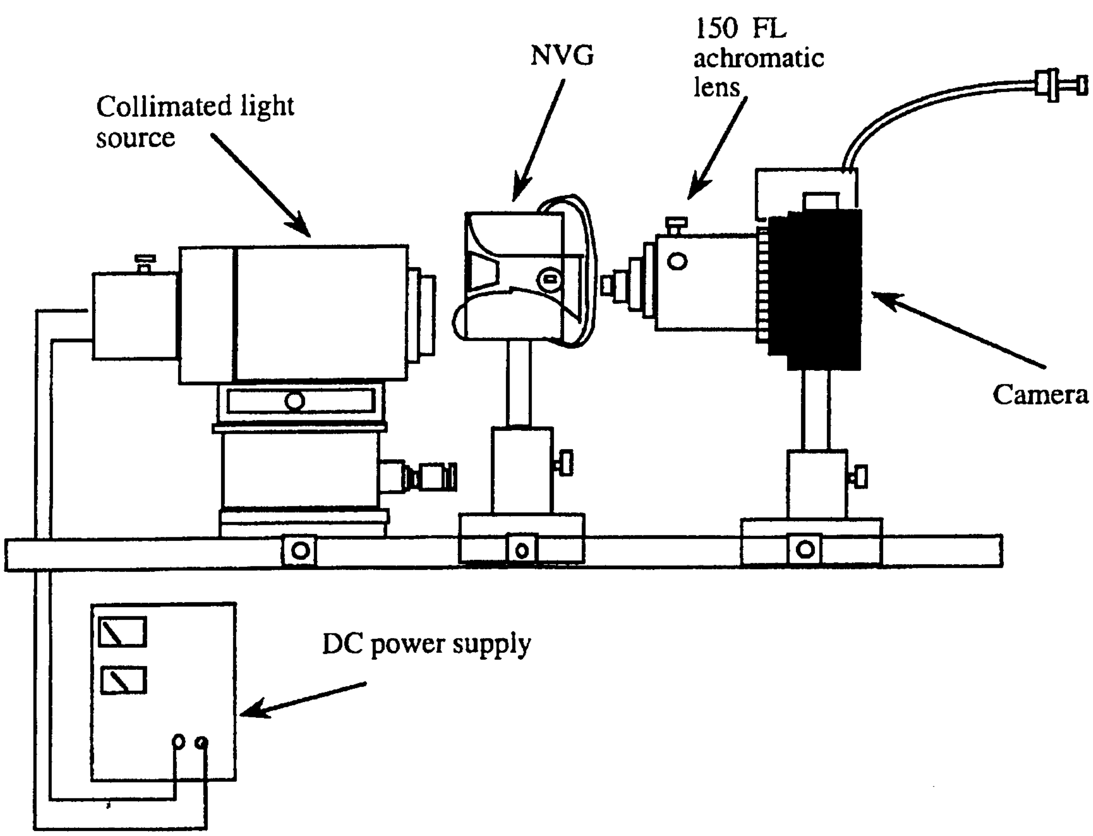

Figure 13. Equipment arrangement for the photographic resolution procedure.

direction are chosen from the photographs. Like the visual acuity data, this data can be converted to and recorded in arc minutes, cycles/milliradian, or Snellen acuity units using Equations 5.1 through 5.6.

6.4 Comments

The first time a camera, lens, and collimator are brought together to produce resolution photos, it would be wise to photograph the collimator output directly with the camera and lens. This creates a reference photograph and measures the limiting resolution of the resolution test system. The reference photo also records any astigmatism that might result from using poorly corrected optics.

This procedure is potentially hazardous to the NVG under evaluation because of the way the image intensifier tube processes physically small luminance sources. Excessively long periods of time due to alignment, focusing, or setting exposure times, during which the goggle is exposed to the collimator output are the main cause of problems. Damage could range from a slight phosphor blemish that fades with time to a serious non-removable burn. The risk of damage could be reduced by using a positive 1951 USAF tri-bar pattern in the collimator at the cost of losing some of the test system's ability to image it through the goggles.

VISUAL FIELD PARAMETERS

7.1 Introduction

The visual field parameters tested include intensified field of view, luminance uniformity, and modulation contrast. All of these parameters deal with data which is collected from a linear, photometric scan across the center of the NVG's visual field. A single measurement arrangement has been developed to capture information on all three parameters. Only small modifications in the procedure are required to collect the modulation contrast data.

The measurement of the intensified field of view gives an indication of the angular size of the real world scene the NVG can process and present to the user at any one particular time. This normally does not change much from ocular to ocular or from system to system of similar design. But, it can be an important factor when comparing different NVG designs.

Luminance uniformity measures the NVG output for uniform brightness throughout its entire visual field. A uniform luminance distribution implies that any photometric measurements taken in any part of the NVG field of view will result in similar measurements with only small deviations. However, previous tests on NVGs have demonstrated a common trend of variability in luminance across their field of view. Therefore, this is actually a test of luminance non-uniformity.

When an NVG is presented with a high contrast target, like an object with a bright side and a dark side separated by a sharp border, the high luminous output from the lighted areas tends to spill into the darker areas, making small dark targets surrounded by a bright background more difficult to see. Modulation contrast provides an indication of the maximum contrast an NVG can produce when viewing a 100% contrast target.

7.2 Approach

The equipment required for these measurements include a rotary table on which to mount the NVG, a photometer, a uniform 2856 K light source, and a strip chart recorder. In addition to this, a high contrast, split field target is used for the modulation contrast measurement only. Figure 14 depicts the arrangement of the equipment for this measurement procedure when using a collimated light source. For most of this procedure, either a collimator or an integrating sphere may be used, provided the NVG's full field of view is filled. But, the modulation contrast measurement must use the collimator as its light source. For the results of this procedure to be truly meaningful, the split field target must be removed to infinity. The best way to accomplish this in the limited space of the laboratory is to place it in the focal plane of the collimator.

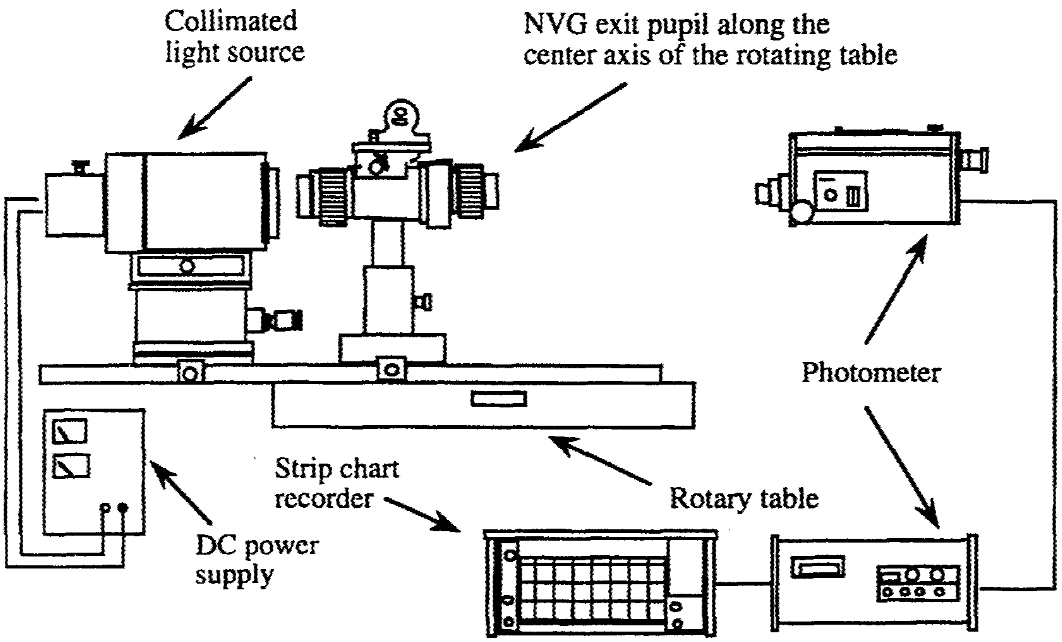

Figure 14. Test setup for the visual field measurements.

The NVG is mounted on the rotary table such that the goggle's proper eye position is directly over the table's axis. The collimator is then mounted on the rotary table such that it is close to and centered on the objective lens of the NVG being tested. The illumination from the light source is then adjusted so that it is bright enough to maximize the luminance output of the goggle intensifier tube. Full moon illumination is a good choice. The photometer is positioned so that it measures the luminance on the phosphorus screen of the image intensifier tube through the eyepiece of the NVG. A measuring FOV of less than 1/2° should be selected on the photometer.

In this procedure, the light source and NVG rotate together while the photometer remains stationary. The table is then rotated until the photometer is measuring a point just off the edge of the field of view of the NVG. The strip chart recorder is turned on and the rotary table is activated such that it sweeps through an angle greater than the field

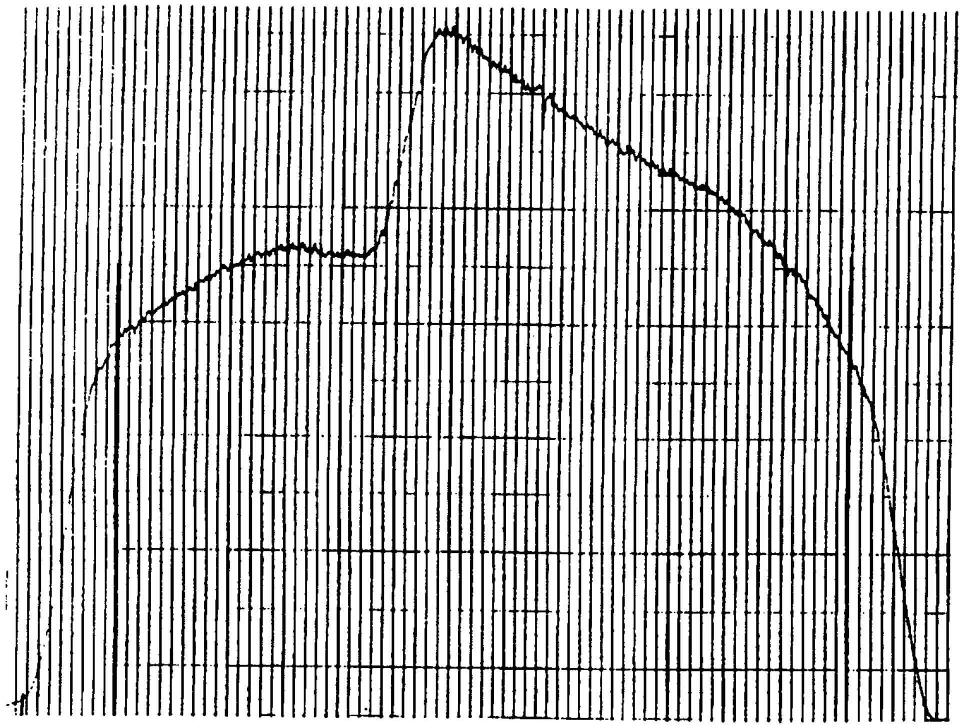

Figure 15. Example of typical NVG field of view and luminance uniformity.

of view of the NVG. The resulting chart recorder trace appears in Figure 15.

The angular rate of the rotary table and the linear rate of the strip chart recorder need to be recorded and compared to generate a calibration factor, R_C, which will relate the strip chart recorder measurement to degrees. Measurements made in this fashion would be meaningless without it.

This procedure describes the measurement of field of view and luminance non-uniformity. These are just different reductions of the same plotted raw data. When measuring contrast modulation, the procedure is the same except a high contrast, split field target is placed at the image plane of the collimator. The resulting chart recorder plot has a somewhat different profile, as seen in Figure 16, than the plot for the field of view and luminance non-uniformity measurements.

7.3 Results

By the end of the procedure, at least two strip chart recorder plots per ocular have been generated. In the case of the intensified field of view and luminance uniformity, the

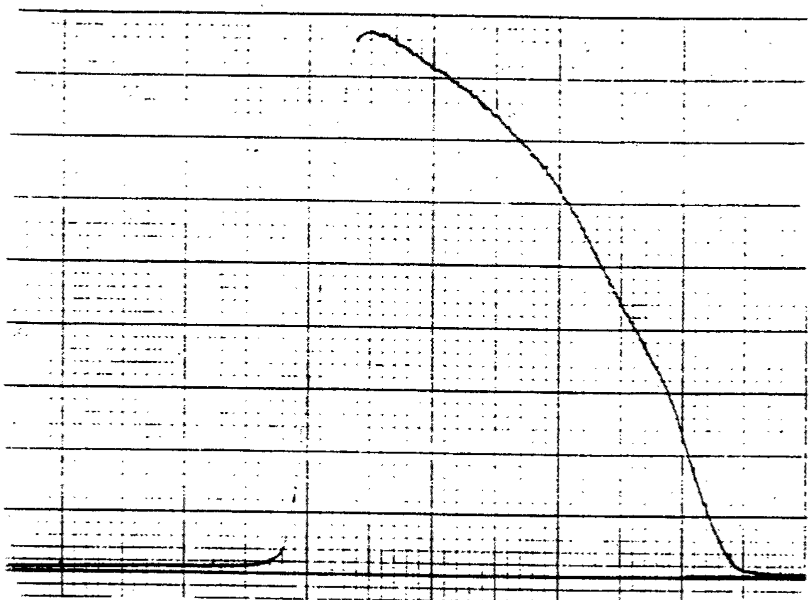

Figure 16. Modulation contrast strip chart recording for a typical NVG.

graph will show a line that starts near zero luminance at the edge of the FOV, rises to maximum luminance, then falls back to zero luminance again at the other edge of the FOV, as in Figure 15. For modulation contrast, a graph is produced that shows the luminance profile across the bright and dark areas of the split field target (Figure 16).

Intensified Field of View Analysis

A qualitative assessment of the NVG field of view can be easily extracted from the strip chart recording by comparing data acquired from a recently tested system to older data. For a more detailed, quantitative analysis, the distance between the initial and final luminance inflection points on the strip chart recording must be measured and converted to degrees using Equation 7.1,

$$\theta = (R_c)(R_d) \tag{7.1}$$

where θ is the field of view of the NVG, R_c (deg/in) is the calibration factor, and R_d is the distance between the initial and final luminance inflection points. Figure 15 illustrates the field of view for a typical NVG.

Luminance Non-Uniformity Analysis

The same strip chart recording used for the intensified field of view measurement is the basis for determining luminance uniformity across the field. If luminance were uniform, the graph would have a uniform horizontal line across the field. Luminance non-uniformity appears as a variation in the line across the chart graph, and typically is a fall-off in luminance from center to edge. Due to this fall-off and due to equipment limitations, it is difficult to measure the luminance at the edge of the goggle's FOV. Therefore, the luminance non-uniformity analysis is restricted to the central 80% of the tested system's measured field of view. Figure 15 demonstrates the luminance non-uniformity of a typical NVG.

To calculate luminance non-uniformity, three specific measurements must be taken from the graph. These are the maximum luminance, L_{max}, the luminance at the point bordering the right side of the central 80% of the measured field of view, $L_{80\%R}$, and the point bordering the left side of the central 80% of the field of view, $L_{80\%L}$. A value for luminance non-uniformity, LNU, expressed as a percentage, can be calculated from these numbers using Equation 7.2.

$$LNU = \frac{2L_{\max} - (L_{80\%L} + L_{80\%R})}{2L_{\max} + L_{80\%L} + L_{80\%R}} * 100\% \qquad (7.2)$$

The mathematical procedure required to calculate luminance non-uniformity is somewhat involved and is therefore easier to express it as a single equation. More detailed examinations of the mathematics involved in the luminance non-uniformity calculation and the derivation of this equation are available in Appendix A.

Modulation Contrast Analysis (Near Field and Far Field Contrast)

The strip chart recording from the measurement of the split field target is used to determine the modulation contrast. The data is reduced by listing near field and far field contrast, which would be the contrast measured at specified angles close to (5°) and farther from (10°) the edge of the dark field. Contrast is calculated by using the modulation contrast equation (Equation 7.3).

$$C_i = \frac{L_{\max} - L_{\min(i)}}{L_{\max} + L_{\min(i)}} \qquad (7.3)$$

C_i is the contrast calculated at i degrees from the drop-off edge, L_{max} is the measurement at the highest peak of the graph, and $L_{min(i)}$ is the measured point at i degrees from the drop-off edge. Figure 16 demonstrates the modulation contrast for a typical NVG.

7.4 Comments

These methods provide a relatively easy objective assessment of the NVG visual field parameters as long as the specifications of the procedure are followed carefully. An error will result if the parameter is not measured with an input light source which produces a uniform output and fills the entire NVG field of view. These measurements provide hard copies (Figures 7.2 and 7.3) of information which can be extracted directly from the graphs.

The analysis of the data collected using this procedure is somewhat subjective and is limited by the technician's ability to locate the points of interest accurately. Equipment limitations make an exact determination of the location of the edges of the measured FOV and the location of the light/dark border in the modulation contrast measurement is difficult. These factors must be considered when reviewing information about a tested system's visual field parameters.

COMBINER TRANSMISSIVITY

8.1 Introduction

Transmissivity is the ratio of the luminance of a light source measured through a medium to the luminance of the source measured directly (11). Some night vision goggles use a beam-splitter as an image combiner to relay the intensified image to the user. When the goggle is switched off, the combiner allows the user to see cockpit information without removing or manipulating their goggles. Combiner transmissivity is measured on these systems to determine how much of the light from the outside scene, such as an instrument panel of the cockpit, passes through the combiner.

8.2 Approach

Figure 17 depicts the equipment arrangement needed to measure the combiner transmissivity. This procedure requires a regulated light source and a telephotometer or spectral scanning radiometer.

The spectroradiometer is placed at least six feet in front of and focused on the light source. The baseline spectral radiance (or luminance if using a telephotometer) of the regulated light source is measured from 380 nm to 1000 nm at 10 nm intervals. The NVG is then positioned such that the beam splitter is between the spectroradiometer and the regulated light source. The apparent spectral radiance (or luminance depending on the instrument) is once again measured through the beam splitter from 380 nm to 1000 nm. The ratio of the radiance of the source as seen through the beam splitter to the radiance of the source viewed directly is calculated for each measured wavelength.

8.3 Results

Once the radiance values measured through the image combiner for each wavelength are known, they are divided by their corresponding radiance value from the baseline spectral scan of the light source. Fortunately the radiometer used performs this function and eliminates the need for the operator to calculate each ratio by hand. If the device used to measure transmissivity cannot handle mathematical manipulations, then the operator must calculate the percent transmissivity for numerous wavelengths to draw

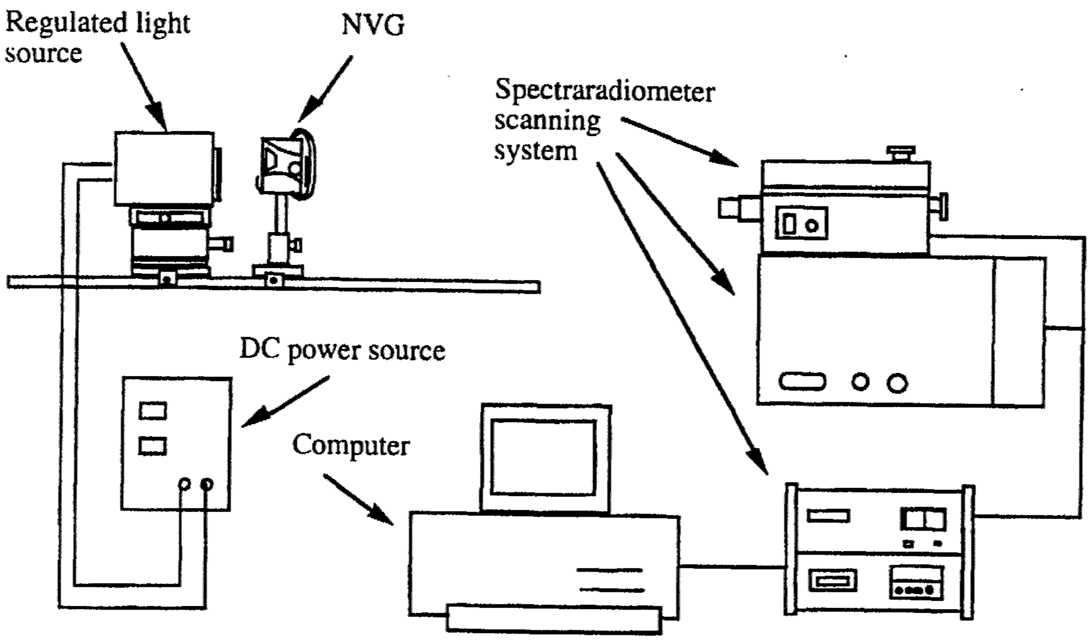

Figure 17. Test arrangement for the combiner transmissivity procedure.

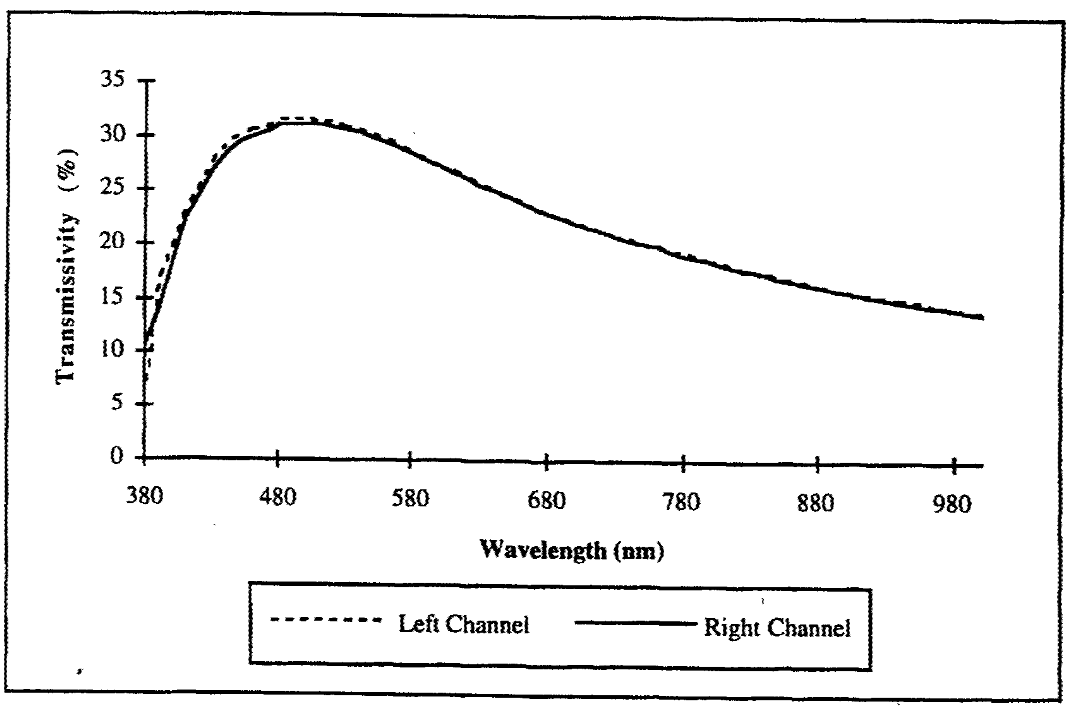

Figure 18. Example of typical NVG combiner transmissivity data.

the necessary graph. These percentages are then plotted against wavelength. Figure 18 shows a typical NVG image combiner transmissivity curve.

8.4 Comments

Figure 18 illustrates that the transmissivity of the beam-splitter at any wavelength can be determined graphically from the data collected during the procedure. Note that one must be careful of reflections and stray light sources during this measurement. Spurious light will cause erroneously high transmissivity values, if detected during the measurement of the combiner, or lower transmissivity values if detected while measuring the source baseline.

UNINTENSIFIED FIELD OF VIEW

9.1 Introduction

The unintensified field of view is a measure of how much the eye can see outside the intensified field of view of the NVG. It is simply a measure of peripheral vision and is concerned strictly with the observation around the NVG. For NVGs which have a combiner as an eyepiece, this measurement will also include the unintensified field of view as seen through it.

9.2 Approach

This procedure requires the use of a field perimeter, a holding fixture for the NVGs, and trained observers. Figure 19 depicts the arrangement of the equipment and the position of the subject.

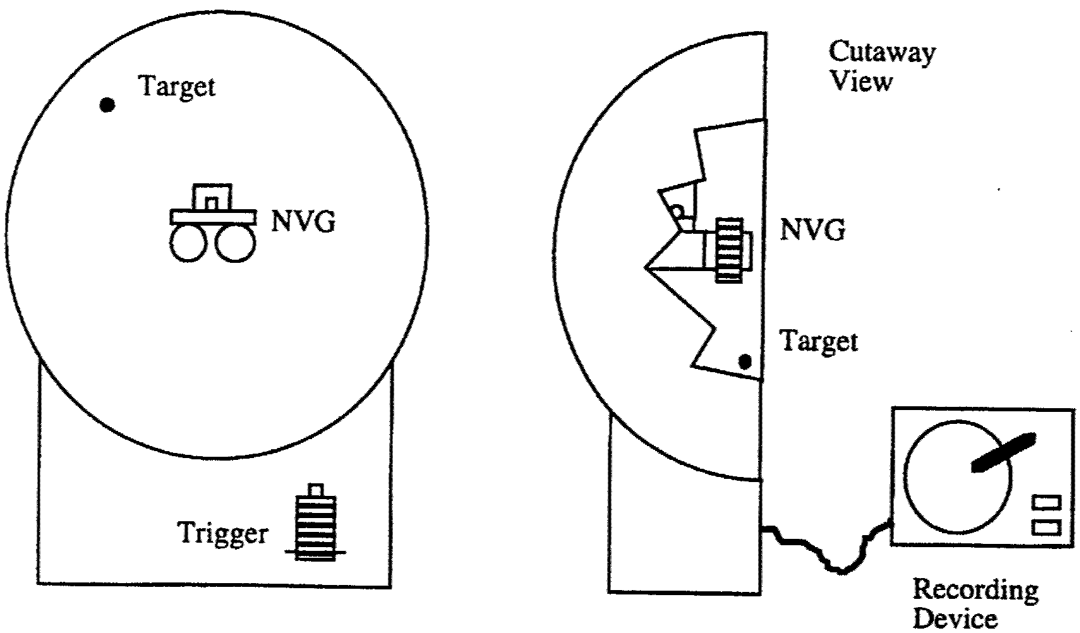

Figure 19. Test arrangement for the unintensified field of view measurement.

The NVG is mounted to the field perimeter so that the eye position of the observer is both in the correct eye position for wearing the NVG and in the correct position for measuring the peripheral field of view. The point light target of the field perimeter is positioned outside the field of view of the observer and brought radially inward toward the eye position until the observer can see it. The angle at which the point becomes visible is recorded on a field map for the meridian measured. This is repeated every 15 degrees until a full map of the field of view is obtained. This is measured for both the right eye position and the left eye position. A measurement without the NVG is also taken to provide a baseline graph. The results are typically recorded in units of steradians.

9.3 Results

Figure 20 is an example of a typical perimeter field graph. The number of steradians that are available to the observer without the NVG (baseline graph) is compared to the graph produced with the NVG. It may be possible to determine from the chart what limits the visual field, facial features or the NVG. Once that information is obtained, the results are then expressed as a percentage, such as the unintensified FOV with the NVG is 87% of the baseline without the NVG. The number of steradians available with the NVG is also recorded.

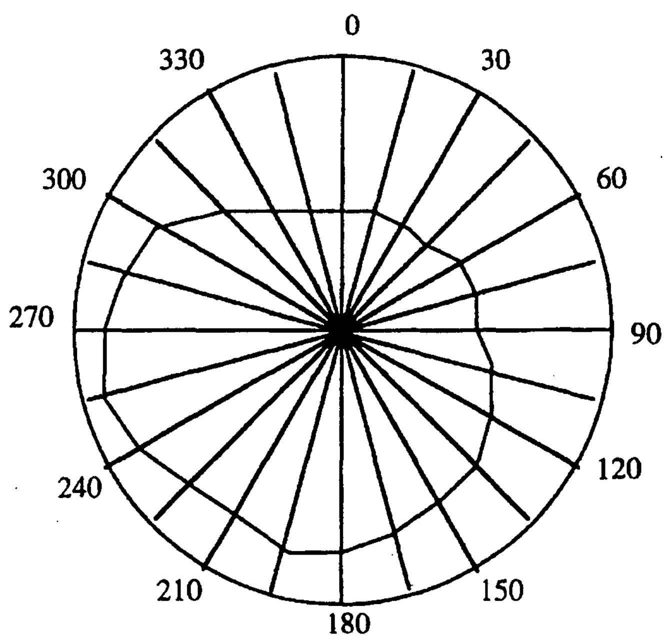

Figure 20. Example of typical perimeter field graph.

9.4 Comments

This is a highly subjective measurement. It relies on the use of a human observer in addition to an operator of the field perimeter. The results will vary considerably with the facial features of the subject and with the use or lack of chemical, biological, and neurological protective equipment.

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APPENDIX A

Derivation of the Luminance Non-Uniformity Equation

In the section of this report discussing the evaluation of NVG visual field parameters, an equation was given to compute the percent luminance non-uniformity of a system from three measurements made from a chart recorder trace (Equation 7.2). The origin of this equation is not perfectly obvious. This appendix will closely examine the luminance non-uniformity calculation and show the validity of Equation 7.2.

Luminance non-uniformity is a comparison of the actual luminance profile of an NVG image to an ideal, flat, uniform luminance value. It can be expressed either as a percentage, as in this report, or as a ratio of center FOV luminance to edge FOV luminance, as in the ANVIS image intensifier assembly specification. Equipment limitations make measuring the luminance output at the extreme edge of the intensified image difficult. Because of equipment limitations and measurement difficulties, the evaluation is limited to the central 80% of the tested NVG's field of view.

The calculation, expressed as a percentage, requires a low end, a mean, and a maximum luminance value. The maximum value can be measured directly from the chart recorder trace and is denoted as L_{max}. The other values are not as easily acquired.

The minimum luminance value can be found by comparing $L_{80\%L}$ and $L_{80\%R}$. These are the luminance values at the left and right most points, respectively, which define the central 80% of the NVG's measured field of view. The locations of these measurements on a typical chart recorder trace are shown in Figure A-1. Ideally, the field of view chart recorder trace, from which these measurements are taken, should be symmetric. Therefore, $L_{80\%L}$ and $L_{80\%R}$ should equal each other and equal the minimum luminance value. Unfortunately, this is rarely the case. The minimum luminance value, L_{low}, is then calculated as the average of the two, as in Equation A.1.

$$L_{low} = \frac{L_{80\%L} + L_{80\%R}}{2} \qquad \text{(A.1)}$$

The mean luminance value, L_{mean} , is calculated by averaging the maximum luminance value and the minimum luminance value, as in Equation A.2.

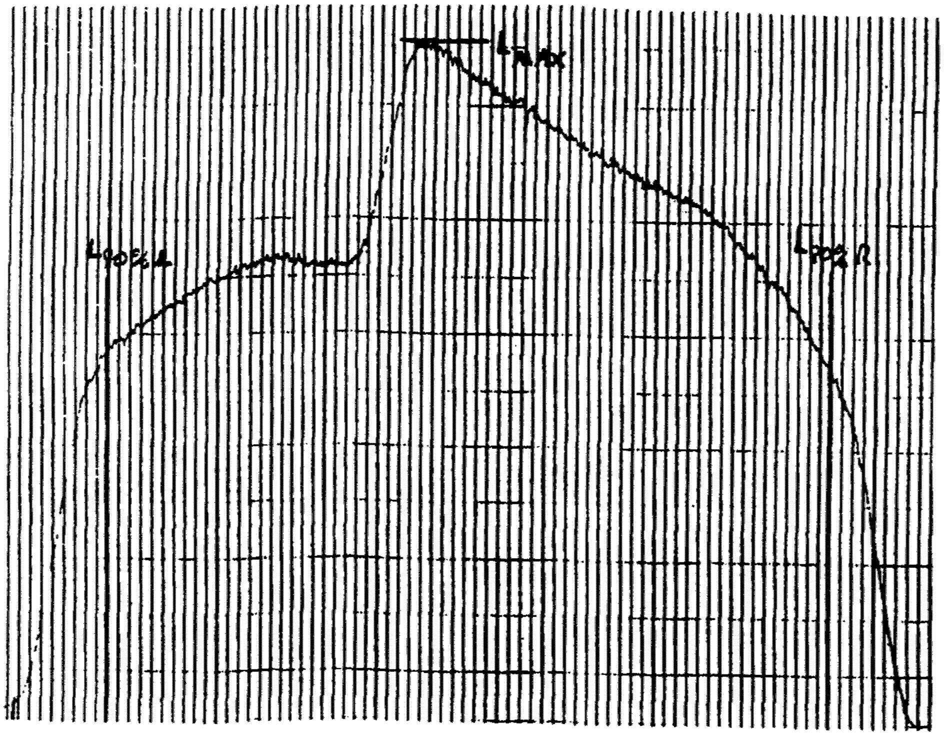


Figure A-1. Chart recorder trace used to determine luminance non-uniformity.

$$L_{mean} = \frac{L_{max} + L_{low}}{2} \qquad \text{(A.2)}$$

Substituting Equation A.1 into Equation A.2 yields

$$L_{mean} = \frac{2L_{max} + L_{80\%L} + L_{80\%R}}{4} \qquad \text{(A.3)}$$

The actual luminance non-uniformity value, *LNU*, is then calculated taking the difference of the maximum luminance value and the mean luminance value, dividing by the mean luminance value, and multiplying by 100% to express it as a percentage (Equation A.4).

$$LNU = \frac{L_{max} - L_{mean}}{L_{mean}} * 100\% \qquad \text{(A.4)}$$

Substituting Equation A.3 into Equation A.4 will yield a luminance non-uniformity equation in terms of only L_{max}, $L_{80\%L}$, and $L_{80\%R}$ equal to Equation A.5.

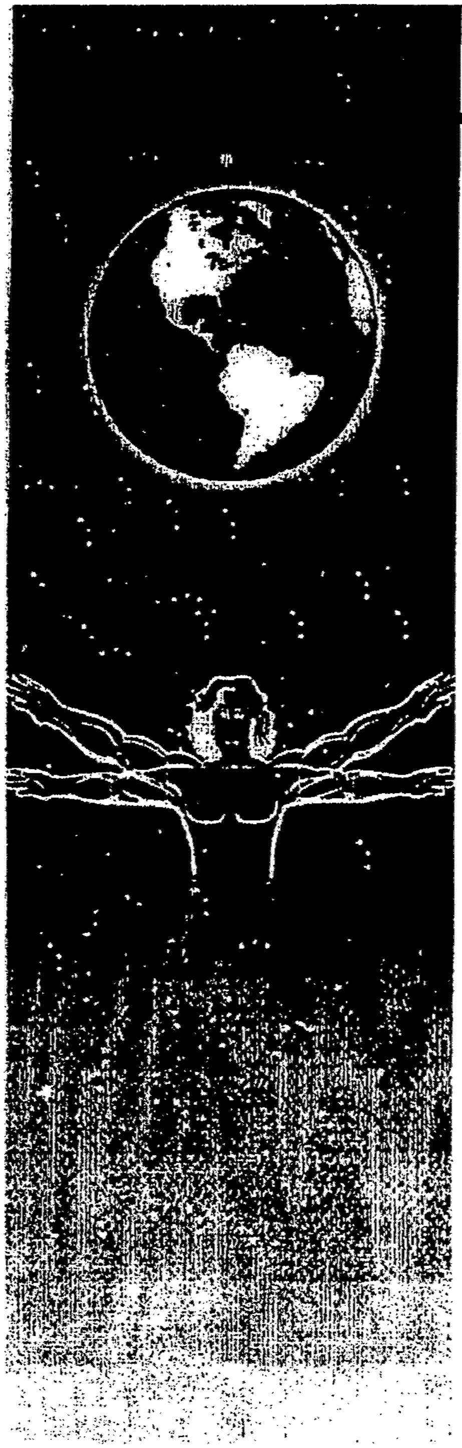
$$LNU = \frac{2L_{max} - (L_{80\%L} + L_{80\%R})}{2L_{max} + L_{80\%L} + L_{80\%R}} * 100\% \qquad (A.5)$$

This evaluation is quicker and easier to use than running the entire calculation for each ocular of each goggle evaluated and reduces the possibility of mathematical error.

U.S.G.P.O.:1994-550-057/81060

Pinkus, A. R., & Task, H. L. (1998). *Interlaboratory study (ILS) of the standard test method for measuring the night vision goggle-weighted transmissivity of transparent parts.* (Report No. AFRL-HE-WP-TR-1998-0016). Wright-Patterson AFB OH: Air Force Research Laboratory.

AFRL-HE-WP-TR-1998-0016



UNITED STATES AIR FORCE RESEARCH LABORATORY

INTERLABORATORY STUDY (ILS) OF THE STANDARD TEST METHOD FOR MEASURING THE NIGHT VISION GOGGLE-WEIGHTED TRANMISSIVITY OF TRANSPARENT PARTS

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CREW SYSTEM INTERFACE DIVISION
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MARCH 1998

INTERIM REPORT FOR THE PERIOD APRIL 1995 TO DECEMBER 1997

Approved for public release; distribution is unlimited

Human Effectiveness Directorate
Crew System Interface Division
2255 H Street
Wright-Patterson AFB, OH 45433-7022

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13. ABSTRACT *(Maximum 200 words)*
Night vision goggles (NVGs) are now being used in aircraft and other applications (e.g., marine navigation, surveillance, vehicles) with increasing frequency. These devices amplify near-infrared (NIR) spectral energy. A transparency may have excellent visible transmissive characteristics but could have poor NIR transmissivity. Overall visual performance (acuity) can be degraded if the observer uses the NVGs while looking through a transparency that has attenuated transmissivity in the NIR region. ASTM P94-02, Standard Test Method for Measuring NVG-Weighted Transmissivity of Transparent Materials addresses this issue. This Interlaboratory Study (ILS) determined the precision of P94-02. The method describes both analytical and direct measurement techniques that determine the NVG-weighted transmissivity (T_{NVG}) of transparent pieces. T_{NVG} is the integrated value (450 through 950 nm) of the spectral transmissivity of a transparent part weighted (multiplied) by both the spectral sensitivity of a given set of NVGs and the light source, divided by the integrated value of the NVGs times the light source. The higher the T_{NVG} the more compatible a transparency is with NVGs, i.e., there is more light energy available to be amplified by the goggles which usually corresponds to better visual acuity performance of the observer (finer detail seen).

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1. TITLE
INTERLABORATORY STUDY (ILS) OF THE STANDARD TEST METHOD FOR MEASURING THE NIGHT VISION GOGGLE-WEIGHTED TRANSMISSIVITY OF TRANSPARENT PARTS

Committee F-7 on Aerospace and Aircraft Enclosures.
Subcommittee F-7.08 on Transparent Enclosures and Materials
RR: P94-02: XXXX

2. INTRODUCTION
There are several ASTM Standards that address light transmissivity through transparencies (ASTM Standards F 1316-90D and 1003-61) in the visible spectrum (400 through 700 nm). However, night vision goggles (NVGs) are now being used in aircraft and other applications (e.g., marine navigation, surveillance, personnel carriers) with increasing frequency. These devices amplify both visible and near-infrared (NIR) spectral energy. A transparency may have excellent visible transmissive characteristics but could have poor NIR transmissivity. Overall visual performance (acuity) can be degraded if the observer uses the NVGs while looking through a transparency that has attenuated transmissivity in the NIR region (Pinkus and Task, 1997, see Appendix A). ASTM P94-02, Standard Test Method for Measuring Night Vision Goggle-Weighted Transmissivity of Transparent Materials (see draft in Appendix B) addresses this issue. This ILS was undertaken in order to determine the precision of P94-02. The method describes both analytical and direct measurement techniques that determine the NVG-weighted transmissivity (T_{NVG}) of transparent pieces including ones that are large, curved, or held at the installed position. This ILS investigated just the analytical method since only one lab is presently capable of implementing the direct test method. T_{NVG} is the integrated value (450 through 950 nm) of the spectral transmissivity of a transparent part weighted (multiplied) by both the spectral sensitivity of a given set of NVGs and the light source, divided by the integrated value of the NVGs times the light source. The higher the T_{NVG} the more compatible a transparency is with NVGs, i.e., there is more light energy available to be amplified by the goggles which usually corresponds to better visual acuity performance of the observer (finer detail seen).

3. TEST PROGRAM INSTRUCTIONS AND TEST METHOD
The cover letter for test instructions to participating labs, follows.

SUBJECT: Interlaboratory Study for ASTM Standard P94-02: Standard Test Method for Measuring Night Vision Goggle-Weighted Transmissivity of Transparent Materials.

FROM: AL/CFHV
2255 H Street, Room 300
Wright-Patterson AFB OH 45433-7022

Dear Colleague,

Please find enclosed the instructions and materials needed by you to conduct spectral transmissivity measurements as discussed at the April 8th, 1997 ASTM Task Force committee meeting in St. Louis. The test has been simplified by the elimination of the Excel spread sheet. I am now simply supplying four (4) plastic samples. The spectral transmissivity scan data are then returned to me for completion of the data analysis of which the details are described in the attached draft test method [P94-02, see Appendix B]. You may retain the draft for your use and records.

The data collection procedure is as follows:

(1) Please handle the samples carefully as to not cause any (further) damage.

(2) Do not clean them with any solvents. Use part specific, prescribed cleaning materials and methods.

(3) Spectral measurements are made from 450 nanometers (nm) through 950 nm in 5 nm incremental steps, with the arrow on top and pointed towards the specrtophotometer's sensor.

(4) Perform sample measurements sequentially, i.e., measure #1, #2, #3, #4.

(5) Repeat Step (4), five times, per instrument, yielding 20 sets of spectral data. Thus, the test sequence for the samples is:

Measure samples	[#1, #2, #3, #4]
Repeat	[#1, #2, #3, #4]
Repeat	[#1, #2, #3, #4]
Repeat	[#1, #2, #3, #4]
Repeat	[#1, #2, #3, #4]

(6) Repeat this process on more than one instrument, if available (instruments are statistically analyzed as "labs" and I need as many "labs" as possible).

(7) Label each spectral printout with:

Sample # and repetition #
Instrument make and model #
Date and time of the measurement

(8) These measurements can be made over a period of days, if desired. The variability in the data due to an extended measurement period will more accurately reflect real-world conditions (i.e., variability due to temperature, positioning, drift, etc.).

(9) Since these test samples need to be sent to several labs, please complete all measurements within two weeks of receipt and return data and samples to the address, above, so I can forward the samples to the next company.

Sincerely,

Alan Pinkus, PhD
Research Psychologist

6 Attachments:
1. Cover Letter
2. Plastic Sample #1
3. Plastic Sample #2
4. Plastic Sample #3
5. Plastic Sample #4
6. Draft Test Method P94-02

4. LIST OF PARTICIPATING LABORATORIES

There were six labs (instrument types).

Lab #1: EG&G Radoma GS1252 Spectraphotometer (15 May 1997)
Air Force Research Lab/HECV (formally Armstrong Lab/CFHV)
2255 H Street, Room 300
Wright-Patterson AFB OH 45433-7022
POC: Alan Pinkus (937-255-8767)

Lab #2: Cary 5G Spectraphotometer (16 Jun 1997)
Air Force Research Lab (formally Armstrong Lab/OEO)
8111 18th Street
Brooks AFB TX 78235-5215
POC: Dennis Maier (210 536-3709)

Lab #3: Perkin Elmer Lambda 9 Spectraphotometer (16 Jun 1997)
Air Force Research Lab (formally Armstrong Lab/OEO)
8111 18th Street
Brooks AFB TX 78235-5215
POC: Dennis Maier (210 536-3709)

Lab #4: Hitachi U-2000 (2 Jul 1997)
Polycast, Inc.
70 Carlisle Pl
Stamford CT 06902
POC: Kuang Tran (203-327-6010

Lab #5: Model 736 Radiometer (21 Jul 1997)
Texstar, Inc.
1170 108th Street
PO Box 534036
Grand Prairie TX 75053-4036
POC: Lance Teten (214-647-1366)

Lab #6: UV/VIS/NIR (8 Sep 1997)
Sierracin/Sylmar Corp.
12780 San Fernando Rd
Sylmar CA 91342
POC: John Raffo (818-362-6711)

5. DATA REPORTS

See Appendix C

6. STATISTICAL DATA SUMMARY

The four test stimuli were 2 inch square samples of transparent plastic material: #1, 0.875 inches thick acrylic, #2 laminated (F-111), #3 gold-coated (F-16) and #4, 3 mm acrylic. Samples #2 and #3 were cut from actual aircraft windscreens. The main source of error in the test method is due to the variability among spectraradiometric (spectraphotmetric) instruments not the T_{NVG} calculation.

Absolute radiometric calibration of the instrument is not essential since T_{NVG} is a ratio. In this ILS, the six instruments were treated as labs. The samples were measured using spectraradiometric instruments but the actual calculation of T_{NVG} (in accordance with test method P94-02) was performed later, prior to data analysis. T_{NVG} equals the integral with respect to wavelength, of the transparent part's spectral transmissivity [$P(\lambda)$] times the spectral energy distribution of the light source [$S(\lambda)$] times the NVG spectral sensitivity [$G(\lambda)$] divided by the integral with respect to wavelength, of the spectral energy distribution of the light source times the NVG spectral sensitivity. Since the specific spectral energy distribution of the light source in Equation 1 is typically not known for operational conditions (it depends on the spectral energy distribution of the illumination source on the scene and the spectral reflectivity of the various objects in the scene) the NVG-weighted transmission coefficient was calculated using $S(\lambda) = 1$ for all wavelengths. This simplifies the equation and typically does not significantly affect the results for the vast majority of broad-band reflectance distributions normally encountered. (Pinkus and Task, 1997; Equation 1 in Appendix A). Just the analytical method section of P94-02 was studied since only one lab (Air Force Research Lab/WPAFB/HECV, formally the Armstrong Lab) has the capability to perform the other, direct method. An ILS for the direct method may be performed at a later date. Tables 1 through 4 summarize the ILS results.

Tables 1 through 4. Results summary of four plastic samples (thick acrylic, laminated, gold-coated and 3 mm acrylic), measured by 6 labs (instruments) 5 times each: T_{NVG} means ($\bar{x}$), standard deviations (s), cell deviations (d), h and k statistics, grand mean (GM), repeatability (S_r), standard deviation of cell averages ($S_{\bar{x}}$), as defined in ASTM Practice E 691.

Table 1 (1.92 1.75)

#1 (THICK)	REPS									
LABS	1	2	3	4	5	$\bar{x}$	s	d	h	k
EG&G	0.895	0.888	0.897	0.899	0.877	0.891	0.009	-0.012	-0.987	0.846
CARY 5G	0.904	0.903	0.899	0.904	0.903	0.903	0.002	-0.001	-0.072	0.173
PERK/ELM L9	0.901	0.898	0.894	0.896	0.890	0.896	0.004	-0.008	-0.634	0.378
HIT U-2000	0.902	0.902	0.902	0.903	0.902	0.902	0.000	-0.001	-0.085	0.015
736 RADIOM.	0.936	0.924	0.926	0.921	0.926	0.927	0.006	0.023	1.897	0.532
UV/VIS/NIR	0.902	0.903	0.901	0.904	0.900	0.902	0.001	-0.001	-0.119	0.120

GM	$S_{\bar{x}}$	S_r	S_R
0.903	0.012	0.011	0.015
	95%=	0.030	0.043
		r	R

Table 2

#2 (LAM)	REPS									
LABS	1	2	3	4	5	$\bar{X}$	*s*	*d*	*h*	*k*
EG&G	0.853	0.850	0.861	0.859	0.860	0.857	0.005	-0.010	-0.816	0.432
CARY 5G	0.868	0.866	0.867	0.862	0.864	0.865	0.002	-0.001	-0.114	0.202
PERK/ELM L9	0.867	0.864	0.858	0.862	0.857	0.861	0.004	-0.006	-0.439	0.382
HIT U-2000	0.869	0.868	0.865	0.870	0.858	0.866	0.005	-0.001	-0.080	0.462
736 RADIOM.	0.897	0.897	0.881	0.888	0.895	0.892	0.007	0.025	1.964	0.646
UV/VIS/NIR	0.863	0.860	0.862	0.859	0.859	0.860	0.002	-0.006	-0.514	0.168

GM	$S_{\bar{x}}$	S_r	S_R
0.867	0.013	0.011	0.016
	95%=	0.030	0.044
		r	*R*

Table 3

#3 (GOLD)	REPS									
LABS	1	2	3	4	5	$\bar{X}$	*s*	*d*	*h*	*k*
EG&G	0.533	0.539	0.540	0.541	0.527	0.536	0.006	-0.007	-0.844	0.789
CARY 5G	0.547	0.547	0.546	0.546	0.547	0.547	0.001	0.003	0.375	0.067
PERK/ELM L9	0.541	0.541	0.535	0.535	0.532	0.537	0.004	-0.006	-0.762	0.520
HIT U-2000	0.541	0.541	0.541	0.543	0.542	0.542	0.001	-0.002	-0.201	0.117
736 RADIOM.	0.561	0.557	0.563	0.550	0.564	0.559	0.006	0.016	1.834	0.777
UV/VIS/NIR	0.539	0.543	0.541	0.538	0.540	0.540	0.002	-0.003	-0.402	0.259

GM	$S_{\bar{x}}$	S_r	S_R
0.543	0.009	0.007	0.011
	95%=	0.021	0.030
		r	*R*

Table 4

#4 (3mm)	REPS									
LABS	1	2	3	4	5	$\bar{X}$	s	d	h	k
EG&G	0.878	0.878	0.880	0.886	0.877	0.880	0.004	0.002	0.300	0.583
CARY 5G	0.879	0.881	0.879	0.878	0.877	0.879	0.001	0.001	0.096	0.218
PERK/ELM L9	0.878	0.875	0.871	0.873	0.865	0.872	0.005	-0.006	-0.869	0.781
HIT U-2000	0.881	0.876	0.879	0.879	0.881	0.879	0.002	0.001	0.181	0.313
736 RADIOM.	0.897	0.884	0.891	0.879	0.890	0.888	0.007	0.010	1.573	1.133
UV/VIS/NIR	0.869	0.872	0.870	0.869	0.870	0.870	0.001	-0.008	-1.280	0.209

GM	$S_{\bar{x}}$	S_r	S_R
0.878	0.006	0.006	0.008
	95%=	0.017	0.023
		r	*R*

The critical values of the h and k statistics, used to determine outliers (ASTM Practice E 691, Table 12, p. 14, where $p = 6$ and $n = 5$), are 1.92 and 1.75, respectively. Only one lab (Table 2, sample #2, 736 Radiometer) exceeded the critical h (bolded) at 1.964. The data were reexamined for typographical errors but none were found. The prescribed method was followed so the data were retained for final analysis. Table 5 summarizes the repeatability *(S_r)* and reproducibility *(S_R)* values and Table 6 summarizes the 95% repeatability *(r)* limits and the 95% reproducibility *(R)* limits for the individual samples as well as the means.

Table 5. Repeatability *(S_r)* and reproducibility *(S_R)* values in T_{NVG}, derived from the data sets in Appendix C.

	REPEATABILITY (S_r) WITHIN LABS	**REPRODUCIBILITY (S_R) BETWEEN LABS**
SAMPLE #1	0.011	0.015
SAMPLE #2	0.011	0.016
SAMPLE #3	0.007	0.011
SAMPLE #4	0.006	0.008
MEAN	**0.009**	**0.013**

Table 6. 95% repeatability *(r)* limits and 95% reproducibility *(R)* limits in T_{NVG}.

	95% *r* LIMITS WITHIN LABS	95% *R* LIMITS BETWEEN LABS
SAMPLE #1	0.030	0.043
SAMPLE #2	0.030	0.044
SAMPLE #3	0.021	0.030
SAMPLE #4	0.017	0.023
MEAN	**0.025**	**0.035**

S_r ranged from 0.006 to 0.011 T_{NVG}
S_R ranged from 0.008 to 0.016 T_{NVG}

r ranged from 0.017 to 0.030 T_{NVG}
R ranged from 0.023 to 0.044 T_{NVG}

Since the accuracy of the measurements should not and did not depend upon the type of the transparent material, it is logical to calculate a mean T_{NVG} of the 4 sample sizes to derive the composite precision values indicative of this method.

The composite (mean) repeatability *(S_r)* and reproducibility *(S_R)* values:
Mean $S_r = 0.009\ T_{NVG}$
Mean $S_R = 0.013\ T_{NVG}$

The composite (mean) 95% limits for repeatability *(r)* and 95% limits for reproducibility *(R)* values:
Mean $r = 0.025\ T_{NVG}$
Mean $R = 0.035\ T_{NVG}$

Note: The 95% limits were calculated using the formulae, below. Since the 95% limits are based on the difference between two test results, the √2 factor was incorporated into the calculation (ASTM Practice E 177; 27.3.3).

r = 95% repeatability limit (within laboratories)
S_r = repeatability standard deviation

$$r = 1.960 * \sqrt{2} * S_r$$

R = 95% reproducibility limit (between laboratories)
S_R = reproducibility standard deviation

$$R = 1.960 * \sqrt{2} * S_R$$

7. RESEARCH REPORT SUMMARY

Precision: An interlaboratory study was conducted to determine the precision of ASTM P94-02 (draft), Standard Test Method for Measuring Night Vision Goggle-Weighted Transmissivity of Transparent Materials. Six labs (instruments) were used to measure four plastic samples, five times each. Statistical analysis (ASTM Standard Practices E 691 and E 177) revealed that the method's mean repeatability (S_r) was 0.009 T_{NVG} and the mean reproducibility (S_R) was 0.013 T_{NVG}. The mean 95% limits for repeatability (r) was 0.025 T_{NVG} and the mean 95% limits for reproducibility (R) was 0.035 T_{NVG}.

Bias: The procedure in this test method has no bias because the NVG-weighted transmissivity is defined only in terms of the test method.

8. REFERENCES

F 1316-90 Standard Test Method for Measuring the Transmissivity of Transparent Parts. *Annual Book of ASTM Standards*, Vol. 08.01. Mar 1991.

D 1003-61 Standard Test Method for Haze and Luminous Transmittance of Transparent Parts. *Annual Book of ASTM Standards*, Vol. 15.09. Sep 1961.

Pinkus, A. and Task, H. L. (1997). The Effects of Aircraft Transparencies on Night Vision Goggle-Mediated Visual Acuity. *SAFE Symposium 1997*, Sep 8-10, pp. 93-104.

ASTM Standard Practice E 691. Conducting an Interlaboratory Study to Determine the Precision of a Test Method.

ASTM Standard Practice E 177. Use of the Terms Precision and Bias in ASTM Test Methods.

APPENDIX B. P94-02 Test Method

REVISED DRAFT (Dec 16, 97)

P94-02 Standard Test Method for Measuring the Night Vision Goggle-Weighted Transmissivity of Transparent Parts[1]

INTRODUCTION

Test Methods D 1003-61 and F 1316-90 (see Refs. 2.1.1 and 2.1.2) apply to the transmissivity measurement of transparent materials, the former being for small flat samples and the later for larger, curved pieces such as aircraft transparencies. Additionally, in D 1003-61, the transmissivity is measured perpendicular to the surface of test sample and both test methods measure only in the visible light spectral region. Night vision goggles (NVGs) are being used in aircraft and other applications (e.g., marine navigation, driving) with increasing frequency. These devices amplify both visible and near-infrared (NIR) spectral energy. Overall visual performance can be degraded if the observer uses the NVGs while looking through a transparency that has poor transmissivity in the NIR region. This method describes both direct and analytical measurement techniques that determine the NVG-weighted transmissivity of transparent pieces including ones that are large, curved, or held at the installed position.

1. Scope

1.1 This test method describes apparatuses and procedures that are suitable for measuring the NVG-weighted transmissivity of transparent parts including those which are large, thick, curved, or already installed. This test method is sensitive to transparencies that vary in transmissivity as a function of wavelength.

1.2 Since the transmissivity (or transmission coefficient) is a ratio of two radiance values, it has no units. The units of radiance recorded in the intermediate steps of this test method are not critical; any recognized units of radiance (e.g., watts/m^2-str) may be used, as long as it is consistent (see Ref. 2.2.1).

1.3 *This standard does not purport to address the safety problems associated with its use. It is the responsibility of the user of this standard to establish appropriate safety and health practices and determine the applicability of regulatory limitations prior to use.*

2. Referenced Documents

2.1 *ASTM Standards:*

2.1.1 D 1003-61 Standard Test Method for Haze and Luminous Transmittance of Transparent Parts. *Annual Book of ASTM Standards*, Vol. 15.09. Sep 1961.

2.1.2 F 1316-90 Standard Test Method for Measuring the Transmissivity of Transparent Parts. *Annual Book of ASTM Standards*, Vol. 08.01. Mar 1991.

2.2 *Published Documents:*

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[1] This test method is under the jurisdiction of ASTM Committee F-7 on Aerospace and Aircraft and is the direct responsibility of Subcommittee F07.08 on Transparent Enclosures and Materials.

2.2.1 *RCA Electro-Optics Handbook.* (1974). Lanchaster PA: RCA|Solid State Division|Electro Optics and Devices. Technical Series EOH-11.

2.2.2 Wyszecki, Gunter. and Stiles, W. S. (1982). *Color Science: Concepts and Methods, Quantitative Data and Formulae* (Second Edition). New York: John Wiley and Sons.

3. Terminology

3.1 *Definitions*:

3.1.1 *Analytical test method* - the test method that uses spectral transmissivity data of a transparent part collected by the use of either spectraphotometric or spectraradiometric instrumentation. The data are then examined using analytic methods to determine the NVG-weighted transmissivity of the part .

3.1.2 *Direct test method* - the test method that uses the actual luminous output, as measured by a photometer, properly coupled to the eyepiece of the test NVG. The NVG-weighted transmissivity of the part is then determined by forming the ratio of the NVG output luminance with the transparent part in place to the luminance output without the part.

3.1.3. *NVG-weighted spectral transmissivity* - the spectral transmissivity of a transparent part multiplied by the spectral sensitivity of a given NVG (see Fig. 1).

3.1.4 *NVG-weighted transmissivity* (T_{NVG}) - the spectral transmissivity of a transparent part multiplied by the spectral sensitivity of a given NVG integrated with respect to wavelength (see Fig. 1, Equations 1 and 2).

3.1.5 *NVG spectral sensitivity* - the sensitivity of an NVG as a function of input wavelength.

3.1.6 *photometer* - a device that measures luminous intensity or brightness by converting (weighting) the radiant intensity of an object using the relative sensitivity of the human visual system as defined by the photopic curve. (see Refs. 2.2.1 and 2.2.2)

3.1.7 *Photopic curve* - the photopic curve is the spectral sensitivity of the human eye for daytime conditions as defined by the *Commission Internationale d'Eclairage (CIE)* 1931 standard observer (see Refs. 2.2.1 and 2.2.2).

3.1.8 *transmission coefficient* - same as *transmissivity*.

3.1.9 *transmissivity* - the transmissivity of a transparent medium is the ratio of the luminance of an object measured through the medium to the luminance of the same object measured directly.

4. Summary of Test Methods

4.1 *General Test Conditions:* The test can be performed in any light-controlled area (e.g., light-tight room, darkened hangar, or outside at night away from strong light sources). The ambient illumination must be very low due to the extreme sensitivity of the NVGs. A fixture holds the NVG and its objective lens is aimed at and focused on a target. The target can be either an evenly illuminated white, diffusely reflecting surface or a transilluminated screen (lightbox). The illumination is provided by a white, incandescent light source. Handle the samples carefully as to not cause any damage. Do not clean them with any solvents. Use part specific, prescribed cleaning materials and methods.

4.1.1 *Direct Test Method:* Attached directly to the eyepiece of the NVG is a photodetector. It has been found that the measured field of view (FOV) should be smaller than the uniformly illuminated portion of the target. The target illumination is adjusted so that the output of the NVGs is about 1.7 cd/m^2 (0.5 fL). This assures that the NVG input is not saturated; the automatic gain control (AGC) is not active. The luminance output of the NVG is measured and then repeated with the transparent material in place. The transmissivity is equal to the NVG output luminance with the transparent material in place divided by the NVG output luminance without the material (see Section 10.1, Equation 1). The result is the NVG-weighted transmissivity (T_{NVG}) of the transparent material.

4.1.2 *Analytical test method:* Without the sample in place, measure the light source's spectral energy distribution from 450 nanometers (nm) through 950 nm in 5 nm incremental steps. Place the sample into the spectrophotometer or spectraradiometer fixture. Perform spectral measurements, also from 450 nm through 950 nm in 5 nm incremental steps. Obtain, from the NVG manufacturer, the spectral sensitivity of the goggle that will be used in conjunction with the part. Perform analytic method as defined in Section 10.2 by Equation 2, to derive the T_{NVG}.

5. Significance and Use

5.1 *Significance* - This test method provides a means to measure the compatibility of a given transparency through which NVGs are used at night to view outside, nighttime ambient illuminated natural scenes.

5.2 *Use* - This test method may be used on any transparent part including sample coupons. It is primarily intended for use on large, curved, or thick parts that may already be installed (e.g., windscreens on aircraft).

6. Apparatus:

6.1 *Test Environment* - This test method can be performed in any light-controlled area (e.g., light-tight room, darkened hangar, or outside at night away from strong light sources) since the NVGs are extremely sensitive to both visible and near infrared light. Extraneous light sources (e.g., exit signs, telephone pole lights, status indicator lights on equipment, etc.) can also interfere with the measurement.

6.2 *White Diffuse Target* - The white target can be any uniformly diffusely reflecting or translucent material (e.g., cloth; flat white painted surface; plastic). The target area should be either smaller (see Figure 2) or larger (see Figure 3) than the NVG FOV (35-60 degrees typical) in order to minimize potential alignment errors.

6.3 *Light Source* - The light source should be regulated to ensure that it does not change luminance during the reading period. It should be a low output, 2856 Kelvin incandescent light since this type emits sufficient energy in both visible and infrared without any sharp emission peaks or voids (see Ref. 2.2.1). Its output must be uniformly distributed over the measurement area of the white diffuse target. Use of neutral density filters or varying the lamp distance may be needed to achieve sufficiently low luminance levels to be obtained for test, since varying the radiator's output would shift its color temperature.

6.4 *Night Vision Goggles* - A family of passive image intensifying devices that utilize visible and near-infrared light and enable the user to see objects that are illuminated by full moonlight through starlight only conditions. The goggle that is used for test should be the same as that which will be used with the given transparent material (see Appendix B).

6.5 *Photometer* - Any calibrated photometer may be used for this measurement. However, the detector must be properly coupled to the NVG eyepiece and the FOV over which the light is integrated must be known (see Appendix A).

7. Test Specimen

7.1 If necessary, clean the part to be measured using the procedure prescribed for the specific material. Use of nonstandard cleaning methods can irrevocably damage the part. No special conditions other than cleaning are required.

8. Calibration and Standardization

8.1 It is not necessary that the photometer be calibrated in absolute luminance units since the measurement involves the division of two measured quantities yielding a dimensionless value. A generic photodector can be substituted for the photometer if its FOV is known .

9. Procedure

9.1 *General Procedures:* All measurements are performed in a darkened, light-controlled area. In order to control the effects of reflection, verify that there are no extraneous light sources that can produce reflections within the measurement area of the transparent material. To control the effects of haze, verify that no light other than the measurement light, falls on the area being tested.

9.2 *Direct test method:* This method allows analysis of large or small transparent parts placed at either normal (perpendicular to the optical axis) or installed orientations, such as an aircraft windscreen. Figure 2 illustrates the use of a small, transilluminated lightbox. Figure 3 depicts the use of a large, front-illuminated, white, diffusely reflective target, illuminated as uniformly as possible using a regulated white incandescent light source. The size of the target is dependent upon the test location, the obtainable luminance uniformity, and the FOV of the photodetector assembly. In the field, a transilluminated lightbox is probably the easiest to setup and use as it offers the advantage of compact, self-contained portability. It is important to maintain the same target to NVG distance during the measurements. In a light-tight room, a white, diffusely reflecting, front-illuminated surface may be utilized. In the field, the NVG can be held by hand and under laboratory conditions, can be mounted in a sturdy fixture. It is then aimed at and focused on the white target. The photodetector is attached to the NVG eyepiece. With the transparent material removed from the measurement path, the variable white light is adjusted to produce an NVG output luminance of about 1.7 cd/m^2 (0.5 fL). This insures that the NVG's input is not saturated; the AGC is not activated. Due to the extreme sensitivity of NVGs, neutral density filters may need to be placed in front of the light source in order to obtain low enough target luminance. After recording the NVG's output luminance, the transparent material is placed in the measurement path. If the material is a sample, its orientation relative to the measurement path can be simply perpendicular or at the installed angle. If an aircraft transparency is being tested, the NVG should be located at the design eye position relative to the transparency which is mounted in its installed position. Measuring at the installed angle is critical since many materials exhibit variations in transmissivity as a function of angle. The NVG's output, with the test piece in place, is then recorded. In order to prevent damage to the NVGs, verify that they are turned off before the test area lights are turned on.

There are numerous classes of NVGs (generations 2, 3; types A, B) that vary in their spectral sensitivity, intensified FOV, resolution, etc. It is important to select the proper NVG type that will be used in a given application. The NVG must also be in good working condition and meet minimum user performance specifications.

The target illumination source can be an incandescent operating at 2856 Kelvin which is the standard color temperature that is used for many NVG test procedures. The illumination from this source can be varied using neutral density filters since varying the light's voltage would cause a corresponding color temperature shift. If the NVG is to be used to view an area, through a specific transparent material, that is illuminated by a different kind of light source (e.g., mercury vapor; sodium) then that source must be properly noted in the test report.

The luminance output of the NVG is measured and then repeated with the transparent material in place. The transmissivity is equal to the NVG output luminance with the transparent material in place divided by the NVG output luminance without the material (see Section 10.1, Equation 1). The result is the NVG-weighted transmissivity (T_{NVG}) of the transparent material.

9.3 *Analytical test method:* If using a spectrophotometer, the sample is usually limited to about two by two inch sample coupons held in a normal position. In general (but depending on the model) a spectraradiometer can be used to measure large or small parts at normal or installed positions. With the sample removed, measure the light source's spectral energy distribution from 450 nanometers (nm) through 950 nm in 5 nm incremental steps. Place the sample into the spectrophotometer or spectraradiometer fixture. Perform spectral measurements, also from 450 nm through 950 nm in 5 nm incremental steps. Obtain, from the NVG manufacturer, the spectral sensitivity of the goggle type (in 5 nm increments) that will be used in conjunction with the transparent part. Perform analytic method as defined in Section 10.2 by Equation 2, to derive the T_{NVG}.

10. T_{NVG} Calculation

10.1 *Direct test method calculation:* When using a photodetector attached to the NVG eyepiece, the calculation is described by Equation 1. The transmissivity is equal to the NVG output luminance with the transparent material in place (L_T) divided by the NVG output luminance without the material (L_B). The result is the NVG-weighted transmissivity (T_{NVG}) of the transparent material.

$$T_{NVG} = \frac{L_T}{L_B} \qquad (1)$$

where:
T_{NVG} = NVG-weighted transmissivity
L_T = NVG output luminance with the transparent material in place
L_B = NVG output luminance without the transparent material

10.2 *Analytical test method:* Figure 1 is an example of the elements of the T_{NVG} calculation. When substituting a spectraradiometer (see Appendix A) for the NVG and photodetector assemblies (see Figures 2 and 3), the calculation is described by Equation 2. For Equation 2, T_{NVG} equals the integral with respect to wavelength, of the transparent part's spectral transmissivity [$P(\lambda)$] times the spectral energy distribution of the light source [$S(\lambda)$] times the NVG spectral sensitivity [$G(\lambda)$] divided by the integral with respect to wavelength, of the spectral energy distribution of the light source times the NVG spectral sensitivity.

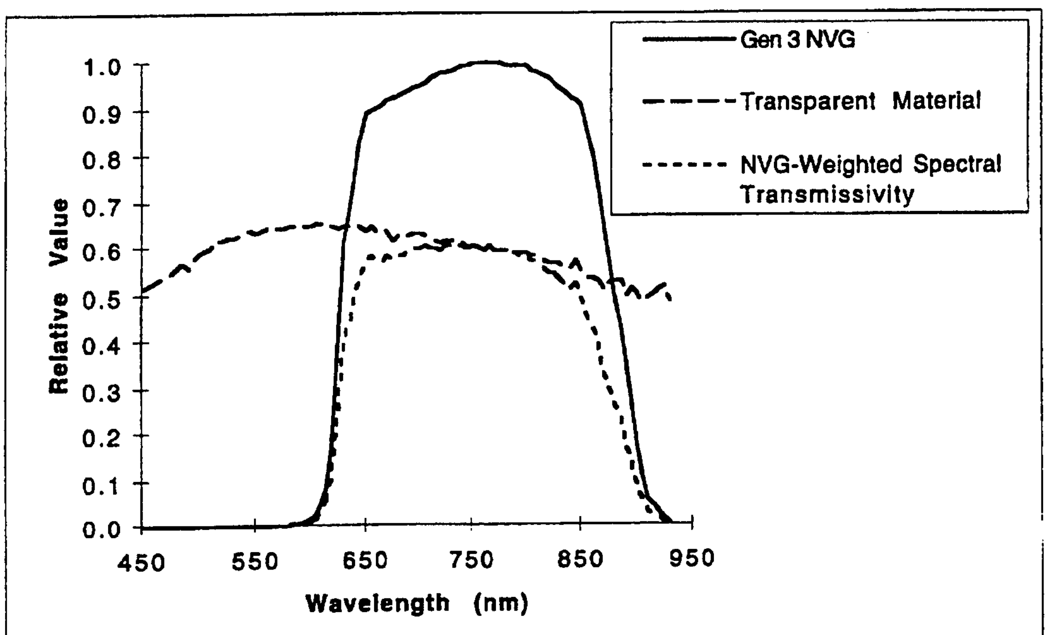

Figure 1. An example of how the spectral sensitivity of a Generation 3 NVG multiplied by the spectral transmissivity of a transparent part equals the NVG-weighted spectral transmissivity of that part. Integrating the curve with respect to wavelength yields the part's NVG-weighted transmissivity (T_{NVG}) value.

$$T_{NVG} = \frac{\int_{450}^{950} P(\lambda)S(\lambda)G(\lambda)d\lambda}{\int_{450}^{950} S(\lambda)G(\lambda)d\lambda} \tag{2}$$

where:

T_{NVG} = NVG-weighted transmissivity
$P(\lambda)$ = spectraradiometric scan through transparent part
$S(\lambda)$ = spectral energy distribution of the light source
$G(\lambda)$ = spectral sensitivity of night vision goggle

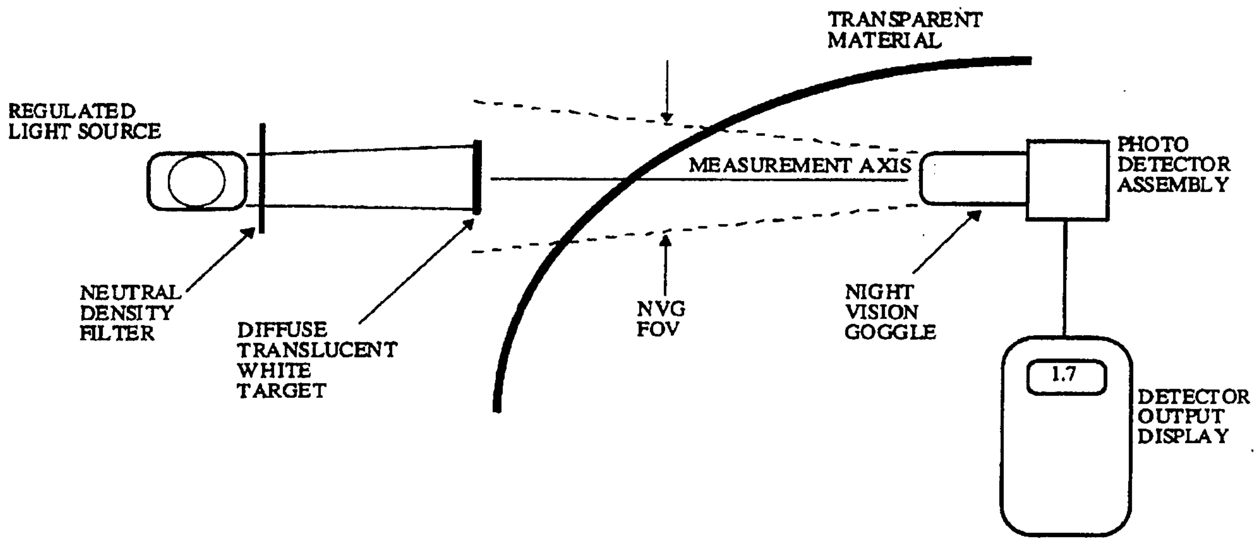

Figure 2. Direct test method equipment setup to measure the night vision goggle-weighted transmissivity of a transparent part using a transilluminated lightbox that underfills the NVG FOV.

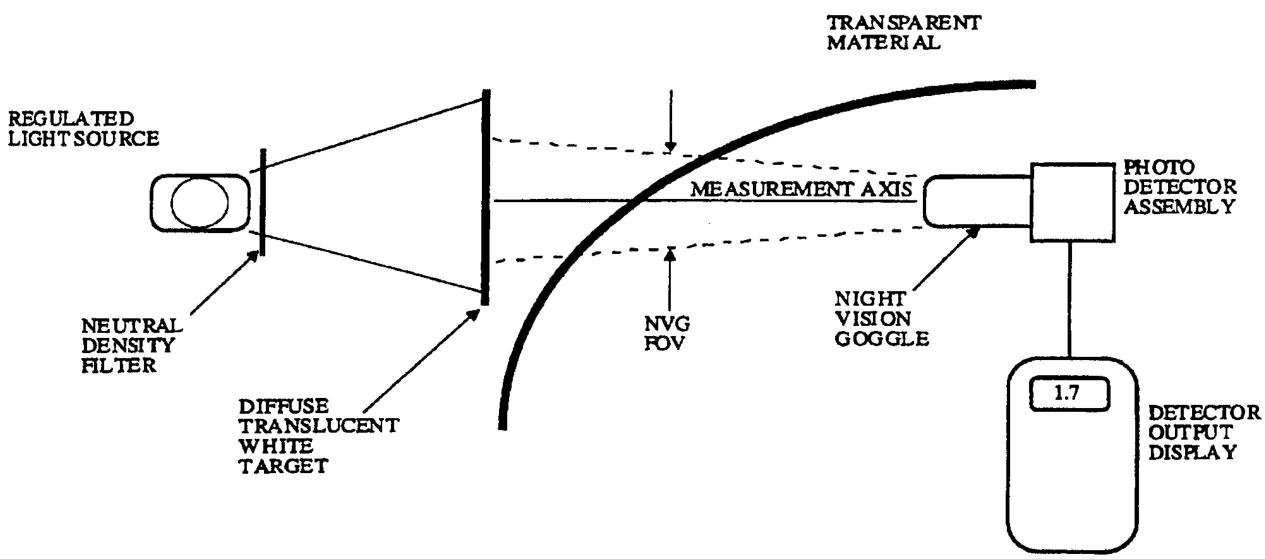

Figure 3. Direct test method equipment setup to measure the night vision goggle-weighted transmissivity of a transparent part using a transilluminated lightbox that overfills the NVG FOV.

11. Precision and Bias

11.1 An interlaboratory study (ASTM RR XXXX) was conducted to determine the precision of ASTM P94-02, Standard Test Method for Measuring Night Vision Goggle-Weighted Transmissivity of Transparent Materials. Six labs (instruments) were used to measure four plastic samples, five times each. The statistical summaries are shown in Tables 1 and 2.

Table 1. Repeatability *(S_r)* and reproducibility *(S_R)* values in T_{NVG}, derived from the data sets in Appendix C.

	REPEATABILITY (S_r) WITHIN LABS	**REPRODUCIBILITY (S_R) BETWEEN LABS**
SAMPLE #1	0.011	0.015
SAMPLE #2	0.011	0.016
SAMPLE #3	0.007	0.011
SAMPLE #4	0.006	0.008
MEAN	**0.009**	**0.013**

Table 2. 95% repeatability *(r)* limits and 95% reproducibility *(R)* limits in T_{NVG}.

	95% *r* LIMITS WITHIN LABS	**95% *R* LIMITS BETWEEN LABS**
SAMPLE #1	0.030	0.043
SAMPLE #2	0.030	0.044
SAMPLE #3	0.021	0.030
SAMPLE #4	0.017	0.023
MEAN	**0.025**	**0.035**

S_r ranged from 0.006 to 0.011 T_{NVG}
S_R ranged from 0.008 to 0.016 T_{NVG}

r ranged from 0.017 to 0.030 T_{NVG}
R ranged from 0.023 to 0.044 T_{NVG}

11.1.1 Since the accuracy of the measurements should not and did not depend upon the type of the transparent material, it is logical to calculate a mean T_{NVG} of the 4 sample sizes to derive the composite precision values indicative of this method. In summary, the statistical analysis (ASTM Standard Practices E 691 and E 177) revealed that the method's mean repeatability *(S_r)* was 0.009 T_{NVG} and the mean reproducibility *(S_R)* was 0.013 T_{NVG}. The mean 95% limits for repeatability *(r)* was 0.025 T_{NVG} and the mean 95% limits for reproducibility *(R)* was 0.035 T_{NVG}.

11.1.2 The 95% limits were calculated using the formulae, below. Since the 95% limits are based on the difference between two test results, the √2 factor was incorporated into the calculation (ASTM Practice E 177; 27.3.3). For r = 95% repeatability limit (within laboratories) and S_r = repeatability standard deviation.

$$r = 1.960*\sqrt{2}*S_r$$

For R = 95% reproducibility limit (between laboratories) and S_R = reproducibility standard deviation.

$$R = 1.960*\sqrt{2}*S_R$$

11.2 The procedure in this test method has no bias because the NVG-weighted transmissivity is defined only in terms of the test method.

12. Appendix A

12.1 Major suppliers of photometers:

International Light Inc., Newburyport MA
Labsphere, North Sutton NH
Minolta Corp.
Photo Research, Chatsworth CA

12.2 Major photometric light source manufacturers:

Acton Research Corp., Acton MA
DBA Systems Inc., Melbourne FL
Electro Optical Industries Inc., Santa Barbara CA
Graseby Infrared, Orlando FL
Hoffman Engineering Corp., Stamford CT
Labsphere Inc., North Sutton NH
Optronic Laboratories Inc., Orlando FL.
Oriel Corp., Strattford CT
Pyrometrics Corp., Millington NJ.

12.3 Major manufacturers of night vision goggles:

ITT, Roanoke VA
Litton, Phoenix AZ

5. HUMAN FACTORS INTERFACE ISSUES WITH NIGHT VISION GOGGLES

This last section provides several articles that treat human factors issues associated with NVG characteristics, such as field of view and interface issues with other aircrew equipment. In addition, this section presents articles that involve ancillary NVG equipment, such as the night vision goggle head-up display (NVG HUD). This system was developed by AFRL/HEC in the early 1980s, as a means of injecting symbology information into the pilot's NVG image intensifier scene.

These articles are reprinted to provide the reader with a reference and background to better understand NVG human factors interface issues.

Aleva, D. L. (1999). **Field of view effects upon a simulated flight and target acquisition task.** *Proceedings of the 37th SAFE Association,* http://www.safeassociation.com

Task, H. L. (1992). **Night vision devices and characteristics.** *AGARD Lecture Series 187: Visual Problems in Night Operations* (pp. 7-1 through 7-8). Neuilly Sur Seine, France: NATO Advisory Group for Aerospace Research & Development. (NTIS No. AGARD-LS-187)

Donohue-Perry, M. M., Riegler, J. T., & Hausmann, M. A. (1990). ***A compatibility assessment of the protective integrated hood mask with ANVIS night vision goggles.*** (Report No. AAMRL-TR-90-030). Wright-Patterson AFB, OH: Armstrong Aerospace Medical Research Laboratory. (DTIC No. A229956)

Riegler, J. T., & Donohue-Perry, M. M. (1990). ***A field evaluation of the compatibility of the protective integrated hood mask with ANVIS night vision goggles.*** (Report No. AAMRL-TR-90-031). Wright-Patterson AFB, OH: Armstrong Aerospace Medical Research Laboratory. (DTIC No. A230237)

Genco, L. V. (1985). **Night vision support devices human engineering integration.** *AGARD, Visual Protection and Enhancement* (pp. 6-1 through 6-8). (NTIS No. AGARD-CP-379)

Simons, J. C., Unger, S. E. & Craig, J. L. (1985). ***Night vision goggle head-up display for fixed-wing and rotary-wing special operations.*** (Report No. AAMRL-TR-85-044). Wright-Patterson AFB, OH: Armstrong Aerospace Medical Research Laboratory.

Craig, J. L. (1984). ***Night vision goggle (NVG) heads-up display (HUD).*** Proceedings of the Tri-Service Aeromedical Research Panel: Vision research and aircrew performance (Report No. NAMRL Monograph - 13, pp. 74-79). Pensacola NAS, FL: Naval Aerospace Medical Research Laboratory.

Marasco, P. L., & Task, H. L. (1998). **Examination of a method for improving night vision device depth of field.** *SAFE Journal 28(3)*, 94-100.

Marasco, P. L. (2002). **The impact of helmet-mounted display visor spectral characteristics on visual performance.** *Proceedings of SPIE – The International Society for Optical Engineering Helmet- and Head-Mounted Displays VII, USA, 4711,* 174-184.

Sedillo, M. R. (2000). **Night vision goggle cockpit integration.** *Proceedings of the 38th SAFE Association,* http://www.safeassociation.com

Task, H. L. (1992). **Cockpit/NVG visual integration issues.** *AGARD Lecture Series 187: Visual Problems in Night Operations* (pp. 8-1 through 8-6). Neuilly Sur Seine, France: NATO Advisory Group for Aerospace Research & Development. (NTIS No. AGARD-LS-187)

Pinkus, A. R., & Task, H. L. (2000). **Night vision goggles objective lens focusing methodology.** *Proceedings of the 38th SAFE Association,* http://www.safeassociation.com

Aleva, D. L. (1999). Field of view effects upon a simulated flight and target acquisition task. *Proceedings of the 37th SAFE Association*, http://www.safeassociation.com

Field Of View Effects Upon A Simulated Flight And Target Acquisition Task

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ABSTRACT

Pilot flight performance and target acquisition were evaluated for 40 degree and 100 degree fields of view in the Synthetic Immersion Research Environment at the Air Force Research Laboratory. The facility consists of an F-16 like cockpit mockup and a 40-foot diameter dome display. The simulation environment includes textured ground and sky features with embedded ground targets. Daytime simulators of night vision goggles were worn by the pilots to limit field of view. Pilots were able to acquire and designate 16 percent more targets with the 100 degree field of view than with the 40 degree field of view. Pilot flight performance was not found to be affected by field of view.

INTRODUCTION

Current generations of night vision goggles (NVGs) are limited to a 40 degree field of view. Pilots have described the use of these goggles as trying to fly while looking through a straw. The Air Force Research Laboratory is currently developing a new night vision goggle, called the Panoramic Night Vision Goggle, which will provide a 100 degree field of view. In order to significantly increase the field of view of night vision goggles, a novel approach was required. This approach uses four image intensifier tubes instead of the usual two to produce a 100 degree wide field of view.

NVGs with fields of view ranging from 30° (GEC-Marconi Avionics' Cat's Eyes NVGs) to 45° (GEC-Marconi Avionics' NITE-OP and NITE-Bird NVGs) have been used in military aviation for more than 20 years. The vast majority of NVGs in use today (AN/AVS-6 and AN/AVS-9) provide a 40° FOV. An extensive survey of military (U.S. Air Force) NVG users conducted during 1992 and 1993 revealed that increased FOV was the number one enhancement most desired by aircrew members followed closely by resolution.[1] This was a major motivating factor for the development of an enhanced NVG capability. While pilot acceptance of the panoramic goggle prototype is extremely positive, no objective performance data are yet available.

BACKGROUND

While current operational flight testing of the PNVG at Nellis Air Force Base has yielded very positive subjective evaluation of the advantages of increased field of view, no objective evaluation of pilot performance is yet available. Several other experimenters have reported improved operator performance as a function of increased field of view. Those most applicable are described below.

Szoboszlay et al. conducted an experiment in which a series of prescribed low altitude maneuvers were performed by eleven

US pilots and 4 UK pilots with an instrumented rotorcraft.[2,3] The pilots wore a specially constructed helmet visor which limited the field of view. Horizontal limits were: unrestricted, 100, 80, 60, 40 and 20 degrees. The vertical limit remained constant at 40 degrees, and all except the 20 degree field of view had a 40 degree overlap._The aircraft flight path was measured with a laser tracker. On board flight data were recorded giving the position of the aircraft in three dimensions, radar altitude and attitude.

Standard statistical comparisons were made of the task performance at each field of view compared to the performance at unrestricted field of view. Only for the precision landing and hovering turn and the entire bob-up, did fields of view greater than 40 degrees show significant differences compared to the performance with unrestricted field of view. Data for U.S. pilots were analyzed for each maneuver to determine the limit beyond which increasing field of view did not result in increased performance. There was considerable variation due to maneuver with range of 40 to 98 degrees.

Pilots flying with restricted field of view often thought they were flying the aircraft better than they actually were. At 60 degrees field of view, one pilot who was very experienced in flying AH-1S aircraft and NVGs stated that his poor situational awareness and performance "was very insidious" since he felt that he was performing much better than he actually was. Nearly all pilots missed seeing the RPM warning indicator at the top of the instrument panel. Several pilots commented that with restricted field of view they could not see multiple cues at the same time and had to switch between cues. This required more head movement and a different scan technique. Some commented that a large amount of head movement caused problems in controlling the aircraft as well as some disorientation.

Kenyon et al. studied field of view effects in the laboratory for a critical tracking task.[4] The tracking task required stabilization of the roll motion of a visual scene driven by an unstable first order plant. The fields of view studied were in the range of 10 - 120 degrees. A dedicated graphics workstation read and stored the subject's control input and generated the out-the-window scene which was displayed on a 19-inch color monitor. The visual conditions were produced by having the subject view the face of the CRT through the Expanded Field Display, an optical system that expands the CRT image over a 120 degree field of view. Particular fields of view were created by cutting circular holes in black matte paper. These masks were inserted into the viewing system. Five male subjects participated in this experiment. The primary measure was effective time delay. A transition time constant was also calculated as an indicator of task difficulty.

The subjects' performance was worst at the 10 degree field of view. The most improvement occurred up to the 40 degree field of view. The best performance occurred at 80 or 100 degree field of view. The subjects reported that the task was easiest at the 80 degree field of view. The authors suggested that increasing the field of view from 40 to 80 degrees, while improving performance only slightly, greatly reduced the subjects' workload.

Wells et al. studied field of view effects upon a target acquisition and replacement task combined with a tracking task.[5] The targets were arrowhead shaped, 2.2 degree high and wide within a gaming area 120 degrees left and right and 90 degrees upwards from straight ahead. The targets were viewed in combination with a terrain scene or a blank background. There were two search conditions: slow search up to three minutes to find and memorize target positions, and search and remove as fast as possible.

The subjects were required to visually acquire, remember the location of, monitor (for threat mode indicated by shape change), and shoot 3 or 6 objects. The secondary tracking task required the subject to keep an inverted "T" straight and level on the display. The field of view was 120x60 degrees for terrain and the tracking task. Fields of view were 20x20, 45x42.5, 60x50, 90x60 and 120x60 (azimuth x elevation) for targets.

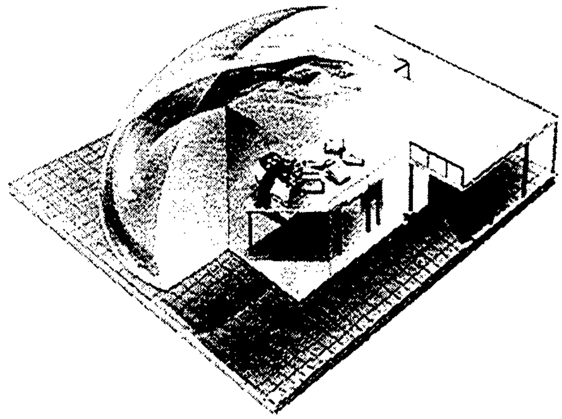
This experimental set-up simulated viewing the output from a head-steered sensor on a see-through helmet-mounted display. Two helmet-mounted displays were used with a combined maximum field of view of 120x80 with a 40 degree binocular overlap. The position of the helmet was measured in 6 axes with an electromagnetic helmet position tracker; this information was used to present space-stabilized images on the displays. A computer generated stroke-drawn world of 4 pi steradians at optical infinity updated at 20Hz. A head-stabilized reticle cross was always present in the center of the field of view. The subjects were 10 paid volunteers. The number of objects hit, mean time threatened, replacement error and RMS tracking error were recorded.

For the shoot and replace task alone, there was a significant interaction between target density and field of view and a performance decrement only at the 20 degree field of view for the higher target density. Data were similar under dual task conditions. However, there was a significant effect of field of view upon tracking error. These data show a trend of decreasing error with increasing field of view up through 90 degrees. The authors concluded that the decrement in secondary task performance with decreasing fields of view suggests that the subjects had to allocate more resources to the primary task when working with smaller fields of view. The increase in tracking error with the small fields of view occurred despite longer allowed search times for the conditions with smaller fields of view.

While all of the above studies show some advantages of fields of view larger than 40 degrees, we were particularly interested in the comparison of 40 degrees and 100 degrees which represent NVGs currently in use and the PNVG respectively. The pilot study reported herein evaluated these two fields of view for performance of a primary low level flight task with secondary target acquisition task.

METHOD

Flight performance and target acquisition were evaluated for two pilots in the Synthetic Immersion Research Environment at the Air Force Research Laboratory . The facility, which is shown in Figure 1, consists of an F-16 like cockpit mockup and a 40-foot diameter dome display. Flight controls available to the pilot included a sidestick controller, throttle, and rudder pedals. A head up display (HUD) and three head down displays (HDDs) provided basic flight information, navigation instrumentation and radar warning receiver (RWR) scope. The simulation environment included textured ground and sky features. An out-the-window visual scene was displayed on the surface of the dome. The terrain data used for the simulation was a 50 by 60 nautical mile area near Albuquerque, New Mexico. Embedded in the terrain database were numerous stationary SCUD-like targets. A head-coupled target designator was also displayed on the surface of the dome.



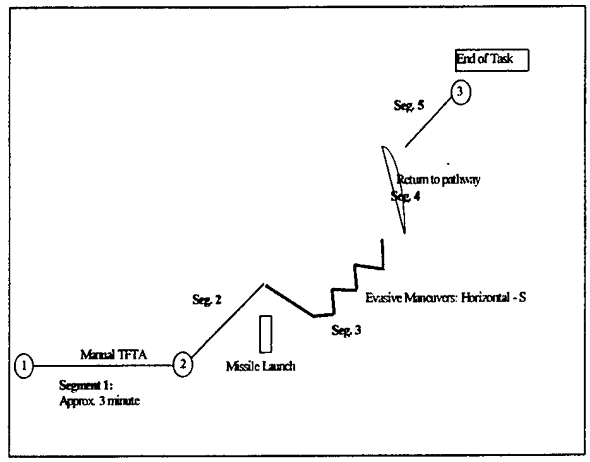


Figure 1. Synthesized Immersion Research Environment

Figure 2. Flight path graphic.

Forty eight unique flight paths were predefined within the 50 by 60 nautical mile gaming area. Each flight path was defined by 3 points: (1) a start point, (2) a turn point and (3) an end of task point. A flight path graphic is shown in Figure 2. This effectively divided the flight path into two segments. The mission was a low level ingress with intent to deliver a weapon; however, the weapon delivery segment was not included in the simulation. The mission simulation began with the pilot's ownship on course at approximately 500 feet above ground level (AGL). The pilots were instructed to maintain an altitude of 500 feet AGL and airspeed of 350 knots. At a variable time early in the second segment, a missile launch event took place. The pilot was required to perform evasive maneuvers and release chaff in response to the missile launch event. As soon as the missile was no longer a threat, the pilot was required to recover the aircraft to the preplanned flight path. Several parameters of the pilot's performance were scored. These included airspeed, altitude, maneuver to avoid missile and frequency of chaff release. If the total score was not within acceptable parameters, the mission was aborted.

In addition to the flight task, the pilots were required to scan the surrounding terrain and designate as many of the ground targets as possible. This was accomplished by moving the head-coupled target designator over the target and pulling the trigger on the sidestick controller. The pilots were instructed to treat the precision navigation flight task as their primary task and the targeting task as a secondary task.

Daytime simulators of night vision goggles were worn by the pilots to limit field of view. Two fields of view were evaluated; these were 40 degrees and 100 degrees. The 40 degree field of view represents the currently fielded night vision goggles while the 100 degree field of view represents the newly developed PNVG.

Prior to the data collection trials, the pilots were given a familiarization briefing of the cockpit and the mission to be flown. They were then allowed to fly several trials with unlimited field of view until they felt comfortable with the task to be performed. They then flew three practice trials with the 100 degree and 40 degree field of view NVG simulators. If any trial was aborted due to unacceptable flight performance or crashing into terrain, it was repeated.

For the data collection, the pilots flew each of three distinct flight paths four times - twice with the 40 degree field of view and twice with the 100 degree field of view – for a total of twelve trials. These three flight paths were different from those flown by the pilots during the practice trials. While a large number of targets are in the vicinity of the flight path, many are obscured by terrain. The number of targets actually visible to the pilot was dependent upon the altitude and actual flight path of the aircraft; generally between 40 and 60 targets were visible at some time during each trial. Each trial took approximately four to five minutes.

RESULTS

Analyses of variances were conducted to examine the effects of field of view upon several flight parameters including the percent of time above 500 feet AGL, mean altitude (feet), standard deviation of altitude (feet) and RMS lateral course error. None of these parameters were found to differ significantly as a function of field of view. The number of target designations was found to differ significantly as a function of field of view. The mean number of target designations for the 40 degree field of view was 24.5 while that for the 100 degree field of view was 28.5. The targets actually visible to the pilot during each trial were counted and the percentage of these targets that were designated was calculated. The pilots designated 48.7 percent of the visible targets while wearing the 40 degree field of view simulator and 60.2 percent while wearing the 100 degree field of view simulator. This difference was not statistically significant.

DISCUSSION

The lack of significant effects upon any of the flight performance parameters indicates that pilots were able to maintain an acceptable level of flight performance with either the 40 or 100 degree field of view. The significant effect of field of view upon number of target designations indicates that pilots were able to increase target acquisition performance while maintaining flight performance. The 100 degree field of view resulted in a 16 percent increase in the number of target designations over that with the 40 degree field of view. Pilots indicated that with the wider field of view they felt more comfortable in looking away from the flight path in search of targets.

The current data represents only two pilots. Certainly data must be collected for several more pilots and further analyses conducted. The lack of statistical significance for the percent of visible targets designated was probably due to the small sample size. Also of interest for future experimentation is the effect of increased field of view in enabling the pilot to detect airborne targets.

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NIGHT VISION DEVICES AND CHARACTERISTICS

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INTRODUCTION

Night vision goggles (NVGs) are widely used to enhance visual capability during night operations. NVGs are basically composed of an objective lens which focuses an image onto the photo-cathode of an image intensifier tube which in turn produces an amplified image that is viewed through an eyepiece lens. There are several versions of NVGs in use and in development. These include the AN/PVS-5,AN/AVS-6, PVS-7, Cat's Eyes, Nite-Op, Eagle Eyes, Merlin, and others. The first section of this paper provides a brief description and characterization of each of these NVGs.

There are several parameters that are used to characterize the image quality and capability of the NVGs. These parameters include field-of-view (FOV), resolution, spectral sensitivity, brightness gain, distortion, magnification, optical axes alignment, image rotation, overlap, beamsplitter ratio, exit pupil diameter, eye relief, and others. Each of these is discussed in the second section of this paper.

CURRENT NIGHT VISION GOGGLES

In general, all NVGs are similar in that they all have three basic components: an objective lens system, an image intensifier, and an eye lens system. However, there are several ways in which these different components can be designed and configured which vary the trade-off between some of the design parameters.

The heart of any NVG is the image intensifier tube. Both second and third generation tubes are in wide use in fielded systems today. The second generation image intensifier tubes (typically referred to as "gen II") are sensitive to light from about 400 nm to about 900 nm whereas the more sensitive third generation tubes are sensitive from about 600 nm to a little over 900 nm (see figure 1). This compares to a human visual spectral sensitivity that ranges from about 400 nm to 700 nm. The "gen III" tubes are about 4 to 5 times more sensitive to night sky illumination than the "gen II" tubes but they also cost significantly more.

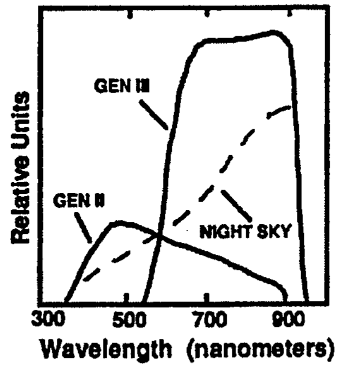

Figure 1. Spectral sensitivity of second and third generation image intensifier tubes.

The following sections provide a brief description of several fielded and developmental NVGs with an abbreviated table of some of their key characteristics.

PVS-5

The US Army developed the PVS-5 NVGs for use by vehicle drivers and ground troops. When these NVGs were initially fielded they all used a second-generation image intensifier tube. Although in later years some have been produced with a so-called "second gen plus" tube which provided about twice the gain as the original gen II tube. There are currently three versions of the PVS-5 (a,b, and c) which vary in their mounting mechanism, objective lens and image intensifier tube characteristics; but they all have the same basic construction. The PVS-5 is composed of two in-line oculars. Each ocular has an objective lens located directly in front of the image intensifier tube. The objective lens produces an image of the outside scene directly on the photo-cathode of the image intensifier tube. Since the objective lens inverts the image of the outside scene it is necessary to employ a fiber optics "twister" to rotate the amplified image back to an upright orientation. An eyepiece lens is located directly behind the output of the image intensifier and acts as a simple magnifier lens for viewing the output image. The objective lens and eyepiece lens have the same focal length to produce a system with approximately unity magnification. The eyepiece lens is adjustable to accommodate -6 to +2 diopters of correction to compensate for wearers who require eyeglasses.

The housing for the PVS-5 is somewhat bulky with a padded back surface that rests against the face. When originally fielded the PVS-5 was mounted to the head by a series of straps that went around and over the head. Later versions were modified to attach to a flyers helmet and had much of the housing cut out to permit the wearer to view under the NVGs at flight instruments (McLean, 1982). This led to the PVS-5c version. Table 1 is a brief summary of the key characteristics of the PVS-5 NVG.

Table 1. PVS-5 Characteristics

Field-of-view (FOV):	40 degrees circular
Resolution:	20/50 - 20/70 Snellen
Exit pupil:'	None
Beamsplitter:	No
Eyelens Adjustment:	-6 to +2 diopters
Weight:	880 gm (31 oz)

The PVS-5 NVG does not have a real exit pupil since it does not use a relay lens. The resolution ranges shown in Table 1. reflects the range of values that have been published by different authors over the past 10-12 years. Since the image intensifier tube is a key component in limiting resolution it is most probable that the 20/50 Snellen acuity (published in more recent documents) is a result of improved image intensifier manufacturing and design.

AN/AVS-6 (ANVIS)

The AN/AVS-6, or aviator's night vision imaging system (ANVIS), NVG was developed by the US Army specifically for use in helicopter flying. These were also designed using third generation image intensifier tubes which has led to some confusion in terminology. The ANVIS NVGs have also been referred to as third gen NVGs and the PVS-5s as second gen NVGs primarily because those tubes came with the original systems. However, second generation plus tubes have been installed in ANVIS type housings so the correct designation should include both the NVG type (e.g. ANVIS or PVS-5) and the image intensifier tube (e.g. second gen, second gen plus, or third gen) to prevent confusion.

The ANVIS NVGs look very much like a pair of binoculars. The fundamental optical design is very similar to the PVS-5 in that an objective lens focuses an image onto the photo-cathode of the image intensifier tube, a fiber optics twister re-inverts the output image that is viewed by a simple magnifier eyepiece lens. The mounting system is substantially different in that the ANVIS was originally designed to attach to a helmet. The mounting system provides adjustments for inter-pupillary distance, tilt, vertical, and fore/aft position. The objective lens was also of a lower F/number (ratio of focal length to diameter of lens) to improve its light gathering capability and thereby increase the overall gain of the NVG. Table 2 is a summary of the key characteristics of the AN/AVS-6 NVG.

Table 2. AN/AVS-6 Characteristics

Field-of-view:	40 degrees circular
Resolution:	20/40 - 20/50 Snellen
Exit pupil:	None
Beamsplitter:	No
Eyelens Adjustment:	-6 to +2 diopters
Weight:	775 gm

AN/PVS-7

In an effort to reduce costs for providing NVGs to ground forces the US Army developed the PVS-7 NVGs. This NVG is unique in that it is biocular: it has one objective lens, one image intensifier but two eyepieces. The objective lens and image intensifier tube configuration is similar to the PVS-5 and ANVIS; however, since the optical system used to split the image for the two eyes re-inverts the image it was not necessary to twist the fiber optics to do the re-inversion. However, a fiber optics conduit was still used (without twist) since it was integral to the manufacture of the tube.

Another significant difference between this NVG and the ones previously discussed is that it uses a relay lens to transfer the image from the output of the image intensifier tube to the eyepiece lenses. This causes the creation of a real exit pupil (see later section on NVG characteristics). Table 3 is a summary of the key characteristics of the PVS-7 NVGs.

Table 3. PVS-7 Characteristics

Field-of-view:	40 degrees circular
Resolution:	20/40 - 20/50 Snellen
Exit pupil:	10 mm dia
Beamsplitter:	No
Eyelens Adjustment:	-6 to +2 diopters
Weight:	580 gm (w/mount)

It should be noted that the PVS-7 NVGs are not considered suitable for piloting aircraft for safety reasons: if the image intensifier tube fails then the image is lost to both eyes whereas with the PVS-5 or ANVIS if one channel fails the other is still available.

NITE-OP NVGS

The Nite-Op NVG was developed by Ferranti International for the British military as an improvement over the ANVIS NVGs. The basic design is very similar to the ANVIS NVGs but the mounting system is much more ruggedized and the field-of-view is larger. In addition, the eyepiece lenses are much larger in diameter, which permits larger eye relief and/or larger mounting/positioning tolerance with respect to the wearer's eyes. Table 4 is a summary of key characteristics of the Nite-Op NVGs.

Table 4. Nite-Op NVGs

Field-of-view:	45 degrees circular
Resolution:	20/40 - 20/50 Snellen
Exit pupil:	None
Beamsplitter:	No
Eyelens Adjustment:	-3.5 to +0.5 diopters
Weight:	750 gm

Cat's Eyes NVGs

The Cat's Eyes were developed and are produced by GEC Avionics in UK. The front-end optical system is similar in basic design to the ANVIS but the eyepiece optics are significantly different. These NVGs were designed to provide a see-through combiner (beamsplitter) in front of each eye which allows the wearer to see his instrument panel or head-up display (HUD)directly without going through the image intensifier. This concept was developed to allow a pilot to view his aircraft HUD without the loss of image quality that might occur if he/she viewed the HUD through the image intensifier system.

However, this design concept requires that the optical path after the image intensifier tube be folded which leads to a smaller obtainable field-of-view. In addition, the beamsplitter reduces the luminance from the image intensifier tube thus reducing the gain of the system. Table 5 is a summary of the Cat's Eyes NVGs.

Table 5. Cat's Eyes NVGs

Field-of-view:	30 degrees w/clipping
Resolution:	20/40 - 20/50 Snellen
Exit pupil:	None
Beamsplitter:	Yes
Eyelens Adjustment:	None
Weight:	750-800 gm

The folding of the optical system results in a circular 30 degrees field-of-view with some clipping of the image in the lower right and lower left. This makes the actual FOV appear something like a baseball diamond viewed from above.

EAGLE EYES NVGs

All of the previously discussed NVGs have been fielded and are in use in military applications somewhere in the world for either ground or aviator use. The Eagle Eyes NVG designed by Night Vision Corporation is still under development. The unique feature of the Eagle Eyes NVGs is that the optical system for both the objective lens and eyepiece lens are folded to produce a low profile NVG that fits fairly close to the face. In order to do this, the objective lens apertures are spaced further apart than the distance between the two eyes producing some stereopsis exaggeration at close distances. The Eagle Eyes are also designed with a beamsplitter eyepiece lens system to permit direct viewing of the HUD and/or instrument panel. Table 6 is a brief summary of the key characteristics of the Eagle Eyes.

Table 6. Eagle Eyes NVGs

Field-of-view:	40 degrees circular
Resolution:	20/40 - 20/50 Snellen
Exit pupil:	None
Beamsplitter:	Yes
Eyelens Adjustment:	None
Weight:	580 gm

Due to the nature of the folding in the Eagle Eyes optical system there is very little eye relief and the peripheral vision is reduced. These were the trade-offs to obtain the extremely low profile of these NVGs.

MERLIN NVGS

MERLIN (Modular, Ejection-Rated, Low-profile, Imaging for Night) is under development by ITT corporation. It uses two separate, independently adjustable oculars and a unique image intensifier tube design. The image intensifier tube and power supply have been repackaged. The tube does not use a fiber optics faceplate or twister, which allows for improved resolution. The optical system does employ a relay lens that produces a real exit pupil. The system is designed to fit onto existing HGU-53 and HGU-55 aviator helmets. Table 7 is a summary of the MERLIN characteristics.

Table 7. MERLIN NVGs

Field-of-view:	35 degrees circular
Resolution:	20/35 - 20/40 Snellen
Exit pupil:	10 mm dia
Beamsplitter:	Yes or No (optional)
Eyelens Adjustment:	None
Weight:	800 gm

OTHER NVG SYSTEMS

There are several other NVG systems that have been developed but due to their proprietary status they are not discussed here. The systems that have been presented provide a fairly complete coverage of the different approaches (beamsplitter vs. no beamsplitter; pupil forming vs. non-pupil forming; folded vs. non-folded optics; biocular vs. binocular; fiber optics twister vs. no twister; etc) that have been tried.

Another device that is closely related to the NVGs and has been retrofit to some NVGs is the NVG-HUD. The NVG-HUD was designed to provide critical flight information symbology overlaid on the NVG FOV. Several different designs have been developed to retrofit to existing NVGs and there is a desire by some organizations to include the symbology generation capability as an integral part of the NVG for airborne use.

NIGHT VISION GOGGLES CHARACTERISTICS

There are many parameters that are used to characterize night vision goggles. This section of the paper discusses a large number of these parameters and how they relate to vision. Table 8 is a list of these parameters.

Table 8. NVG Design Parameters

Field-of-view	Signal-to-noise ratio
Image quality	Luminance uniformity
Exit pupil size	Luminance level
Eye relief	Luminance gain
Image location	Beamsplitter ratio
Magnification	Fixed pattern noise
Image rotation	Binocular parameters
Distortion,	Optical axes alignment

Field-of-View

Probably the first parameter that most people are concerned with in an NVG is the field-of-view (FOV). The FOV is the angular subtense of the virtual image displayed to the wearer. This is typically expressed in degrees for both the vertical and horizontal dimensions, or for the diameter of the FOV if it is circular. Another practical problem is the trade-off with resolution (image quality). The image intensifier has a finite number of picture elements (pixels). As the FOV is increased these pixels are spread over a larger angular expanse resulting in a larger angular subtense per pixel which corresponds to a lower angular resolution to the observer. (Note: this is an oversimplification of this trade-off since image quality is more complex than the concept of pixels implies but the general direction of the trade-off is the same: larger FOV means lower visual resolution).

The total NVG FOV can be made larger by making the FOV of each ocular of a binocular NVG partially overlap the other. The visual effects of partial overlap may outweigh the value of the extended horizontal FOV if the overlap is too little. At least one study suggests that there is little performance difference between 100% overlap and 80% overlap for visual recognition performance (Landau, 1990) implying that an 80% overlap binocular NVG may be a good compromise between the need for larger FOV without impacting visual performance.

Image Quality

Image quality is a complex subject that involves several other parameters (Task, 1979). Probably the key indicator of image quality is the modulation transfer function (MTF) of the display, which describes how much contrast is available as a function of spatial frequency (detail). Two parameters related to the MTF are gray-shades (contrast) and resolution (maximum spatial frequency that can be seen or "resolved"). For simplicity, the resolution of a display relates to the number of pixels. As noted earlier, the resolution tends to decrease as FOV increases which implies that image quality also decreases with increasing FOV; another trade-off of two desirable attributes.

There are some practical problems in measuring the resolution of the NVGs. The simplest approach to measuring resolution is to have a trained observer look through the NVGs at a calibrated test pattern under controlled lighting conditions. However, the results obtained still depend on the visual capability of the observer and on the type of test pattern used. Probably the most popular test pattern for determining resolution is the USAF 1951 Tri-Bar resolution pattern. Others that have been used include a Landolt "C," a tumbling "E," a standard Snellen chart, sine-wave gratings and more recently a test pattern made up of patches of square-wave gratings of different spatial frequencies (US Pat No. 4,607,923). These different approaches yield somewhat different results.

It should also be noted that the resolutions listed in the previous tables were all for ideal lighting conditions. As the light level is significantly reduced the resolution of the NVGs drops considerably (20/200 Snellen acuity or lower).

Exit Pupil

Most NVGs do not have a real exit pupil since they do not use relay optics. The exit pupil is the image of the stop of the optical system. An exit pupil is formed as a result of using relay optics to produce an intermediate image plane, which is then viewed by an eyepiece lens. This is in contrast to a simple magnifier optical system that uses a single lens system (no intermediate image) and therefore does not produce a real exit pupil. In a darkened room with the NVG activated the exit pupil can be observed by placing a piece of white paper near the designed eye position. If the NVG forms a real exit pupil then a circular spot of light will be observed imaged on the paper. As the paper is moved closer to and further away from the optical system there is a point at which the disc of light has a minimum diameter with sharply defined edges. The diameter of this disk of light is the diameter of the exit pupil of the system (Self, 1973).

When the eye pupil is fully within the exit pupil of the NVG then the entire FOV is observed; if the eye pupil is only partially in the exit pupil (and the exit pupil is unvignetted) then the observer will still see the entire FOV but it will be reduced in brightness. This can be particularly disconcerting for NVGs used in high performance aircraft because the pilot may not know whether he is starting to lose the exit pupil or if he is starting to lose consciousness from high acceleration maneuvers. Once the eye pupil is outside the exit pupil then none of the NVG FOV can be seen. It should also be noted that the NVG FOV may become vignetted (lose part of the image) if the eye pupil is too close to or too far away from the exit pupil.

From a visual capability standpoint it is important for the exit pupil to be as large as possible to ensure the eye pupil will remain within it to permit viewing of the NVG. However, large exit pupils typically come only at the expense of greater size of optics and weight on the head. In addition, if the FOV is very large then the eye must rotate to view the edge of the display. Since the eye rotates about a point within the eye, the eye pupil moves within the NVG exit pupil. If the NVG exit pupil is not large enough then it is possible for the entire display to disappear every time the observer tries to move his eyes to view the edge of the display. Exit-pupil-forming optical systems also increase the difficulty of making accurate adjustments for binocular or biocular NVGs in that each eye pupil should be centered in each exit pupil of the NVGs.

Eye Relief

The eye relief is the distance from the exit pupil to the nearest part of the NVG optical system. If the NVG is non-pupil-forming then the eye relief is the distance from the NVG optical system to the furthest back position of the eye where the eye can still see the entire FOV of the NVG.

As with so many other NVG parameters, larger eye relief usually means larger and heavier optics. The reason for having a large eye relief is to allow the use of eyeglasses with the NVG (Self, 1973; Task et al, 1980).

Image Location (optical image distance)

All NVGs produce a virtual image, which is viewed by the observer. The virtual image is produced at an optical distance that depends on the adjustment of the eyepiece (if the NVG has an adjustable eyepiece). For NVGs that do not have an adjustable eyepiece the virtual image is typically adjusted for near infinity. The adjustable eyepiece was provided to allow the wearer to set his eyeglass prescription (spherical power) on the eyepiece so he would not require eyeglasses to see the NVG image clearly.

Luminance Level

The luminance of the NVG image depends both on the luminance of the image source and the transmission efficiency of the optical system (note: it does NOT depend on the amount of magnification since it produces a virtual image). For NVGs that use a combiner the NVG image luminance level also depends on the combiner (beamsplitter) reflectance and transmittance coefficients.

Binocular Parameters

There are several other parameters that become important if the NVG is binocular. These include inter-pupillary distance (IPD-the distance between the exit pupils of the two oculars), image alignment between the two oculars, luminance balance, magnification balance, and image rotation balance.

There are several undesirable visual effects that may occur in binocular NVGs. These include binocular disparity (retinal rivalry) due to luminance imbalance, image misalignment, accommodation differences, and/or differential distortion. When binocular disparity is sufficiently severe the observer may see double images or may suppress one of the two disparate images. A more insidious problem is when the binocular disparity is not large enough to cause a loss of image fusion but is enough to result in "eye strain" or visual fatigue. This can lead to headache or nausea during extended use but may not show any effects for short-term use.

There have been some efforts to define the limits for these types of parameters (Self, 1973 and 1986; Landau, 1990).

Luminance and luminance gain

In most of the literature relating to NVGs these parameters are usually referred to as brightness and brightness gain. However, since luminance is what one measures and brightness is the visual sensation that one sees it is more appropriate to use the terms luminance and luminance gain for these parameters.

Night vision goggles are essentially light amplifiers, they cannot work in complete darkness. However, they do have a different spectral sensitivity than the human eye, which makes the concept of luminance gain a little more difficult to define. For example, the eye cannot see light at 900 nanometers but the NVGs are very sensitive to light in this wavelength range. Since luminance gain is the ratio of output luminance to input luminance and since luminance is only defined for the spectral sensitivity of the eye, it is possible to obtain an infinite luminance gain for a 900 nanometer input source (i.e. the luminance of any amount of light at 900 nanometers is zero since the eye is not sensitive to this wavelength but this will produce a non-zero output luminance; dividing output by the input results in dividing by zero producing an infinite gain). To overcome this problem it is necessary to define a specific spectral distribution for the input light source that does have a non-zero luminance. A blackbody radiator at 2856K was selected since it is a standard lamp source and has a spectrum that closely approximates night sky illumination. This is the same standard source that was selected by the US Army for measurement of the image intensifier tubes that are contained within the NVGs.

The luminance gain is usually measured for a specific input luminance since the gain can change with input level. The luminance output is measured on axis at the highest input luminance.

Luminance uniformity

Due to the fiber optics and light fall-off with angle typical of lens systems the central part of the field-of-view of the NVG image is usually of higher luminance than the edge of the FOV. This is measured by scanning with a photometer across the entire FOV to obtain a luminance profile of the NVG image. Uniformity can be specified by comparing the luminance at the center of the FOV with the luminance at a specified off-axis angle (e.g. 18 degrees off axis for the 40 degree FOV NVG). The uniformity is then expressed as a ratio of center luminance to edge luminance (e.g. 3:1).

Distortion, image rotation, magnification, and input/output optical axes alignment

These four parameters are grouped together because they can be measured using the same basic set-up and data. The different quantities are obtained by performing different analyses on the data.

Distortion is probably the most difficult parameter because there are several types of distortion that the NVGs may incur. The optical system may cause barrel or pincushion distortion and the fiber optics twister (which is in many but not all NVG designs) may produce shear effects or "S" distortion. Of all of these, the procedure herein described is primarily directed at the "S" distortion although evidence of shear and barrel distortion may also be detected. "S" distortion originates in the fiber optics plug, which is used to invert the image on the image intensifier. The fused fiber optics plug is heated and twisted approximately 180 degrees. The "S" distortion is so named because there is usually a small amount of residual effect due to the twist that produces an "S" shaped curve for a straight-line input. The more the line departs from a straight line the worse the distortion.

As noted above, the fiber optics plug is twisted through approximately 180 degrees but may be somewhat more or less than a true 180-degree twist. Any departure from a perfect 180 twist will result in the output image rotated compared to the input image. This effect may also be enhanced by inaccurate alignment of folding mirrors in a folded optical system. The measurement procedure herein described allows one to measure the amount of image rotation.

Most NVGs are designed to have unity magnification. However, if there is a mismatch between the objective lens of the NVG and the eyepiece lens it is possible to have a small amount of magnification (or minification).

Since the combination of objective lenses, folding optics, image intensifier and eyepiece lenses is relatively complex, it is possible to have a mismatch between the input optical axis and the output optical axis. Thus objects that are at a particular field angle in reality may appear at a different field angle through the NVGs.

Many of these effects discussed are typically not a significant problem by themselves or for a single ocular. But the combination of a small amount of distortion, rotation, magnification and/or misalignment in one ocular with a different amount (and direction) of these effects in the other ocular may result in a significant binocular rivalry problem.

A complete description of the procedures for measuring these parameters is beyond the scope of this paper but can be found in Task et al (1989).

Signal-to-Noise Ratio

Typically the signal-to-noise ratio (SNR) is not specified or measured for the NVG as a whole but rather is specified as a parameter of the image intensifier tube by itself. The SNR is a measure of how much scintillation appears in the NVG. The lower the SNR the noisier the image looks and the poorer the image appears. The details of measuring SNR are beyond the scope of this paper; suffice to state that in general, observed resolution is poorer for lower SNR tubes (Riegler, et. al.; 1991).

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AAMRL-TR-90-030

A COMPATIBILITY ASSESSMENT OF THE PROTECTIVE INTEGRATED HOOD MASK WITH ANVIS NIGHT VISION GOGGLES (U)

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13. ABSTRACT *(Maximum 200 words)* Potential compatibility problems found with the Protective Integrated Hood Mask (PIHM) and the Aviator's Night Vision Imaging System (ANVIS) were evaluated. The PIHM is worn under a standard HGU-55/P helmet and is designed to protect USAF aircrew members in a chemical environment. Visual acuity through ANVIS/PIHM, ANVIS horizontal and vertical intensified fields of view while wearing PIHM, and distortion and transmissivity of the PIHM visor were determined. Acuity through ANVIS with and without PIHM was assessed under quarter moon and starlight illumination. Acuity was tested using 20% and 90% contrast Landolt C targets depicted in one of four orientations. ANVIS/PIHM viewing resulted in acuity reductions of approximately 6% for both contrast levels at quarter moon illumination. No acuity loss was present at starlight illumination. Tests of horizontal and vertical ANVIS intensified fields of view resulted in no significant losses when PIHM was donned. Distortion and transmissivity data for the PIHM visor were compared to a clear AF visor, and it was found that the PIHM visor did not deviate significantly from the clear AF visor. Overall conclusions were that potential compatibility problems of ANVIS and PIHM integration can be reduced or eliminated with proper fit and adjustment of the ANVIS/PIHM.

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Summary

A laboratory evaluation was conducted on the Protective Integrated Hood Mask (PIHM) to determine its compatibility with the Aviator's Night Vision Imaging System (ANVIS). PIHM will be used by tanker, transport, and bomber aircrews for protection in a chemical environment. ANVIS is a night vision goggle currently used by these same aircrews to aid in visual performance during night missions.

Parameters which were evaluated included: visual acuity, intensified field of view, distortion of PIHM visor, and transmissivity of PIHM visor. For the tests of visual acuity and intensified field of view, the approach was to evaluate visual performance through ANVIS alone, and compare it to performance with PIHM/ANVIS. Distortion and transmissivity of the PIHM visor were evaluated by comparing the measurement data to a standard Air Force clear visor.

The results for the visual acuity and intensified field of view tests indicated no significant reduction in visual performance when the PIHM was donned. Likewise, data obtained from distortion and transmissivity tests showed no significant differences from the standard clear visor.

As a result of this evaluation, it became evident that proper training procedures for donning the PIHM with ANVIS need to be developed and adopted. Optimal visual performance was primarily achieved because the subjects who participated in the evaluation had assistance in donning the equipment from a life support specialist. This specialist ensured exact fit of the PIHM and proper alignment of ANVIS. It is possible that reductions in visual performance will occur if proper PIHM/ANVIS fit is not achieved.

Preface

This evaluation was completed under work unit 7184-18-07 by members of the Crew Systems Effectiveness Branch, Human Engineering Division, Armstrong Aerospace Medical Research Laboratory, Wright Patterson Air Force Base, Ohio and Logicon Technical Services, Inc., Dayton, Ohio. Funding was provided by the Life Support Systems Programs Office (HSD/YAGD).

The authors express appreciation to the following individuals for their assistance on this project: Dr Lee Task, AAMRL/HEF, TSgt Laurie DeCamp, 3246TW/TZFC, Eglin AFB, FL; and David Sivert and Annette Zobel, Logicon Technical Services, Inc. We also wish to thank Bob Sanctis, Modern Technologies, Inc., and Capt Delapena, HSD/YAGD, for their cooperation in obtaining the PIHMs for the evaluation.

Introduction

The Aircrew Eye Respiratory Protection System (AERPS) is designed to protect USAF aircrew members in a potential or known chemical environment without imposing physiological burdens or degrading mission capability. The Protective Integrated Hood Mask (PIHM) is the candidate subsystem of AERPS for use by aircrew members of tanker, transport, and bomber aircraft. The PIHM is designed to be worn under a standard HGU-55/P flight helmet.

Prior to C-130E flight testing, the Life Support Special Program Office, HSD/YAG, requested AAMRL/HEF to evaluate potential compatibility constraints that may result from wearing the Aviator's Night Vision Imaging System (ANVIS) with the PIHM. While wearing the PIHM, ANVIS is mounted to the helmet using a special bracket that allow the night vision goggles (NVGs) to be positioned just in front of the PIHM visor. The mounting bracket used was designed by the Special Mission Operational Test and Evaluation Center (SMOTEC) for pilots of special operations aircraft. Integration of the PIHM with ANVIS results in the PIHM visor being located between the users eye and the ANVIS objective lens.

Since there are normally no obstructions between the user's eye and the ANVIS objective lens, the integration of the PIHM with the ANVIS could limit aircrew visual capabilities during NVG missions. The specific concerns raised by HSD/YAG included: reductions in the ANVIS intensified field of view (FOV), loss of visual acuity, cockpit lighting interference produced by glare from the visor, anthropometric fit of the PIHM/ANVIS combination and the distortion and transmissivity of the PIHM visor.

The AAMRL Night Vision Operations (NVO) laboratory, in support of the AERPS evaluation, conducted both on-site and laboratory testing to assess these compatibility issues. The on-site evaluation was completed at Pope AFB NC using qualified C-130E pilots to examine the PIHM/ANVIS intensified FOV, cockpit lighting compatibility, and a limited anthropometric evaluation. The on-site evaluation demonstrated no significant compatibility problems with the PIHM/ANVIS combination in any of the areas examined. The complete results of the on-site evaluation are described in a separate AAMRL technical report [1].

The purpose of the laboratory evaluation described in this report was to assess the visual acuity through the PIHM/ANVIS combination and provide intensified FOV measurements for a wider range of PIHM sizes. In addition, distortion and transmissivity of the PIHM visor were measured. This report describes the results obtained in the AAMRL NVO laboratory evaluation and in conjunction with the AAMRL field study cited above, provides recommendations for optimal performance of the PIHM/ANVIS integrated system.

Method

2.1 Visual Acuity

Subjects

Visual acuity through the ANVIS, both with and without the PIHM, was measured for five males and one female ranging in age from 21 to 45 years. All subjects had Snellen visual acuity of at least 20/20, corrected or uncorrected.

Apparatus and Stimuli

Each subject was individually tested in the AAMRL zoom lane facility. The zoom lane consists of a computer controlled, motorized cart on a 40 foot track. Landolt C acuity charts having modulation contrasts of 20% and 90% were used. The acuity charts consisted of three to five Cs having one of four orientations (right, left, up, and down) and mounted on a white foam core background. The subject's view of the acuity charts is displayed in Figure 2.1. A moonlight simulator which approximated quarter moon and starlight illumination levels was used to illuminate the chart. The simulator was mounted on a tripod which was adjusted to provide calibrated illumination on the surface of the acuity charts.

Acuity target sizes (in Snellen notation) ranged from 20/32 to 20/71 in increments of $\sqrt[6]{2}$ for the quarter moon illumination level, and 20/80 to 20/300 (also in increments of $\sqrt[6]{2}$) for the starlight illumination level. The results of a pilot study conducted prior to the evaluation were used to determine the acuity size ranges for each illumination and contrast level. A pair of ANVIS third generation NVGs were mounted with velcro strips to a HGU-55/P helmet using the same mounting bracket used at Pope AFB. Medium and large helmets were used for the subjects tested.

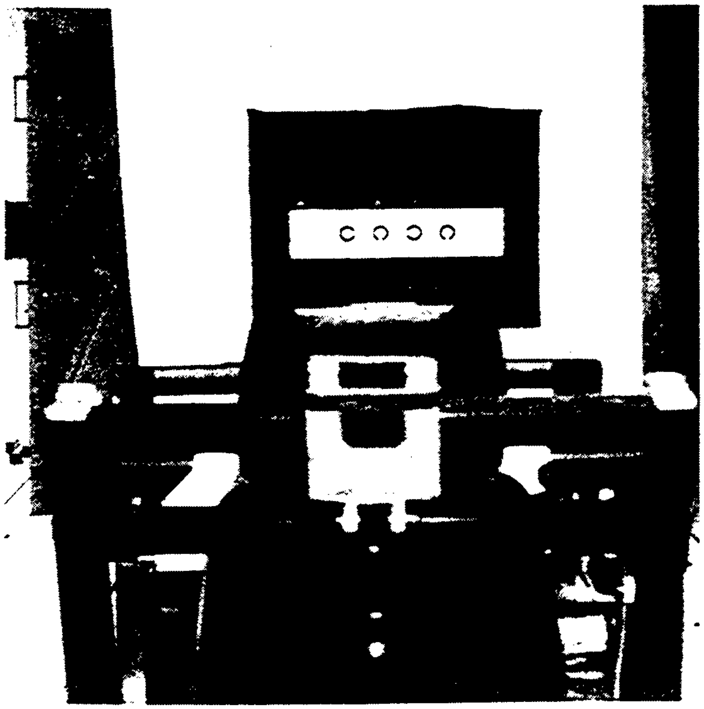

Figure 2.1: Subject's View of Landolt C Acuity Chart

Procedure

Each subject was seated in the motorized cart so that the distance from the NVG objective lens to the acuity chart was 30 feet. The cart was moved to a distance of 12 feet for the low contrast condition at the starlight illumination level. The cart was stationary during each test sequence. Visual acuity was measured for each subject while wearing the ANVIS without the PIHM first (baseline). The subject then donned the PIHM/ANVIS combination and repeated the procedure under a new chart presentation order.

Each subject viewed 23 charts for both the baseline and PIHM conditions. Subjects were required to determine the orientation of the Cs contained on each chart in succession, reading from left to right. If the experimenter was unable to hear any response, the subject was asked to read the entire chart again. Acuity measurements were obtained for 20 and 90 percent contrast targets at both quarter moon (.00589 ft-L.) and starlight (.00024 ft-L.) illumination levels.

2.2 Intensified Field of View (FOV) Measurements

Subjects

Horizontal and vertical intensified FOVs were measured for seven males and one female ranging in age from 21 to 45 years. Four subjects were USAF personnel from the WPAFB

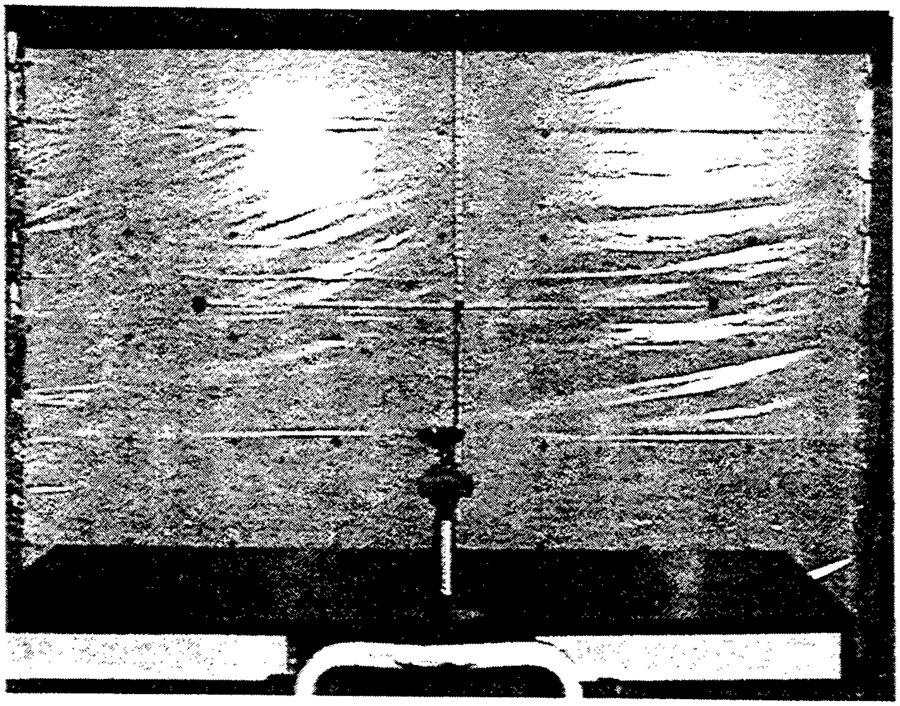

Figure 2.2: Visual Field Used to Measure PIHM/ANVIS Horizontal and Vertical Intensified FOV

Physiological Medical Training Division who were tested with their own custom fit HGU-55/P helmet. The remaining subjects wore HGU-55/P helmets without custom fit liners. All subjects received assistance in donning the PIHM and adjusting the ANVIS from the same life support specialist who supported the on-site evaluation and the two experimenters.

Procedure

Intensified FOVs were measured for each subject using a 5 foot square field marked off on a white projection screen (see Figure 2.2). A small light emitting diode (LED) was positioned in the center of the field to serve as a fixation point. Subjects were seated so that the ANVIS objective lens was at a distance of 6 feet from the center of the visual field. A second LED was moved across the horizontal and vertical scale by the experimenter. The subject called out when the LED was "just visible" at the edge of the intensified NVG image. Two measurements were recorded for each viewing condition. Both the right and left monocular FOVs were measured as well as the FOV for binocular viewing. Baseline FOV measurements (HGU-55/P + ANVIS) were recorded for each subject prior to donning the PIHM. This was done to ensure that each subject was able to attain a full 40 degree intensified field of view based upon helmet fit. After a 40 degree field was obtained, the subject donned the PIHM/ANVIS combination and the FOV measurement was repeated.

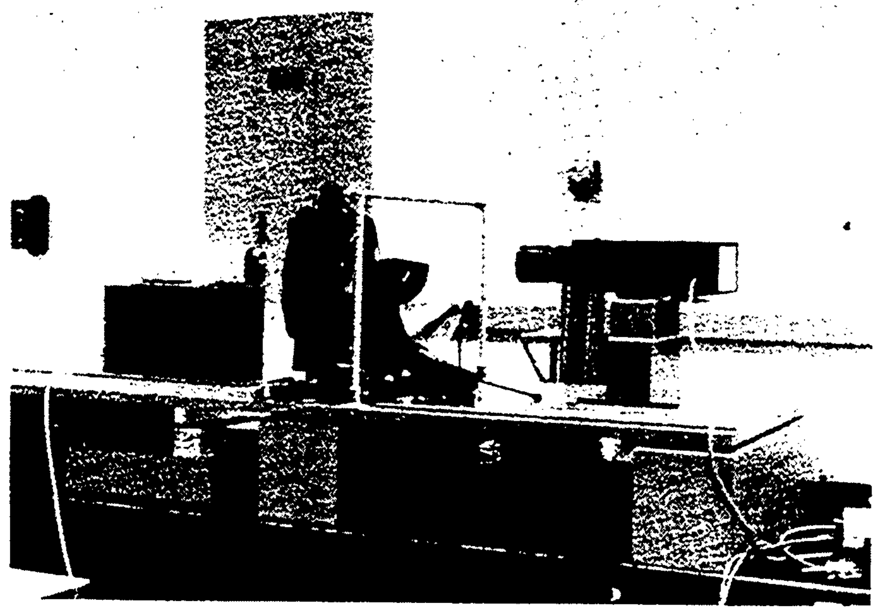

Figure 2.3: Apparatus Used for Measuring Angular Deviation Through PIHM Visors

2.3 Distortion and Transmissivity of PIHM Visor

Distortion

The angular deviation of three PIHM visors was measured using a UDT two axis detector and a helium neon (HeNe) laser, (see Fig 2.3). The amount of error in milliradians was recorded from -15°to +15°in azimuth (in 5°increments) at elevations of +/- 10, 20, 30, 40 and 0 degrees. The error recorded from the left eye was subtracted from the error recorded for the right eye to determine the angular deviation between the two eyes at each position. The eye convergence and divergence data (+ and - horizontal deviation) were then plotted as a function of elevation for each mask. Likewise, plots were made of dipvergence (deviation in vertical axis) in milliradians as a function of azimuth angle for the elevations listed above. These plots are included in Appendix 5.1. Distortion was further assessed by taking photographs through each visor of a large grid board positioned ten feet in front of the camera. These photographs were examined for distortion.

Transmissivity

Transmissivity is the ratio of the light exiting a transparent material to the light that was incident on it. Photopic transmissivity is dependent upon the spectral transmissivity of the PIHM visor, the CIE 1931 photopic response of the human visual system, and the spectral distribution of the object viewed. A neutral material will have the same transmission characteristics regardless of the object viewed. The spectral transmission of three PIHM visors was measured for wavelengths of 380-760 nm using a Photo Research 1980B spectral scanning radiometer. In addition, the spectral transmission of several objects (both natural and man-made) was measured. Using the equation below, the photopic transmissivities of these objects were calculated. The results of these calculations were compared to a standard AF clear visor (which is a fairly neutral material) to determine if visibility through the PIHM visor was significantly different.

$$T = \frac{\int_{380}^{760} T_\lambda \times S_\lambda \times V_\lambda d\lambda}{\int_{380}^{760} S_\lambda \times V_\lambda d\lambda}$$

where: T = photopic transmissivity

T_λ = spectral transmissivity of the visor

V_λ = CIE 1931 photopic sensitivity curve

S_λ = spectral distribution of the object viewed

Results

3.1 Visual Acuity

Visual acuity measurements obtained for ANVIS and the PIHM/ANVIS viewing conditions are listed in Table 3.1 for quarter moon illumination and in Table 3.2 for starlight illumination, respectively. The values in Tables 3.1 and 3.2 represent the Snellen fraction (20/value) for which at least 75% accuracy was achieved. The percent change in visual acuity calculated from the Snellen decimal resulting from ANVIS/PIHM viewing is listed in Table 3.3 for each subject as a function of illumination level and acuity target contrast.

The results showed that slight reductions in visual acuity occurred only at the quarter moon illumination level, averaging across subjects. Inspection of Table 3.1 reveals that this reduction is mostly attributable to subject four. All other subjects displayed little or no change from baseline levels. No visual acuity loss was measured at the starlight illumination level, when averaging across subjects. The differences in visual acuity between baseline ANVIS and PIHM/ANVIS were not statistically significant for either illumination level.

3.2 Intensified Field of View

The degrees of visual angle measured to the right and left of the center fixation point were summed to obtain the full horizontal field of view for each viewing condition. The vertical field of view was obtained by adding the degrees of visual angle measured above and below the fixation point. The monocular and binocular intensified fields of view measured for the PIHM/ANVIS combination are listed in Table 3.4.

The average horizontal FOVs for the right, left, and binocular viewing were 36, 36, and 38 degrees, respectively. Thus viewing through the PIHM/ANVIS combination resulted in a 10 percent horizontal FOV loss for each eye indvidually and a 5 percent loss for viewing

Table 3.1: Visual Acuity (20/) for Baseline and PIHM/ANVIS Viewing Conditions at Quarter Moon Illumination for 20% and 90% Contrast Landolt Cs

QUARTER MOON				
	20% CONTRAST		90% CONTRAST	
SUB.	BASE	PIHM	BASE	PIHM
1	20/57	20/57	20/40	20/36
2	71	71	50	57
3	40	40	32	32
4	45	71	36	45
5	40	40	36	36
6	45	40	32	32
AVG	50	53	38	40

Table 3.2: Visual Acuity (20/) for Baseline and PIHM/ANVIS Viewing Conditions at Starlight Illumination for 20% and 90% Contrast Landolt Cs

STARLIGHT				
	20% CONTRAST		90% CONTRAST	
SUB.	BASE	PIHM	BASE	PIHM
1	20/225	20/225	20/100	20/100
2	225	250	100	111
3	225	250	91	100
4	225	225	91	91
5	225	200	80	80
6	250	225	111	80
AVG	229	229	96	94

Table 3.3: Percent (%) Change in Decimal Visual Acuity From Baseline to ANVIS/PIHM Viewing for 20% and 90% Contrast Landolt Cs

	QUARTER MOON		STARLIGHT	
SUB	20%	90%	20%	90%
1	0%	10%	0%	0%
2	0	-14	-11.1	-11.0
3	0	0	-11.1	-9.9
4	- 57.8	-25	0	0
5	0	0	11.1	0
6	11.1	0	10	27.9
AVG.	-7.8	-4.8	.2	1.2

Table 3.4: Horizontal and Vertical Intensified Field of View (in degrees) for PIHM/ANVIS Viewing.

		HORIZONTAL			VERTICAL		
SUB NO.	PIHM SIZE	MONOC. RT.	MONOC. LT.	BINOC. -	MONOC. RT.	MONOC. LT.	BINOC. -
1	SMALL	34°	38°	38°	40°	38°	38°
2	SMALL	39	37	37	38	39	38
3	MED	35	31	34	33	40	39
4	MED	35	38	40	36	35	37
5	LARGE	37	34	40	38	26*	37
6	LARGE	36	37	39	39	40	39
7	LARGE	38	39	38	36	37	36
8	LARGE	32	35	37	32	33	34
AVG.	-	36	36	38	37	36	37

* Proper positioning of the oculars could not be achieved for this subject.

with both eyes. The average vertical fields of view measured for right, left, and both eyes respectively were 37, 36, and 37 degrees, which represented reductions from baseline of 7 to 10 percent.

3.3 Distortion and Transmissivity

Distortion

Differences in angular deviation (in milliradians) between the right and left eye positions were calculated to determine binocular convergence, divergence, and dipvergence as a function of azimuth angle for each visor. Examination of the data obtained for each mask showed that the angular deviation between the two eye postions was within acceptable limits for eye convergence and dipvergence. It should be noted that no divergence occurred for any of the PIHM visors. Plots of eye convergence and dipvergence are shown in Appendix 5.1. In addition, no distortion was observed in the photographs taken of the grid board through each visor.

Transmissivity

The photopic transmissivities which were calculated for several exterior scene objects as seen through the PIHM visors and clear visor are listed respectively in Table 3.4. Examination of the data shows that transmission of the PIHM visors varied from 88-90%. The transmission of the clear visor was 96%. The difference in transmission between the clear visor and PIHM visors can be considered negligible.

Table 3.5: Photopic transmission (%) calculated for three PIHM visors sizes with respect to exterior scene objects

OBJECT	PIHM VISOR SIZE			CLEAR AF VISOR
	SMALL	MEDIUM	LARGE	
Trees on Hill	90.1%	90.2%	88.2%	95.9%
Grass on Hill	90.1	90.3	88.3	95.9
Pavement	90.1	90.3	86.6	95.9
Blue sky	90.1	90.2	88.3	95.9
Horizon haze	90.1	90.2	88.3	95.9
Gravel on rooftop	90.1	94.0	88.3	95.9
Grass field	90.1	90.2	88.3	95.9
Cream building	90.1	90.3	88.3	95.9
Red brick building	90.2	90.3	88.3	95.9
Dark brown roof	90.2	90.3	88.3	95.9

Conclusions and Recommendations

The laboratory evaluation described in this report examined the compatibility of ANVIS NVGs with the PIHM system. Both the data and observations indicated that the integration of ANVIS with the PIHM did not result in any significant compatibility problems. However, the results demonstrated the importance of following proper PIHM donning procedures and careful adjustment of the ANVIS to ensure optimal performance. The conclusions and recommendations drawn from each test objective are described separately in the following paragraphs.

4.1 Visual Acuity

The results of the visual acuity assessment revealed no significant reduction in visual acuity when wearing the ANVIS/PIHM combination. If a proper system fit is achieved, no acuity reductions from normal ANVIS viewing should be expected when wearing the PIHM/ANVIS combination. It is recommended that careful attention is given to refocussing the ANVIS after donning the PIHM to ensure optimal acuity.

4.2 Intensified Field of View

The PIHM/ANVIS combination resulted in small reductions in the horizontal and vertical intensified fields of view. The average reduction from the 40 degree optimal FOV ranged between 2 and 4 degrees for both the on-site and AAMRL lab evaluation. This rather insignificant effect on the intensified FOV was attributable to the careful attention given to proper donning and adjustment of the PIHM/ANVIS combination. Each subject received assistance in donning the PIHM and adjusting the ANVIS mount from life support specialists prior to testing to ensure that the NVG oculars were centered over each eye and as close to the visor as possible. Without careful adjustment or proper fit, the PIHM/ANVIS combination could potentially reduce intensified field of view significantly. Improper adjustment or alignment of the NVG oculars under normal use could be magnified by the PIHM/ANVIS combination unless assistance is provided when donning the equipment. Therefore, it is recommended that proper training procedures are developed for donning the PIHM/ANVIS.

Training procedures developed for PIHM/ANVIS missions should emphasize PIHM system fit as well as proper ANVIS adjustment. The mounting bracket should allow the NVG oculars to be positioned directly in front of the eyes and level with the line of sight. The vertical adjustment range of the mounting bracket may have to be increased to ensure proper positioning. The NVGs should also be positioned as close to the visor as possible without damaging the visor. Optimal field of view will be achieved with the oculars just touching the visor. Mole skin padding could be placed around the eyepiece (inner) lens to eliminate the risk of scratching the PIHM visor.

4.3 Distortion and Transmissivity

The data obtained for the angular deviation measurements and visor distortion evaluation were within acceptable limits for PIHM/ANVIS use. The transmissivity calculations resulted in values similar to those obtained for the clear visor which has already been adopted by the Air Force for flight use.

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[1] Riegler, Joseph T., Donohue-Perry, Mary M., Hausmann, Martha A. "A Field Evaluation of the Compatibility of the Protective Integrated Hood Mask with ANVIS Night Vision Goggles (U)", Armstrong Aerospace Medical Research Laboratory, June 1990.

Appendix

5.1 Eye Convergence and Dipvergence for PIHM Visors

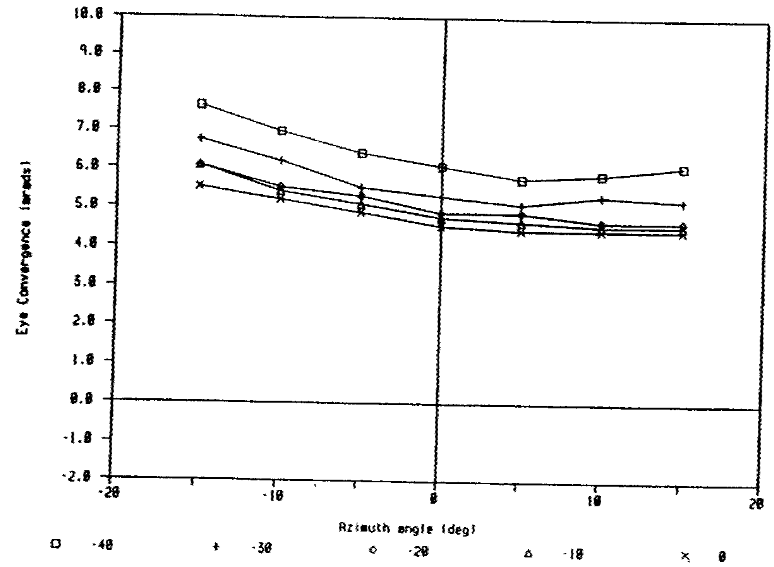

Figure 5.1: Small PIHM Visor Convergence as a Function of Azimuth for Negative Elevation Angles

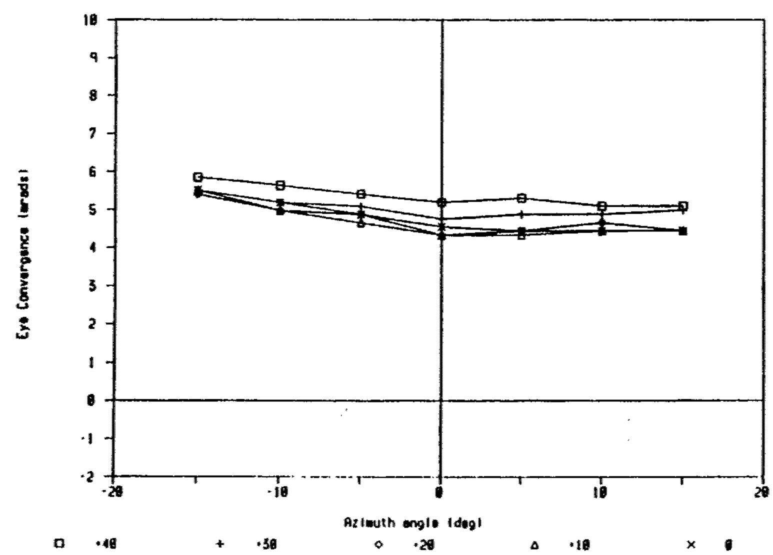

Figure 5.2: Small PIHM Visor Convergence as a Function of Azimuth for Positive Elevation Angles

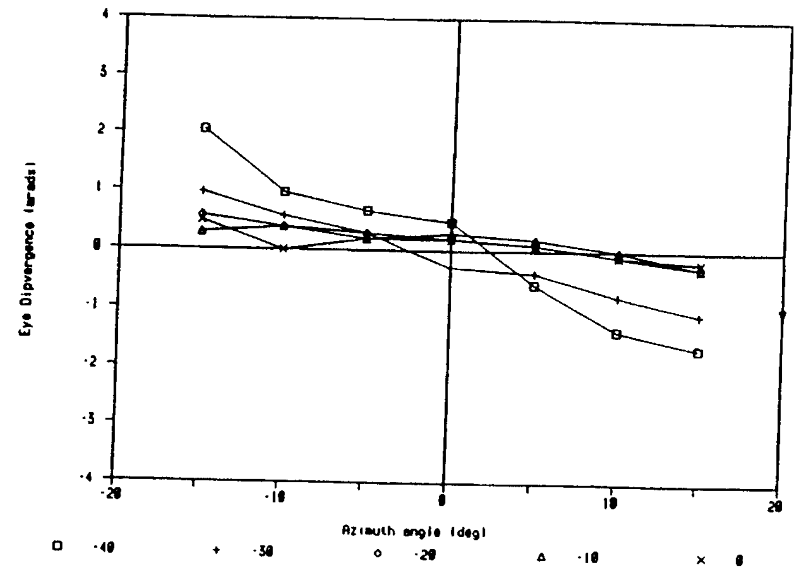

Figure 5.3: Small PIHM Visor Dipvergence as a Function of Azimuth for Negative Elevation Angles

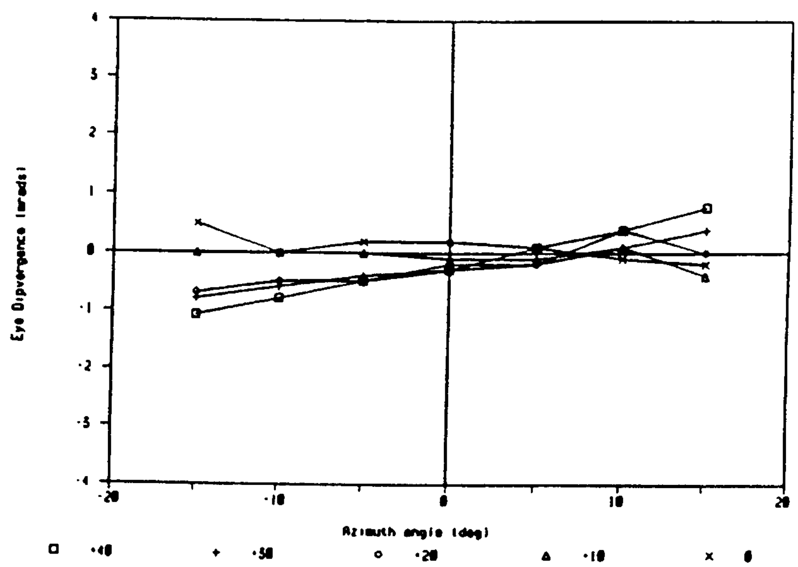

Figure 5.4: Small PIHM Visor Dipvergence as a Function of Azimuth for Positive Elevation Angles

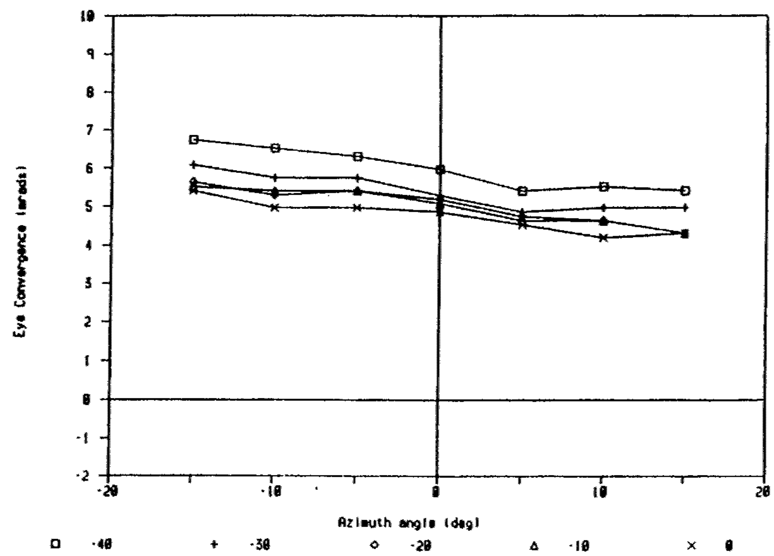

Figure 5.5: Medium PIHM Visor Convergence as a Function of Azimuth for Negative Elevation Angles

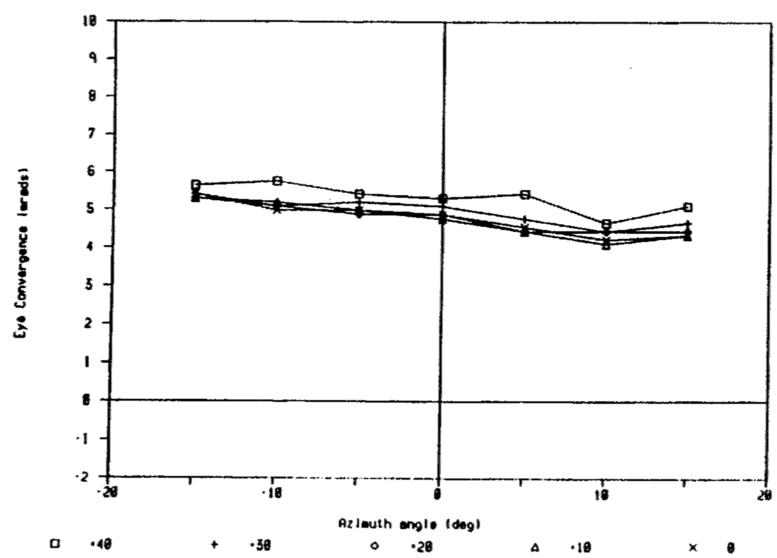

Figure 5.6: Medium PIHM Visor Convergence as a Function of Azimuth for Positive Elevation Angles

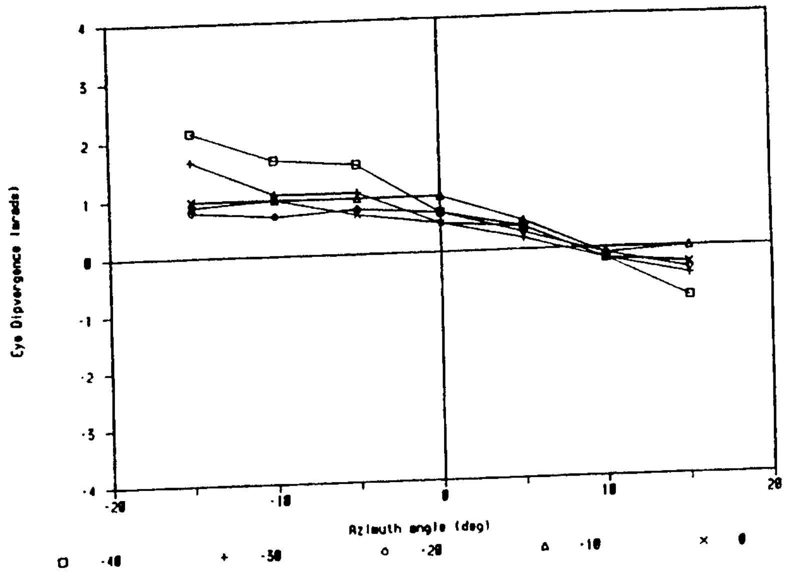

Figure 5.7: Medium PIHM Visor Dipvergence as a Function of Azimuth for Negative Elevation Angles

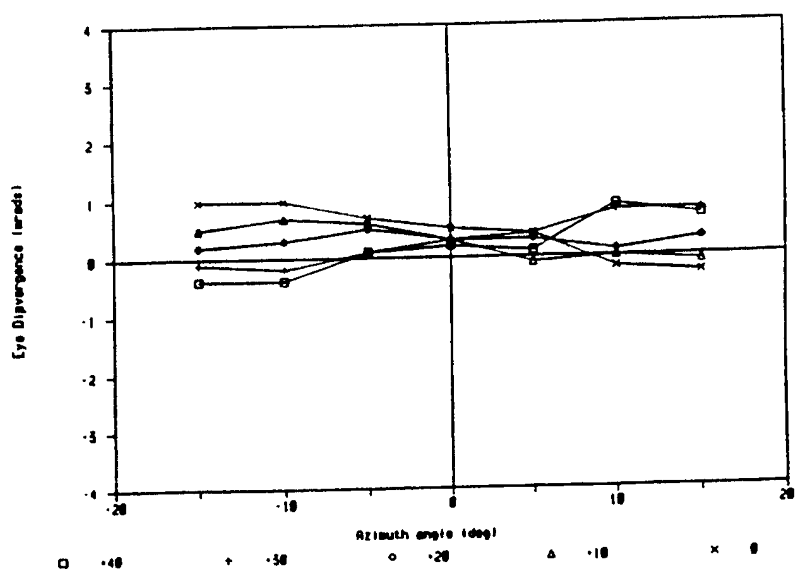

Figure 5.8: Medium PIHM Visor Dipvergence as a Function of Azimuth for Positive Elevation Angles

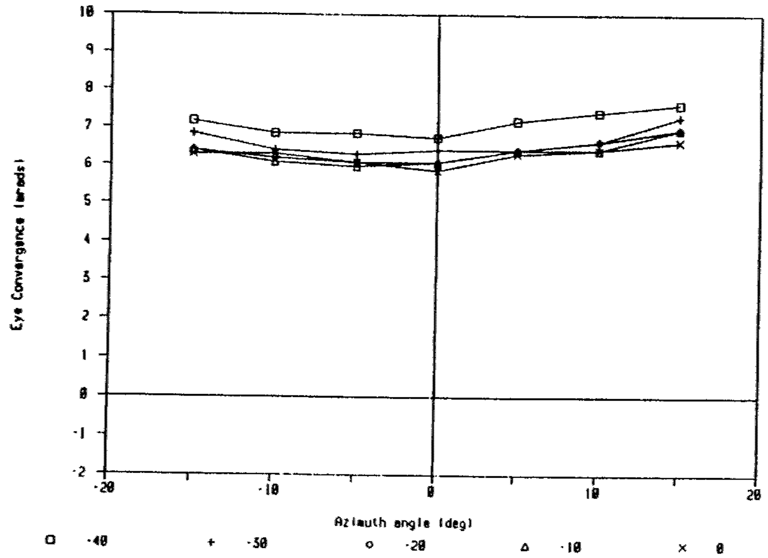

Figure 5.9: Large PIHM Visor Convergence as a Function of Azimuth for Negative Elevation Angles

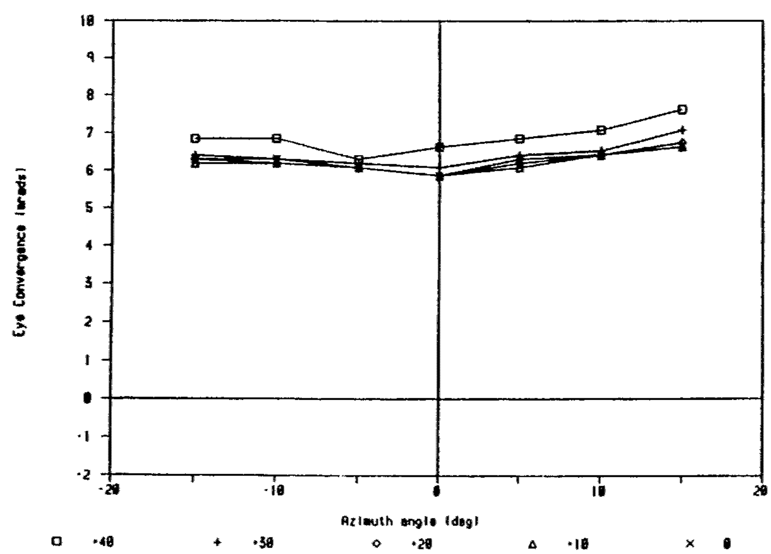

Figure 5.10: Large PIHM Visor Convergence as a Function of Azimuth for Positive Elevation Angles

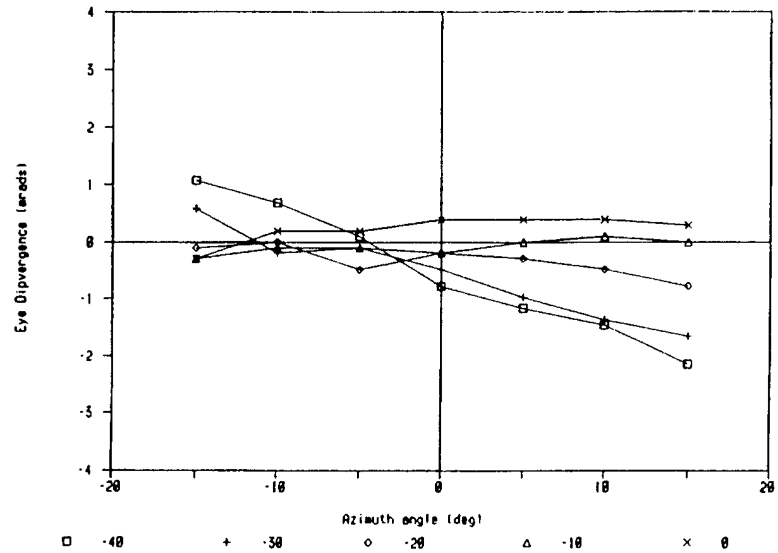

Figure 5.11: Large PIHM Visor Dipvergence as a Function of Azimuth for Negative Elevation Angles

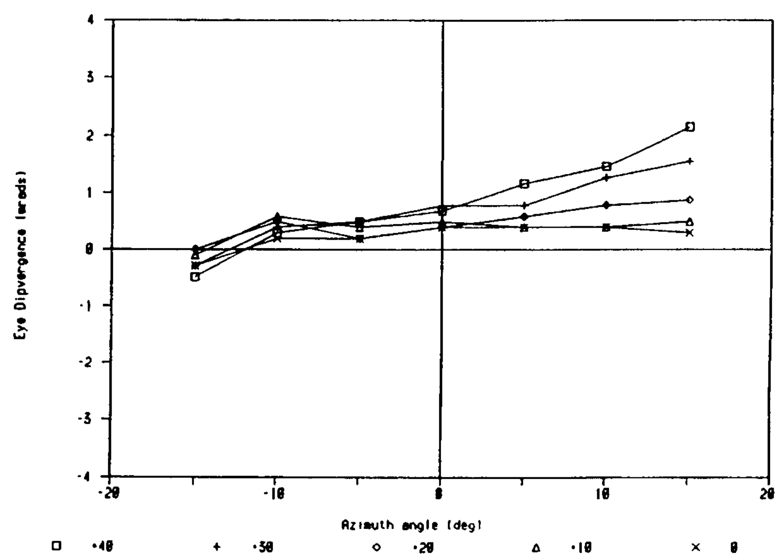

Figure 5.12: Large PIHM Visor Dipvergence as a Function of Azimuth for Positive Elevation Angles

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AAMRL-TR-90-031

A FIELD EVALUATION OF THE COMPATIBILITY OF THE PROTECTIVE INTEGRATED HOOD MASK WITH ANVIS NIGHT VISION GOGGLES (U)

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13. ABSTRACT *(Maximum 200 words)*
An evaluation was conducted to determine potential compatibility problems found while wearing the Protective Integrated Hood Mask (PIHM) with the Aviator's Night Vision Imaging Systems (ANVIS). The PIHM is worn under a standard HGU-55/P helmet and is designed to protect USAF aircrew members in a chemical environment. ANVIS is mounted in front of the PIHM visor using a special bracket. The evaluation consisted of tests performed at Pope AFB, NC using qualified C-130E crewmembers. Examinations of horizontal and vertical intensified fields of view, cockpit lighting compatibility, and a limited fit evaluation were conducted. Testing showed that ANVIS/PIHM viewing resulted in average losses of horizontal and vertical fields of view of 2.6 degrees and 2.1 degrees. C-130E cockpit lighting interference was not found when viewing through the ANVIS/PIHM, or under the ANVIS through the PIHM visor. No significant problems in achieving proper fit with ANVIS/PIHM were found. Overall conclusions were that potential compatibility problems of ANVIS and PIHM integration can be reduced or eliminated with proper fit and adjustment of the ANVIS/PIHM.

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Summary

A field evaluation was conducted on the Protective Integrated Hood Mask (PIHM) to determine its compatibility with the Aviator's Night Vision Imaging System (ANVIS). PIHM will be used by tanker, transport, and bomber aircrews for protection in a chemical environment. ANVIS is a night vision goggle currently used by these same aircrews to aid in visual performance during night missions. The evaluation was conducted at Pope AFB, NC using qualified C-130E aircrew with ANVIS experience.

Parameters which were evaluated include: intensified field of view, cockpit lighting interference, and subjective and photographic assessments of fit. The approach for the evaluation was to compare visual performance with PIHM/ANVIS to performance through ANVIS alone. The fit assessments were completed to allow users the opportunity to comment on fit, and to document specific fit problems.

The results for the intensified field of view test showed no significant reduction in field of view when the PIHM was donned. No cockpit lighting interference was found when viewing underneath ANVIS through the PIHM visor, and viewing through the PIHM/ANVIS combination. All subjects reported no major fit problems when using PIHM/ANVIS, with the exception of some restricted head mobility when PIHM was employed.

As a result of this evaluation, it became evident that proper training procedures for donning the PIHM with ANVIS need to be developed and adopted. Optimal visual performance was primarily achieved because the subjects who participated in the evaluation had assistance in donning the equipment from a life support specialist. This specialist ensured exact fit of the PIHM and proper alignment of ANVIS. It is possible that reductions in visual performance will occur if proper PIHM/ANVIS fit is not achieved.

Preface

This evaluation was completed under work unit 7184-18-07 by members of the Crew Systems Effectiveness Branch, Human Engineering Division, Armstrong Aerospace Medical Research Laboratory, Wright Patterson Air Force Base, Ohio and Logicon Technical Services, Inc., Dayton, Ohio. Funding was provided by the Life Support Systems Programs Office (HSD/YAGD).

The authors express appreciation to the following individuals for their assistance on this project: Mr Jeffrey Craig (associate investigator), and Dr Lee Task, AAMRL/HEF, WPAFB, Ohio; Maj John Schafer, USAFALCENT/RA, Pope AFB, NC; MSgt Bill Beier and TSgt Laurie DeCamp, 3246TW/TZFC, Eglin AFB, FL; and the technical photographic division at Pope AFB, NC. We wish to thank Bob Sanctis, Modern Technologies, Inc., and Capt Delapena, HSD/YAGD, for their cooperation in obtaining the PIHMs for the evaluation. Acknowledgments are also due to Martha Hausmann, Logicon Technical Services, Inc., for her assistance in data analysis.

Introduction

The Aircrew Eye Respiratory Protection System (AERPS) is designed to protect USAF aircrew members in a potential or known chemical environment without imposing physiological burdens or degrading mission capability. The Protective Integrated Hood Mask (PIHM) is the candidate subsystem of AERPS for use by aircrew members of tanker, transport, and bomber aircraft. The PIHM is designed to be worn under a standard HGU-55/P flight helmet.

Prior to C-130E flight testing, the Life Support SPO (HSD/YAG) requested AAMRL/HE to evaluate potential compatibility problems that may result from wearing the Aviator's Night Vision Imaging System (ANVIS) with the PIHM (see Figure 1). While wearing the PIHM, ANVIS is mounted to the helmet using a special bracket that allows the night vision goggles (NVGs) to be positioned just in front of the PIHM visor. The mounting bracket used was designed by the Special Mission Operational Test and Evaluation Center (SMOTEC) for pilots of special operations aircraft. Integration of the PIHM with ANVIS results in the PIHM visor being located between the user's eye and the ANVIS objective lens. Since there are normally no obstructions between the eye and ANVIS, integration of the PIHM with ANVIS could result in visual limitations during NVG missions. Specific concerns raised by HSD/YAG included: reductions in ANVIS intensified field of view, loss of visual acuity, cockpit lighting interference produced by glare from the visor, PIHM/ANVIS combination fit, and distortion and transmissivity of the PIHM visor.

The AAMRL Night Vision Operations (NVO) Laboratory, in support of the AERPS evaluation, conducted both on-site and laboratory testing to assess these compatibility issues. The on-site evaluation was completed at Pope AFB NC using qualified C-130E pilots to examine the PIHM/ANVIS intensified field of view, cockpit lighting compatibility, and PIHM/ANVIS fit. The results of the laboratory evaluation are described in a separate AAMRL technical report [1].

Figure 1.1: PIHM/ANVIS Combination

Method

2.1 Subjects

Two C-130E pilots and three C-130E navigators participated in the evaluation. All subjects had a minimum of 100 hours of NVG flight experience. Each subject was fitted with a HGU-55/P helmet and the proper PIHM prior to the evaluation. Three subjects wore a medium PIHM and two wore a large PIHM. Life support specialists from Eglin AFB assisted each subject in donning the PIHM and achieving a proper fit.

2.2 Apparatus

The evaluation was conducted in a darkened hangar at Pope AFB after dusk. Natural lighting conditions approximated a quarter moon illumination level, thus requiring no additional lighting during the evaluation. Intensified field of view measurements were obtained for each subject using a 5 ft. square visual field (see Figure 2.1). A light emitting diode (LED) positioned in the center of the field was used as a fixation point. A second LED which moved along a vertical and horizontal scale, was used to measure the vertical and horizontal intensified fields of view. The crewstation of a C-130E (shown in Figure 2.2) was used for the cockpit lighting interference evaluation.

2.3 Procedures

Intensified Field Of View (FOV) Measurements

Measurements of the horizontal and vertical intensified FOV were performed on each subject wearing the HGU-55/P helmet and the ANVIS. A baseline measurement without the PIHM was recorded first, followed by a measurement with the PIHM/ANVIS combination. Subjects were seated so that the ANVIS oculars were at a distance of 6 ft. from the LED

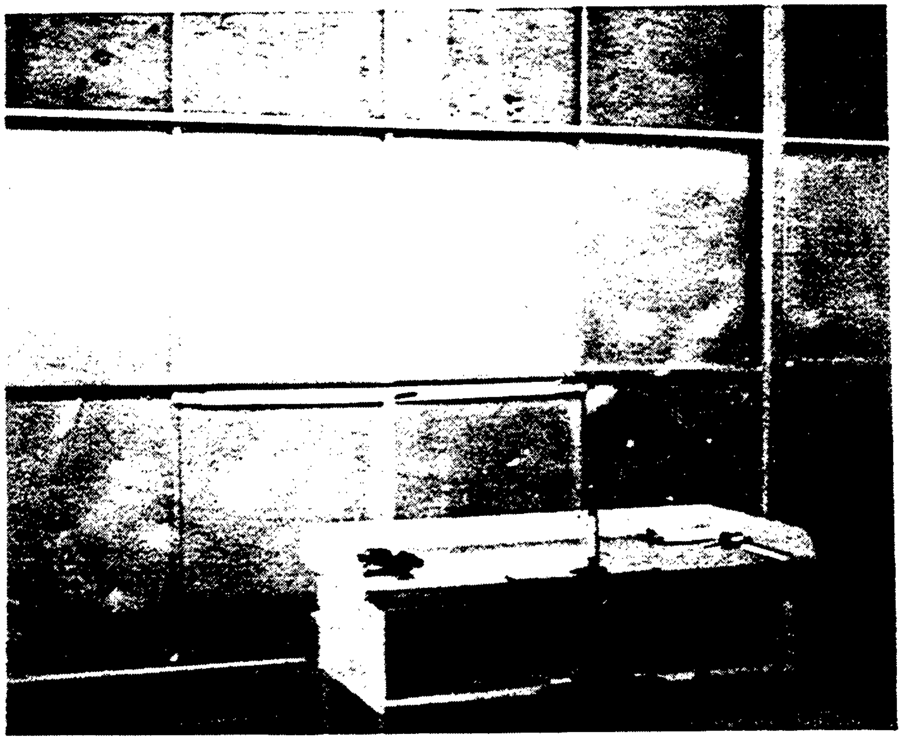

Figure 2.1: Apparatus Used to Measure PIHM/ANVIS Intensified Field of View

Figure 2.2: C-130 Aircraft Used for Cockpit Lighting Evaluation

fixation point. Subjects were positioned in a chin rest to restrict head movement during the measurements. After adjusting the NVGs, the subject was instructed to close one eye and fixate on the center LED. The experimenter then moved a second LED inward along a vertical or horizontal scale beginning at a 22 degree FOV. The subject indicated when the LED was just visible at the edge of the intensified field. This procedure was repeated twice for each eye in both the vertical and horizontal dimensions. The average of the two left and right side measurements was added together to obtain the total FOV for each eye. After baseline FOV was measured, the subject donned his prefitted PIHM/ANVIS combination with the assistance of the life support specialists. The FOV for the PIHM/ANVIS combination was then measured following the same procedure.

Cockpit Lighting Interference

Cockpit lighting interference was evaluated for two different viewing modes: 1) viewing through the PIHM/ANVIS combination and 2) viewing through the PIHM visor but underneath the NVGs. Subjects performed the cockpit lighting evaluation seated at the pilot's station of the C-130E cockpit. The subject was asked to set cockpit lighting at a comfortable NVG mission level. He then viewed an acuity chart positioned at eye level 20 ft. from the windscreen and indicated any reflections that were present. The sources causing the reflections were documented. Subjects then viewed the crewstation through the PIHM but underneath the NVGs and noted any reflections. If no interferences were noted, the test was terminated.

Photographic Evaluation of PIHM/ANVIS Anthropometric Fit

Front and side view photographs were taken of each subject wearing the ANVIS both with and without the PIHM. The photographs were used as documentation to assess any specific fit problems with the PIHM/ANVIS combination.

Evaluation of the PIHM/ANVIS Anthropometric Fit and Visibility

A questionnaire which addressed the PIHM/ANVIS fit and visibility was administered to each subject at the conclusion of the tests outlined above. The questionnaire is included in Appendix 5.1.

Results

3.1 Intensified Field of View Measurements

Tables 3.1 - 3.3 summarize the results of the intensified FOV measurements for each subject. Both horizontal and vertical FOVs are expressed in degrees of visual angle for the right and left eye positions, respectively. When averaging the measurements obtained for each eye, the horizontal and vertical FOVs measured for baseline were 38.8 and 38.1 degrees, respectively. The average horizontal and vertical FOVs measured for the PIHM/ANVIS combination were 36.2 and 36 degrees. Thus, the PIHM resulted in an average horizontal FOV loss of 2.6 degrees or 6.7 percent of baseline. The vertical FOV was reduced by 7 percent of baseline.

The ANVIS are designed to allow a 40 degree horizontal and vertical intensified FOV. Baseline measures were probably slightly less than 40 degrees because of individual differences in ANVIS adjustment and/or fit. It should be noted that each subject donned and adjusted his ANVIS without any assistance prior to the baseline measurements. Subjects were assisted when donning the PIHM/ANVIS combination and careful attention was given to proper adjustment.

3.2 Cockpit Lighting Interference

The results from the qualitative assessment of cockpit lighting interference indicated no problems for viewing through PIHM/ANVIS or through the PIHM and under the ANVIS. One subject reported reflections upon entering the crewstation when the lights were turned up. However, these reflections were no longer present when cockpit lighting was set to normal night mission levels. In addition, no lighting interference was produced when subjects moved their heads side to side while looking around the cockpit.

Table 3.1: Baseline (no PIHM) Horizontal and Vertical Intensified Field of View (in degrees) for Right and Left Eye Positions.

	HORIZONTAL			VERTICAL		
Sub.	Rt.	Lt.	AVG.	Rt.	Lt.	AVG.
1	37°	37°	37°	36°	36°	36°
2	40	39	39.5	39	36	37.5
3	40	40	40	40	39	39.5
4	39	39	39	37	40	38.5
5	38	39	38.5	40	38	39
AVG.	38.8	38.8	38.8	38.4	37.8	38.1

Table 3.2: Horizontal and Vertical Intensified Field of View (in degrees) for PIHM/ANVIS Viewing

	HORIZONTAL			VERTICAL		
Sub.	Rt.	Lt.	AVG.	Rt.	Lt.	AVG.
1	35°	35°	35°	33°	34°	33.5°
2	38	35	36.5	38	39	38.5
3	38	37	37.5	37	35	36
4	36	36	36	35	36	35.5
5	36	36	36	37	36	36.5
AVG.	36.6	35.8	36.2	36	36	36

Table 3.3: Percent (%) Change in Field of View from Baseline

	HORIZONTAL			VERTICAL		
Sub.	Rt.	Lt.	AVG.	Rt.	Lt.	AVG.
1	5.4%	5.4%	5.4%	8.3%	5.5%	6.9%
2	5	10.2	7.6	2.5	7.6	5
3	5	7.5	6.3	7.5	10.2	8.9
4	7.6	7.6	7.6	5.4	10	7.7
5	5.2	7.6	6.4	7.5	5.2	6.4
AVG.	5.6	7.7	6.7	6.2	7.7	7

3.3 Photographic Evaluation of PIHM/ANVIS Fit

Photographs were taken of each subject immediately following the FOV measurements while wearing the ANVIS both with and without the PIHM. Examination of the photographs revealed that the NVG oculars were in proper alignment for all of the subjects while wearing the PIHM/ANVIS combination. No problems were noted with the mounting bracket while wearing the PIHM. The ANVIS oculars did not come in contact with the visor when in the proper viewing position. To ensure optimal field of view the oculars were positioned as close to the visor as possible (approximately 10-20 mm). The photographs showed that for subjects 1 and 2 the oculars were tilted slightly upward during the baseline FOV measurements. As displayed in Table 1, the baseline vertical FOV measured for these two subjects was below the average measured. Photographs of baseline and PIHM/ANVIS fits are included in Appendix 5.2.

3.4 Subjective Evaluation of PIHM/ANVIS Fit and Visibility

The subjective evaluation indicated no significant problems in achieving a proper fit with the PIHM/ANVIS combination. One subject indicated that the mounting bracket needed more vertical adjustment range to ensure proper positioning of the NVGs in front of the eyes. The remaining subjects reported no problems in achieving a proper fit.

Two subjects reported that the visibility through the PIHM/ANVIS combination was better than through the NVGs alone because the "graininess in the NVGs was less" when viewing through the PIHM visor. The remaining three subjects reported that their visibility was unchanged by the PIHM/ANVIS combination. Two subjects reported restricted head mobility while wearing the PIHM/ANVIS combination which limited the range over which they could look from side to side. All subjects reported that the intensified FOV with the PIHM/ANVIS combination appeared to be the same as the intensified FOV without the PIHM. A complete summary of the questionnaire results is included in Appendix 5.1.

Conclusions and Recommendations

The evaluation described in this report was designed to examine the compatibility of ANVIS night vision goggles with the PIHM system. Both the data and observations indicated that the integration of ANVIS with the PIHM did not result in any significant compatibility problems. However, the results of this evaluation demonstrated the importance of following proper PIHM donning procedures and careful adjustment of the ANVIS to ensure optimal performance. The conclusions and recommendations drawn from each test objective are described separately in the following paragraphs.

4.1 Intensified Field of View

The PIHM/ANVIS combination resulted in small reductions in the horizontal and vertical intensified fields of view. The average reduction from the 40 degree optimal ranged between 2 and 4 degrees. This rather insignificant effect on the intensified FOV resulting from the PIHM/ANVIS combination can be attributed mostly to proper fit and adjustment. Each subject received assistance in donning the PIHM and adjusting the ANVIS mount from life support specialists prior to testing to ensure that the NVG oculars were centered over each eye and as close to the visor as possible. Without careful adjustment or proper fit, the PIHM/ANVIS combination could potentially reduce intensified field of view significantly.

The photographs of the baseline FOV measurements recorded at Pope AFB indicated that the NVG oculars were slightly tilted upward for two subjects, resulting in less than optimal FOV's. Loss in FOV could be magnified by an improper PIHM fit, and/or improper adjustment or alignment of the NVGs. Therefore, careful attention should be given to PIHM system fit as well as proper NVG adjustment prior to PIHM/NVG missions.

The mounting bracket should allow the NVG oculars to be positioned directly in front of the eyes and level with the line of sight. The vertical adjustment range of the mounting bracket may have to be increased to ensure proper positioning. The NVGs should also be positioned as close to the visor as possible without damaging it. Optimal field of view will be achieved with the NVG oculars just touching the visor. Mole skin padding could be placed around the NVG lens to eliminate the risk of scratching the PIHM visor. It is recommended that proper training procedures be developed for donning the PIHM and adjusting the ANVIS.

4.2 Cockpit Lighting Interference Assessment

The evaluation results demonstrated no cockpit lighting interference when viewing both through the PIHM/ANVIS combination and through the PIHM visor underneath the NVGs. Crewstation lighting levels were set by each subject to preferred night mission levels. Although no interference was noted for this test, it is possible that increased cockpit illumination levels could result in reflections and/or interference with the PIHM/ANVIS combination. It is recommended that potential sources of lighting interference from the crewstation are identified and eliminated prior to NVG flights with the PIHM.

4.3 Subjective Evaluation of PIHM/ANVIS Fit

The questionnaire results and photographs indicated that the subjects were able to achieve a proper fit with the PIHM/ANVIS combination and that no discomfort was experienced. However, it is recommended that the mounting bracket be modified to allow a greater range of vertical NVG adjustment without increasing the distance at which the oculars are positioned in front of the eyes.

Bibliography

[1] Donohue-Perry, Mary M., Riegler, Joseph T., Hausmann, Martha A., "A Compatibility Assessment of the Protective Integrated Hood Mask with ANVIS Night Vision Goggles (U)", Armstrong Aerospace Medical Research Laboratory, June 1990.

Appendix

5.1 Questionnaire Results

The questionnaire administered to the five crewmembers at Pope AFB is included below. A summary of the responses made to each question is provided.

Aircrew Eye Respiratory Protection System (AERPS) NVG Compatibility Questionnaire

The purpose of this questionnaire is to evaluate the effects of viewing through the protective integrated hood/mask system (PIHM) using ANVIS night vision goggles. The questionnaire addresses visibility, field of view loss, and cockpit lighting interference while wearing the PIHM/NVG system. The results from the questionnaire will aid in determining the severity of these problems as they relate to mission success. Please use the rating scales provided and feel free to add any additional comments. Responses made on this questionnaire will be kept confidential.

Name:

Organization:

NVG Flight Hours:

Helmet Size:

Mask Size:

1. Did you notice any interference or reflectance from light sources within the cockpit when viewing:

a. through BOTH the PIHM and NVG's? Yes - 0 No - 5

b. through the PIHM but underneath the NVG's? Yes - 0 No - 5

2. If yes, describe the sources of the interference.

"Initially with the lights up, there was interference. Decreasing the light source eliminated all reflections."

4. Describe the overall visibility through the PIHM/NVG system as compared to viewing through the NVG's alone.

(1) much worse - 0

(2) worse - 0

(3) same - 3

(4) better - 1

(5) much better - 1

"Grain in NVG is less"

5. Describe the intensified field of view when viewing through the PIHM and NVGs as compared to the NVGs alone.

(1) much worse - 0

(2) worse - 0

(3) same - 4

(4) better - 1

(5) much better - 0

6. Were you able to get a good fit with the PIHM/NVG system?

Yes - 5

"Yes, except the NVG bracket needed to be removed and screws loosened to give more vertical adjustment."

7. What were specific problems you encountered while wearing the PIHM/NVG system?

"Discomfort from PIHM wear."

"Wearing glasses, I had slight pressure on the bridge of my nose."

"Mobility"

8. How would you improve the mounting of the NVGs when used with the PIHM system?

"The Bailey mod on the Pope mount works best for 317 TAW."

"Need a bracket with more vertical range or preset brackets that can be stored for PIHM use so that they will not need to be adjusted in flight." "It was fine."

"Mounting is okay."

9. Do you have any suggestions for improvement to the PIHM/NVG system or to the NVGs alone?

"The hood unit needs to be longer to allow for the increased head movement required when wearing NVGs."

5.2 Photographic Evaluation of PIHM/ANVIS Fit

Photographs of ANVIS baseline and the PIHM/ANVIS combination fit with the HGU-55/P helmet and SMOTEC mounting bracket for four aircrew members are displayed in Figures 5.1 through 5.2.

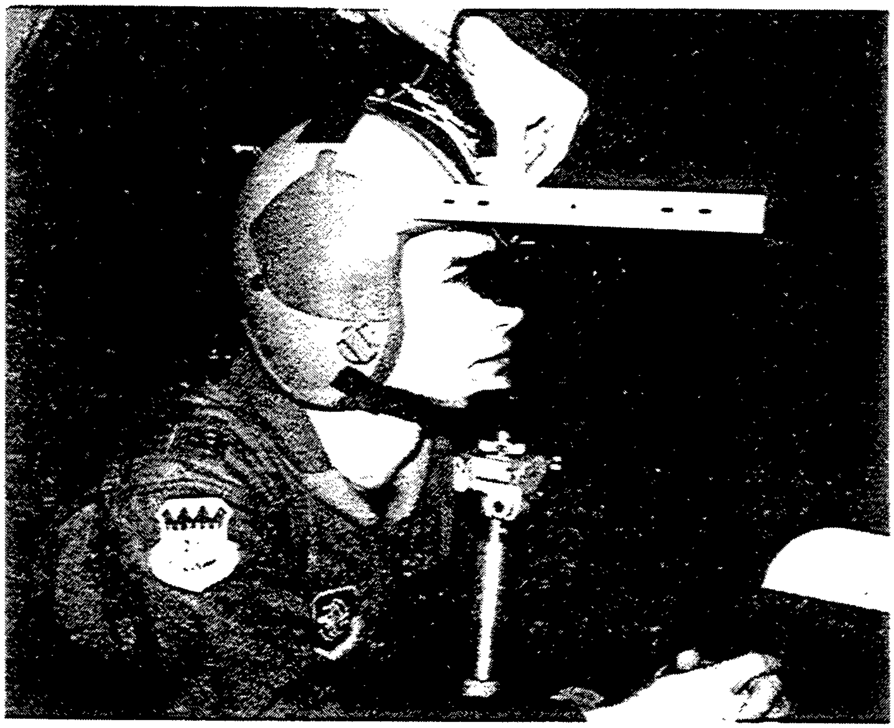

Figure 5.1: Baseline ANVIS Fit with HGU-55/P Helmet and SMOTEC Mounting Bracket

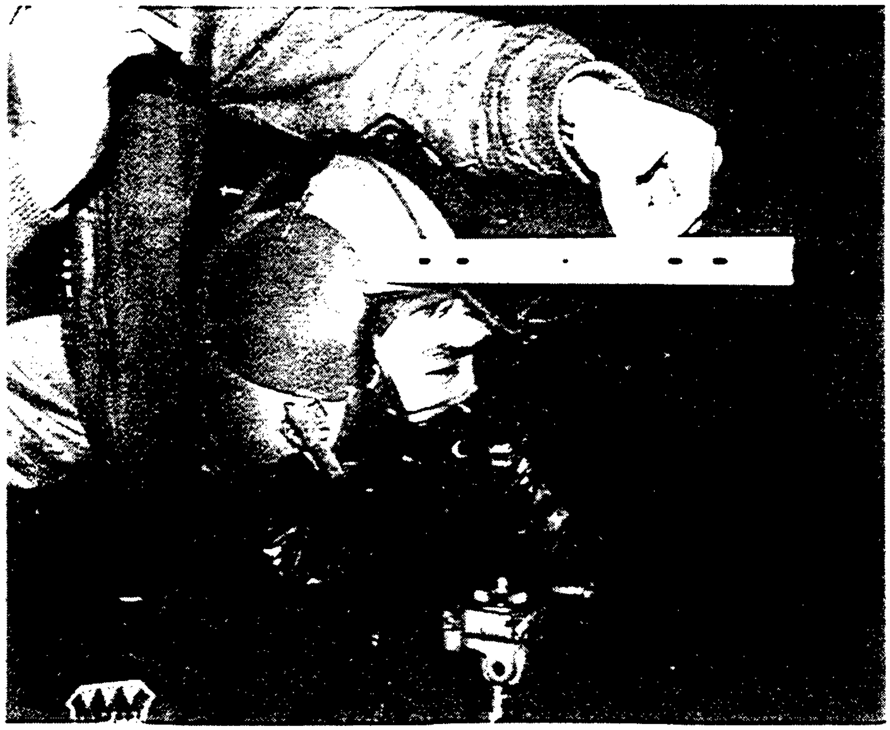

Figure 5.2: PIHM/ANVIS Combination with HGU-55/P Helmet and SMOTEC Mounting Bracket

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Genco, L. V. (1985). Night vision support devices human engineering integration. *AGARD, Visual Protection and Enhancement* (pp. 6-1 through 6-8). (NTIS No. AGARD-CP-379)

NIGHT VISION SUPPORT DEVICES HUMAN ENGINEERING INTEGRATION

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SUMMARY

Although Night Vision Goggles (NVGs) extend the luminance range over which we can use our vision, current AN/PVS systems require special cockpit lighting to be fully effective, reduce visual depth of field and diminish the field of view. All three of these factors are extremely important to pilots performing night operations. This paper describes the results of several operationally oriented efforts conducted by the United States Air Force Aerospace Medical Research Laboratory's Human Engineering Division to improve visual performance, cockpit lighting, and flight information transfer in conjunction with the use of night vision goggles. The efforts include an operational definition of NVG compatible lighting, a recommended approach to improving depth of focus, an attempt to expand field of view, and a description of a NVG HUD using optically injected flight data. All efforts center around using or modifying current AN/PVS NVGs used by US forces.

VISUAL PERFORMANCE THROUGH NVGS

Night vision enhancement devices appear to be gaining wide acceptance among both civil and military organizations as means to improve visual perception under conditions of low luminance. The new devices are not merely light amplifiers (light being defined as that portion of the electromagnetic spectrum to which our eyes are sensitive), but extend our capability to see into the near infrared. Because of this differential sensitivity of our eyes and night vision devices, both lighting engineers and night vision device users must be aware of the possible degradations in performance in either the unaided or enhanced visual systems caused by inappropriate lighting schemes. In many cases, inappropriate lighting may cause visual performance through night vision devices to be less than that experienced without the devices in place.

Although the human eye is sensitive to electromagnetic radiation from about 380 nm to about 780 nm, it is not equally sensitive to all wavelengths of light. During daylight or photopic vision, our retinas are maximally sensitive to light whose wavelength is about 555 nm (a yellow-green). During night, or scotopic vision, our retinas are maximally sensitive to light whose wavelength approaches 505 nm (a blue-green). Figure 1 shows the relative spectral and energy sensitivities of the photopic and scotopic visual systems.

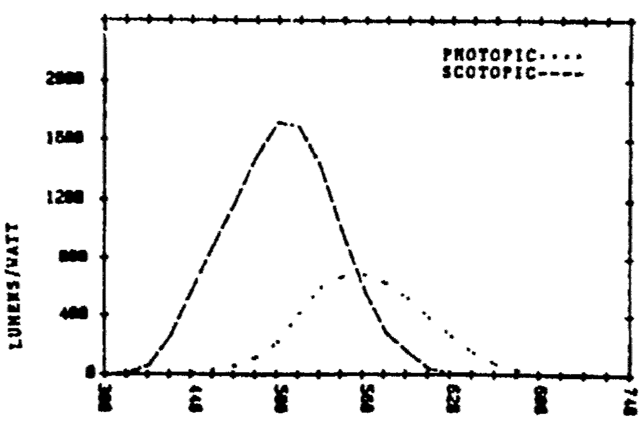

FIGURE 1
ABSOLUTE SPECTRAL AND ENERGY
SENSITIVITIES OF THE UNAIDED EYE

The dynamic range of the photopic visual system is about 10^8 - 10 ML, and the dynamic range of the scotopic system is about 1- 10^{-6} ML. Although our eyes are very sensitive to light when fully dark adapted (under ideal conditions we can see a candle at a distance of about one mile), their resolution acuity is very low. At best, the scotopic visual system's resolution is about 20/200, and exhibits a central scotoma or blind spot. In other words, small objects will disappear when looked at directly.

First generation devices were photomultipliers that were sensitive to a spectral distribution similar to our eyes. They would amplify what visible light was available, and present the information on a monochromatic display. Since the display luminance was high enough to activate the photopic visual system, the limiting factor in resolution was the optoelectronics in the device rather than the eye.

The visual environment at night is relatively poor in visible wavelength energy, but remains relatively rich in longer wavelength (infrared) energy. Passive devices which used these infrared wavelengths could then rely on a statistically larger number of photons to activate the systems and improve resolution. The US Army's AN/PVS 5A second generation night vision goggles (GEN II NVGs) maintained sensitivity to the visible wavelengths, and extended their sensitivity to the near infrared wavelengths. This meant that the second generation devices could not only "see" light whose amplitude was normally too low for our unaided eyes to perceive, but they could also "see" wavelengths to which our retinas were insensitive, and improve resolution above that given by first generation systems. Figure 2 shows relative spectral sensitivities of the human eye and GEN II NVGs. It also shows the relative amounts of radiant energy available at night.

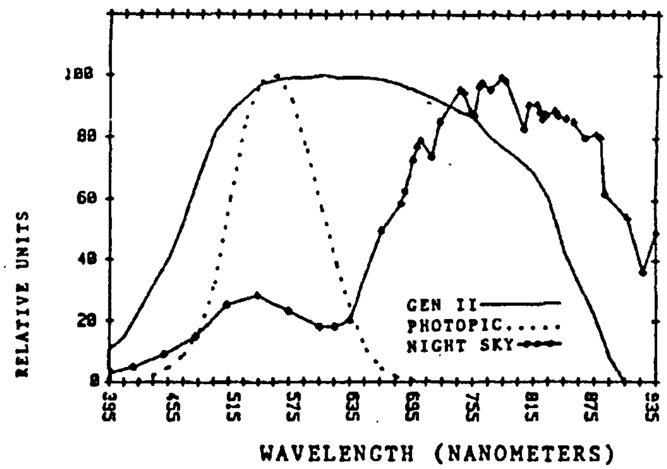

FIGURE 2
RELATIVE SPECTRAL SENSITIVITIES
OF EYE TO GEN II NVG

Scenes viewed through GEN II NVGs are perceived as shades of green because of the phosphor characteristics of the system. The output luminance of the NVGs is sufficient to activate the photopic visual system, but resolution is still limited by the NVGs rather than the eye. Typical visual acuities of individuals wearing operational units under typical night conditions range from 20/80 to 20/50. The unaided daytime visual acuities of these people are 20/20 or better. In addition, the instantaneous binocular field of view (BFOV) is limited to 40° rather than the 180° "unrestricted" field of view. Because of optical inconsistencies in the goggles, stereopsis (one component of depth perception) is poorer than expected for photopic vision, but equal to or better than that experienced with scotopic vision. Table 1 is a summary of various visual thresholds of the unaided eye and the visual system including NVGs.

Table 1

Comparison of Photopic, Scotopic, and NVG-Aided Vision

	Photopic System	Scotopic System	Eye + NVGs
Dynamic Range	10^{8} - 10 ML	1- 10^{-6} ML	10^{+8} - 10^{-8} ML
Receptor (Eye)	Cones	Rods	Rods & Cones
System Resolution	Better than 1 arc-min	10 arc-min	2-3 arc-min(NVG)
Spectral Sensitivity	350 - 700 NM	350 - 700 NM	AN/PVS-5: **** AN/PVS-6: ****
Max Spectral Sensitivity	555 NM	505 NM	AN/PVS-5: **** AN/PVS-6: ****
Perceived Spectral Output	Colors	Greys	Greens
Field of View	~ 180°	~ 180°	40°
Max Retinal Sensitivity	$0^{\circ} \pm 2.5^{\circ}$ (disc)	20°(annulus)	2.5° (disc)
Dark Adaptation Time (full)	10 minutes	30 minutes	Seconds
Dark Adaptation Time (flash)	Seconds	Seconds	Seconds
Dark Adaptation Time (failure)	-	-	Max 2 Minutes

AN/PVS 6 third-generation night vision goggles (GEN III NVGs) have reduced sensitivity to visible wavelengths, and greater sensitivity to longer wavelengths. The GEN III NVG output is also "brighter" than that of the GEN II, insuring the retina is adapted to a photopic level while viewing most scenes through the NVGs. Improvements in the optical system have also contributed to improvements in visual resolution while wearing the goggles, but considering wide variations in both the test method and the goggles themselves, best acuities appear to be in the range of 20/50 to 20/40. The field of view is still limited to 40°, and stereoacuity remains moderately good.

As we gained experience with NVGs in operational environments, several critical human engineering factors became apparent: cockpit (instrument, switch and display) lighting must be compatible with both the NVGs and the unaided eye if both are to be used to their fullest capability; the NVGs could be modified to improve field of view and display characteristics; refocussing from outside the cockpit to see instruments was a problem; new helmet mountings needed to be designed to better distribute the weight; and future NVG design must consider safety and ejection factors.

NVG COMPATIBLE LIGHTING

In order for NVGs to be most effective, the cockpit lighting must be optimized for the NVG's spectral sensitivity. Even low amounts of red and IR wavelengths generated within the cockpit can significantly reduce the goggles' sensitivity to the outside scene. Several vendors are now producing "NVG compatible" lights, even though there is no generally accepted measure of compatibility. The most promising products appear to be those that drastically reduce or eliminate emissions correspoinding to visible red and longer wavelengths, however the absence of red warning lamps may be of some concern to traditional cockpit lighting engineers.

Our definintion of "NVG compatibility" contains two general criteria: 1) the lights will not degrade vision through the NVGs for specified lighting positions or configurations, and 2) the lights will allow good vision of instruments or other objects for the unaided eye. We include not only instrument and panel lights in this definition, but CRT and other displays.

Many users found that normal incandescent sources which were used to provide in-cockpit illumination for the unaided eye would emit too much infrared energy, and cause the NVG to lose sensitivity to out-of-cockpit scenes (because of activation of the automatic gain control). Many filtering systems, electroluminescent lighting schemes, and light emitting diode schemes were investigated; all of which were intended to reduce the emitted IR energy, and maintain sensitivity of the goggles.

We have found it helpful to describe at least three categories of cockpit lighting configurations, and have begun to establish compatibility ratios for most "NVG compatible sources" for each condition. Category 1 includes lights in the direct field of view of the goggles, category 2 includes light reflected from the windscreen or other object into the goggles, and category 3 includes "light pollution" from other sources. When viewing outside scenes, lights which are almost always in the direct field of view of the NVGs should not be considered to have the same effect as light sources normally well out of the NVG field of view.

We have developed a preliminary Compatibility Ratio (CR) that takes into consideration properties of both the unaided eye and the NVGs. This Compatibility Ratio may be used for any lighting configuration, type or placement, and will predict the relative effects of various vendors' products on visual and NVG performance. Essentially, CR is the ratio of the photopic eye rerponse for a particular wavelength to the ANVIS sensitivity to the same wavelength.

Compatibility Ratio may be expressed mathematically as follows:

$$CR = \frac{\int_{400}^{700} V_\lambda \; N \; d_\lambda}{\int_{400}^{1000} G_R \; N \; d_\lambda}$$

Where:

V_λ = Relative photopic eye response for CIE 1931 standard observer

N = Relative spectral radiance for a particular light source (Watts/cm^2 Sr nm)

G_R = Relative ANVIS spectral response as measured or specified by manufacturer or JLC Ad Hoc Committee

Appropriate Compatibility Ratio limits are now being found by empirical determination for a subset of typical cockpit illuminators and categories. Spectroradiometric measurements of other illuminants will then allow ranking or compatibility comparisons of many cockpit lighting types and sources without the necessity of complex simulator devices. The CR will also provide suitable wavelength mixture information to lamp designers.

We are also in the process of defining spectral loci for acceptable NVG compatible cockpit lighting. Assuming the pilot will be able to see various instrument and cockpit indicator lights both with and without the NVGs, the problems of appropriate color coding, equality of hue and equality of luminance for either unaided or aided vision are added to the list of concerns for the illumination engineer. Care must be taken that warning and caution lights are sufficiently different from "normal" illuminants to avoid confusion. Historically, this has been accomplished via color coding the former lights red or yellow, but since these longer wavelengths are not compatible with NVG usage, the choice of spectral components is severely restricted.

NVGS AND VIDEO DISPLAYS

Initial tests indicate color video displays will have to be modified to reduce long wavelength emissions. Essentially, this means eliminating or significantly reducing the output of the red gun, with resultant degradation in visible color separation for the display graphics or symbology. In addition, displays using P-43 or similar phosphors will have to be filtered to reduce the normally tiny long wavelength "bump" on the emission curve. If this is not done, the display will cause the NVGs to lose sensitivity at brightness levels just barely sufficient for comfortable unaided vision.

One possible use of passive NVGs is in conjunction with active FLIR or other systems whose information is presented on a Heads Up Display (HUD). Since the HUD imagery is at optical infinity, refocussing the NVGs is eliminated. However, holographic or diffractive HUD combining glasses are tuned to reflect only the narrow green band of the P-43 phosphor. The imagery generated by these HUDs appears dimmer with AN/PVS 6 goggles than without! The reason for this apparent anomaly is the presence of a minus-blue objective lens coating, which prevents much of the green band from entering the NVGs.

DEPTH OF FOCUS PROBLEMS AND SOLUTIONS

The normal eye can accommodate or focus on objects at different optical distances. When we fixate on distant objects, near objects are blurred. When we change focus to the near object, the distant target is blurred. The range of distances over which we can see clearly without refocussing is called the "depth of focus" or "depth of field". Refocussing is accomplished by the action of the ciliary muscles in each of our eyes, changing the shape of the crystalline lens.

When properly adjusted, the ocular lenses of the night vision goggles place the image of the scene near optical infinity for the wearer's eyes. The NVG's objective lenses are then adjusted to focus on the object of regard. Because of their small f-number, there is very little depth of focus for NVGs. If a pilot had his system focussed for out-of-cockpit viewing, he would be unable to clearly see legends or instruments within the cockpit without manually refocussing each tube. After reading his instruments, he must then refocus for clear distance viewing.

The AN/PVS 6 goggles were provided with an Aviator's Night VIsion System (ANVIS) mount, which allowed the pilot to look under the tubes to see his instruments. This feature attempted to eliminate the refocussing problem encountered with the AN/PVS 5 mounts, which were designed for ground use. Unfortunately, the ANVIS mount moved the center of gravity of the goggles farther from the head, and emphasized the problem of maintaining lighting compatibility for both the goggles and the unaided eyes at the same time. In addition, when the pilot wanted to see instruments near the top of his glare shield, the pilot needed to move his head in an uncomfortable manner to move the goggle tubes out of his field of view. Several other NVG manufacturers produced different systems to reduce the near vision problem, such as the Marconi Cats Eye, and the FJW Industries See-Through Night Vision Goggle (SNVS).

Another answer to the refocusing problem is addressed by shared-aperture optics. The concept of shared-aperture optics is similar to that of pinhole optics, in which light is imaged on a surface without the use of lenses. The shared-aperture concept is similar in that the objective lenses of the NVGs are coated with a minus-blue filter, effectively blocking short visible wavelengths of light. If cockpit lights are filtered or otherwise caused to emit only short wavelengths, these lights will not be seen when looking through the goggles. Now envision a small aperture, similar to that in a pinhole camera, in the minus blue coating. The relatively high energy, short-wavelength instrument light can pass through this aperture, and form a clear image in the NVGs. The large area around the aperture acts as a relatively low f-number optical system to the outside scene, which is rich in long wavelengths. With appropriate shared apertures, and with the system focussed for infinity, the pilot can see both the outside world and his instruments with relatively normal head and eye motions. Figure 4 diagrams the optical concept of shared apertures, which can be incorporated into present AN/PVS systems.

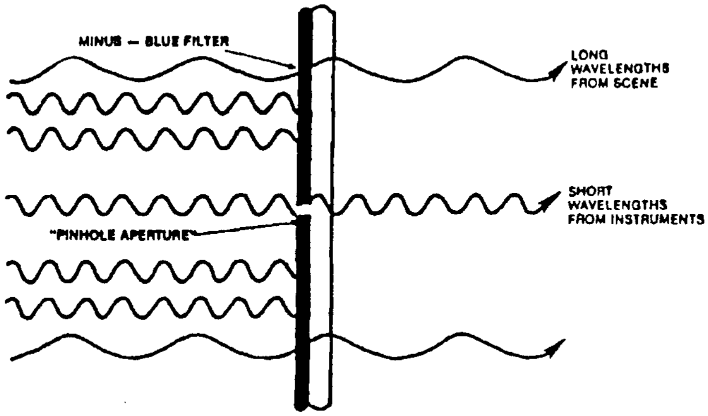

FIGURE 4
OPTICAL CONCEPTS OF SHARED APERTURES

One disadvantage of shared aperture optics is the critical selection of wavelengths suitable for in-cockpit illumination. These wavelengths must be almost totally blocked by the filter coating on the objective lens, thus significantly reducing the number of available illuminant choices.

FIXATION POINT PROBLEMS AND SOLUTION

Unfortunately, with any of the above methods of allowing vision of both the exterior scene and cockpit instrumentation, the pilot is still required to change his visual point of regard from outside to inside views; requiring changes in accommodation (for conventional aperture systems), light adaptation, and fixation posture. While his visual system is busy with one scene, important changes could be taking place in the other. Since NVGs are typically used at very low altitudes, normal aircraft velocities cause high rates of approach, and concurrent rapid changes in visual scene, which may degrade safety.

Scientists at AFAMRL approached the problem of seeing both the outside scene and instrument display by electronically and optically injecting critical flight instrument readings into the optical path of the NVGs. Now, the pilot need adjust his NVG's focus only once -- for distant viewing, and the flight data would also be seen near optical infinity, in the same field of regard as the outside scene. In effect, we created a Heads Up Display (HUD) for the NVGs, so we named it the AFAMRL NVG HUD.

Before using the NVG HUD, the visual duties of crew members of night flying aircraft were partitioned -- some tasked to look outside and others tasked to look only at instruments of various types. The pilot was to look outside the cockpit, while the co-pilot was to look at the critical instruments. Both the radar operator and copilot reported to the pilot verbally over the intercom. All crew members who were to look outside the cockpit wore night vision goggles, and the cockpit lighting was suitably modified to least interfere with the NVGs.

Since the development of the AFAMRL NVG HUD, the visual tasks of the crew can be partitioned in a more normal (i.e. more similar to daylight flying) fashion. The pilot's visual abilities are actually enhanced in that he can now see both the outside scene and flight data at the same time, without refocusing either his eyes or the NVGs. In fact, he need not change his visual regard from any exterior scene of interest; his flight data are projected to appear near the point at which he is looking.

The aircraft for which the NVG HUD was originally designed were not equipped with conventional HUDs, but displayed information on both video displays and round-dial instruments located on a conventional instrument panel. AFAMRL engineers were able to sample data on the computer bus serving the instruments, and use these data to generate a display on a small CRT. Several interactive studies were performed by AFAMRL and MAC to determine the optimum display format and symbology to effectively portray data values.

The CRT display was then coupled to a coherent fiber optics bundle, which was passed to the pilot's helmet. The output of the bundle was collimated and reflected from a beamsplitter or combining glass mounted on the NVG barrel, into the optical path of the

NVGs. In this fashion, the wearer of the NVGs could see the outside scene with both eyes, and the flight data image with one eye.

The brightness of the displayed data can be dimmed by the pilot, so he can "look through" the graphics at the outside scene, using binocular vision. As the need for critical flight data increases, he can increase the relative brightness of the graphics, so he can easily perceive the data with one eye. Since the other eye continually maintains a view of the out-of-cockpit scene, the visual system superimposes the imagery created on the face of the CRT over the outside scene. Since there is a great difference in appearance of the images, there is no retinal rivalry effect, and both the outside scene and the flight data are seen constantly. There have been no reports of the Pulfrich phenomenon while using the system, and no unusual lighting compatibility criteria need be addressed.

FIELD OF VIEW IMPROVEMENTS

Both the AN/PVS 5 and AN/PVS 6 NVGs restrict the wearer's instantaneous binocular field of view to a 40° circle. In order to carry on any visual search pattern, NVG wearers must increase the amount of head and neck motion to cover the same area previously covered by relatively simple eye movements alone. This increased head movement, combined with the weight distribution of the NVGs contributes greatly to neck muscle fatigue. Optically increasing the field of view of the NVGs results in a reduction of resolution. The pilot might see more in his instantaneous field of view, but what he does see will be less distinct.

One possible method of improving the horizontal field of view is "toeing-in" the NVG tubes. Since the NVGs have a magnification factor of 1, moving the tubes from their parallel position will have no effect on the positions of the eyes' lines of sight. Some time ago, AFAMRL produced a prototype NVG arrangement with the tubes "toed-in" 10° each. The result was an instantaneous field of view of 60°, consisting of a binocular overlapping field of view of 20°, and two monocular fields of view, each of 20° (See figure 5). All images in the instantaneous field of view maintain their correct relationships to all other images, and many pilots who tried the goggles were unaware of the presence of two monocular fields until told to alternate closing their eyes. The toe-in concept is not a new one ... it was patented in the US several years ago and is also demonstrated with Marconi's Cats Eye NVGs.

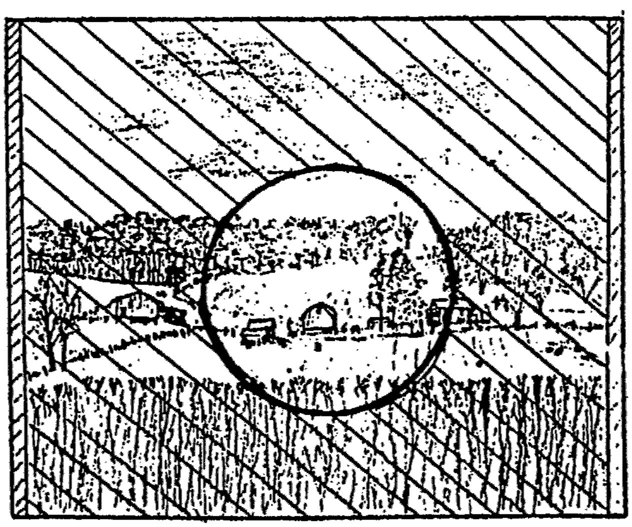

FIGURE 5A
CURRENT 40° FOV

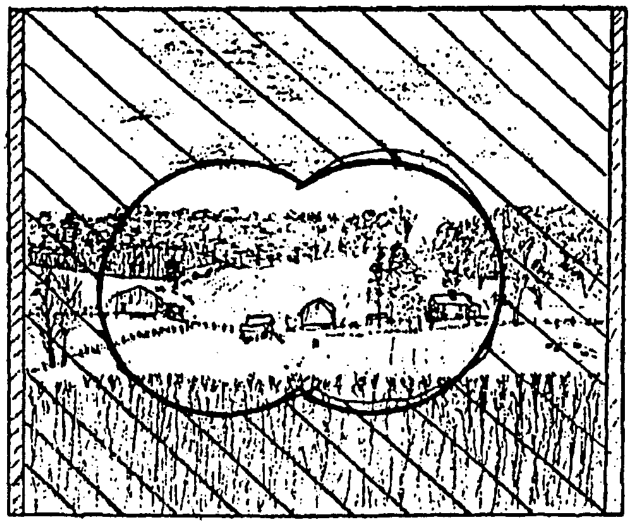

FIGURE 5B
AMRL MODIFIED FOV

FUTURE CONCEPTS

As display technology improves, and computer enhanced imagery matures, it is possible that the pilot of the future need not depend soley on his unaided vision while flying at night or under conditions of poor visibility. We see the early stages of new visual applications in the acceptance of NVGs, HUDs and FLIRs. The concept of providing enhanced imagery to the pilot is not new, but the methods to do this are rapidly evolving. AFAMRL is at the forefront of this technology with its state of the art Visually Coupled Airbourne Systems Simulator (VCASS), which allows the pilot to take advantage of new sensor technology by displaying various imagery on his helmet visor. Systems control, sensor pointing and device switching are performed with normal head and eye movements, providing a wide binocular field of view, with computer enhanced imagery, color and symbology. Artificially induced stereo cues add a new dimension to spatial sense.

The use of night vision enhancement devices appears to be growing in acceptance. Performance with these devices will be further aided by assuring appropriate human engineering factors are considered both in their design and application. It is not necessary to wait for next-generation improvements to become available in order to have an effective night vision system useable by aircraft pilots. NVG modifications and ancillary devices made and planned by AFAMRL and other organizations can be applied to today's second and third generation products.

Simons, J. C., Unger, S. E. & Craig, J. L. (1985). *Night vision goggle head-up display for fixed-wing and rotary-wing special operations.* (Report No. AAMRL-TR-85-044). Wright-Patterson AFB, OH: Armstrong Aerospace Medical Research Laboratory.

AAMRL-TR-85-044

NIGHT VISION GOGGLE HEAD-UP DISPLAY FOR FIXED-WING AND ROTARY-WING SPECIAL OPERATIONS

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This report describes the development and evaluation of night vision goggles (NVGs) modified with head-up display (HUD) symbols for flying night, visual flight rule (VFR), low level operations. The NVG/HUD combines NVG compatible symbols on a monocular presentation with a binocular view of an infrared scene. The Harry G. Armstrong Aerospace Medical Research Laboratory (AAMRL) sponsored the development program for special Military Airlift Command (MAC) operations using fixed- and rotary-wing aircraft.

NVG/HUDs were used by 30 pilots flying eight models of jet and turboprop cargo aircraft and conventional helicopters in night sorties. Questionnaires and interviews were used to guide design changes, suggest training requirements, and assess pilot acceptance. No system performance data were recorded; however, the pilots rated the adequacy of each display symbol (e.g., airspeed, altitude) and its implementation (e.g., size, location, movement) for flying low level operations.

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NIGHT VISION GOGGLE HEAD-UP DISPLAY FOR
FIXED-WING AND ROTARY-WING SPECIAL OPERATIONS

12. (continued)

Simons, John C., Unger, Sheldon, Craig, Jeffrey L.*

16. (continued)

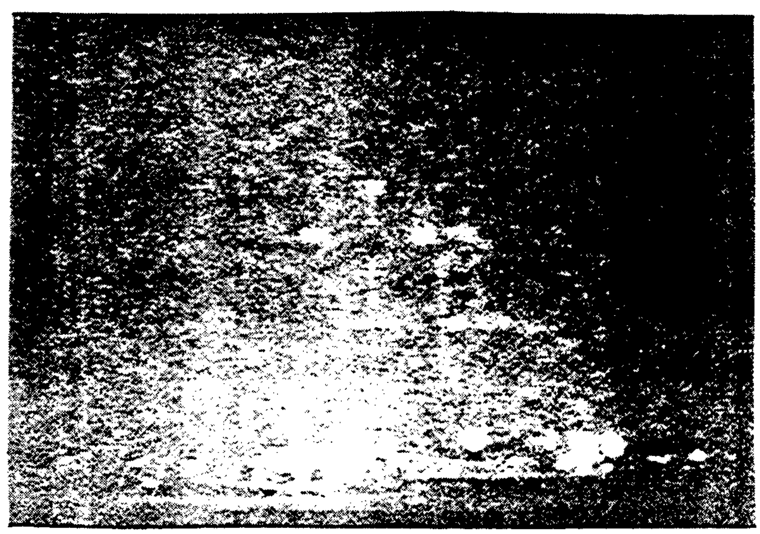
*Harry G. Armstrong Aerospace Medical Research Laboratory

19. (continued)

The system was rated as an absolute requirement by the majority of pilots for most of the missions with minor changes in symbol selection and characteristics. They recommended the 14-degree Instant Field-of-View (IFOV) be expanded within 40-degree IFOV of the NVG goggle and an increase in size for many symbols. Recommendations for cockpit controls, training, and future studies are also reported.

NVG/HUD

NVG/HUD Scene



PREFACE

This report describes the development, evaluation, and application of night vision goggles (NVG) modified with head-up display (HUD) symbols. The NVG/HUD system was designed for flying night, visual flight rule (VFR), low level operations. The results proved to be generalizable to a variety of aircraft and missions. The report was prepared in part by Systems Research Laboratories, Inc. (SRL), 2800 Indian Ripple Road, Dayton, Ohio 45440, under Contract F33615-82-C-0511. The work was performed in support of the Harry G. Armstrong Aerospace Medical Research Laboratory (AAMRL), Project 7184-12-15, Lighting and Light Control, under the direction of Mr. Jeffrey L. Craig for the Human Engineering Division (HE), Wright-Patterson Air Force Base, Ohio 45433.

The authors gratefully acknowledge the contributions of Dr. Harry Lee Task who designed and developed the NVG/HUD display, the assistance of Mr. David Lambertson who designed and reported the aircraft instrumentation interfaces, and to Ms. Carla Reese (SRL) who tabulated the pilot questionnaire responses.

Special acknowledgements are made to the following MAC personnel who coordinated the field and flight test trials:

Capt. Doyle Walker, Airlift Center, Pope Air Force Base, NC
Maj. Terry Silvester, SMOTEC, Hurlburt Field, FL
Maj. Richard Runyon, SMOTEC, Hurlburt Field, FL

Section 1
INTRODUCTION

This report documents the development, evaluation, and application of night vision goggles (NVGs) modified with head-up display (HUD) symbols for flying night, visual flight rule (VFR), low level operations. The NVG/HUD combines NVG compatible symbols, infinitely collimated for a monocular presentation, and a binocular view of an infrared scene. The Harry G. Armstrong Aerospace Medical Research Laboratory (AAMRL) conducted the evaluation program for special Military Airlift Command (MAC) operations.

The NVG/HUD was used by 30 pilots flying eight models of jet and turboprop cargo aircraft and conventional helicopters in night sorties. Questionnaires and interviews were used to guide design changes, suggest training requirements, and assess pilot acceptance of the NVG/HUD device.

This section includes a brief description of requirements for development of the NVG and NVG/HUD for night, low level operations. The approach for qualifying the NVG/HUD in successive aircraft is described, a background discussion of NVG state of the art is presented, and a list of test objectives is included. Section 2 includes the critical mission factors for all of the aircraft. (Unless noted otherwise, the term "aircraft" includes fixed-wing and rotary-wing aircraft.) Descriptions of NVG/HUD equipment, crew experience, and the development of the evaluation questionnaires are also highlighted. Section 3 summarizes the results of the in-flight tests. Section 4 presents the final display/control configurations, suggested training requirements, and recommendations for NVG/HUD applications.

Appendices include descriptions of the NVG/HUD demonstration device used in this study and the questionnaires and their responses used to evaluate the device.

BACKGROUND

Godfrey (1982) describes the development and use of NVGs in military crewstations:

NVGs have now attained a level of sophistication such that aircraft can be safely and comfortably flown using these devices. NVGs operate by amplifying reflected low intensity visible and near infrared (invisible) light. The goggles most commonly referred to are AN/PVS-5 (Generation II) and ANVIS (Generation III) (Aviators Night Vision Imaging System). Generation II goggles can be helmet-mounted but are rather heavy and awkward. The user must see everything through them including cockpit instrumentation. The Generation II produces a bright target image at light levels as low as quarter moon illumination. The latest NVGs (Generation III) are helmet-mounted, lightweight, and well balanced so that the person wearing them can operate unhindered. The design permits use of the goggles to produce a clear green picture of the world around, while at the same time permitting use of the naked eye to look under the goggles and read instrumentation or other information. Generation III NVGs produce a bright target image at light levels as low as starlight illumination.

As with any new technology introduced into areas as complex as an aircraft crewstation, there are a number of problems which must be resolved. The most significant problem is the light which is enhanced to produce a picture of the outside world. The wavelength of this light is between 600 to 900 nanometers. This means that incandescent lamps or any other light whose wavelength is longer than approximately 525 nanometers (green light output) will also be amplified and interfere with the image of the outside scene. Yellows, reds, and infrared either "blind" the goggles or cause them to protectively shut down much as the unaided eye adapts to very bright light.

The response of the goggles used in this study are shown in Figure 1.

APPROACH

AAMRL approached the problem of flying very low levels, at night, by providing HUD symbols on a combining glass over one of the goggle eyepieces. The concept was to provide sufficient position and attitude information to allow an "eyes-out" orientation during special operations. Several modes of mission-oriented symbols were included as pilot options.

As shown in Figure 2, the AAMRL concept was to generate symbols based on digitized data from aircraft sensors, display the symbols on a CRT, and then focus the CRT image on a 400 x 400 element, fiber optic cable. The cable transmitted the image to a combining glass positioned in front of a single

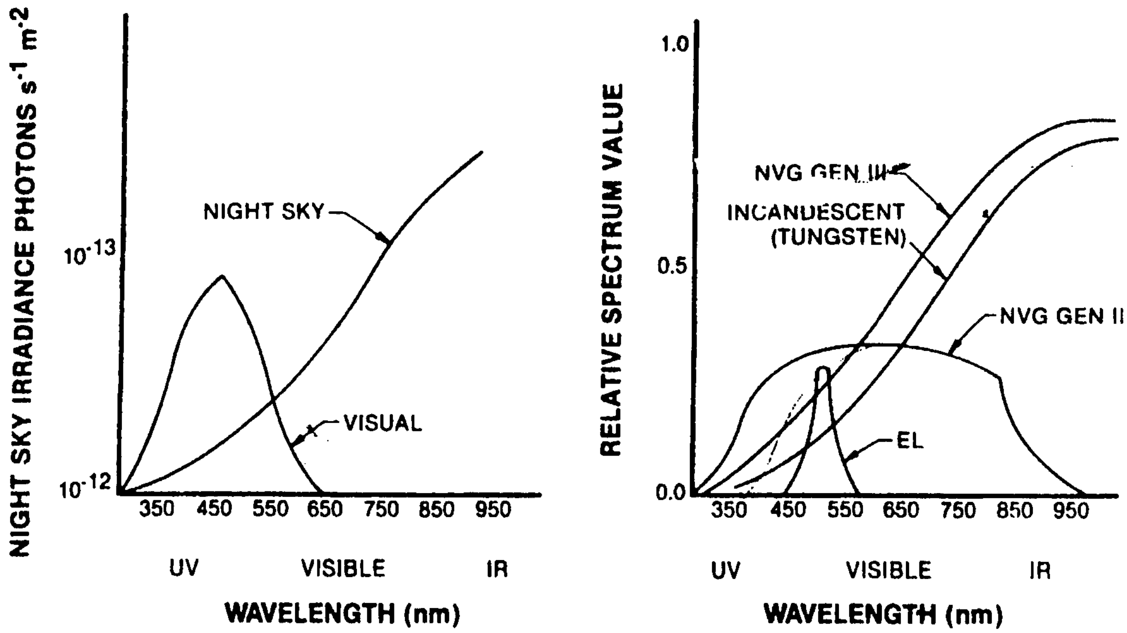


Figure 1. Response of Night Vision Goggles

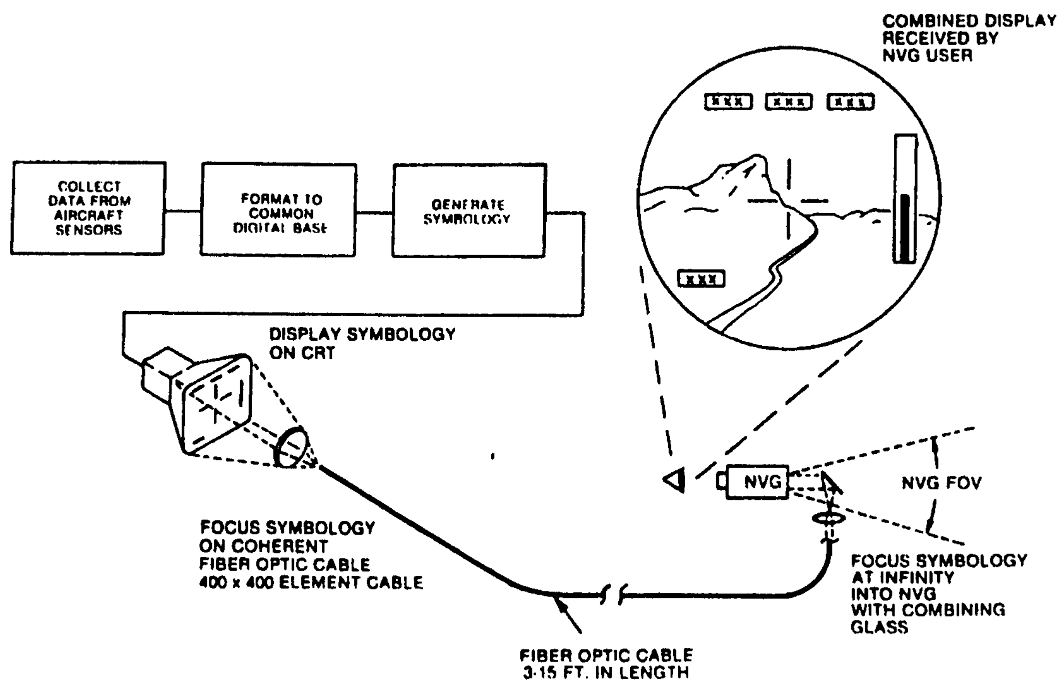


Figure 2. NVG/HUD Concept

NVG lens. The pilot's eye saw the symbols collimated at infinity, and within a wider field-of-view of an infrared image of the real world.

The overall approach was to select a feasible set of military standard HUD symbols and use actual OT&E flight experience with a demonstration device to obtain user modification requirements and acceptance information. For each aircraft test, pretest discussions were held with MAC personnel to derive a symbol set and control panel that appeared to satisfy the aircraft's mission requirements.

HQ MAC authorized the Operational Feasibility Test and Evaluation (OFT&E) of the NVG/HUD based on successful trials in preliminary C-141B flights:

> Operational incidents have highlighted the need to enhance the safety of night special operations missions. At HQ MAC/XPQ request, the AAMRL developed a HUD system for C-141B aircraft that is compatible with NVG use... The C-141B test results verified the usefulness and potential of the system to enhance C-141B special operations missions. (MAC Project Plan 15-84-84)

Over a 1-year period, MAC directed that NVG/HUDs be flown on the following aircraft:

C-141B	C-130E (AWADS)	HH-53H (PAVE LOW)
	MC-130E (TALON)	HH-53B/C (SLICK)
	AC-130 (GUNSHIP)	UH-60A (BLACKHAWK)
	HC-130P	

The AC-130 data were not available for this report and may be requested from AAMRL. The fixed-wing and rotary-wing aircraft used filtered incandescent, filtered electroluminescent (EL), and blue cockpit lights with blue secondary lights to achieve NVG use compatibility.

The test objectives listed in Table 1 were obtained from MAC test directives and personnel and included requirements for detailing hardware, software, training, and operational procedures. A special objective addressed the possible effects of levels of lunar (moon) illumination on NVG adequacy.

TABLE 1. TEST OBJECTIVES

- Determine usefulness and potential to enhance special operations.
- Develop symbols, symbol format for each aircraft (or mission mode when appropriate). Minimize the number of symbols, modes, and controls without compromising crew safety or adding to crew workload.
- Assess effects of night illumination.
- Develop control requirements.
- Determine compatibility with current mission equipment.
- Develop operational procedures.
- Quantify training requirements.

Section 2
METHOD

This section summarizes the mission planning factors, the NVG/HUD equipment, the experience levels of the crews, and the development of the questionnaires used for subjective ratings on system performance.

MISSION PLANNING FACTORS

The mission planning factors that affected NVGs during special low level flight usage are listed in Table 2.

TABLE 2. MISSION PLANNING FACTORS

	Factors		
Aircraft	Altitude (feet)	Airspeed (knots)*	Sortie Duration (hours)**
C-141B	500-1000	230-300	4
C-130E	500-1000	210-220	6-7
MC-130E	500-1000	210-220	6
AC-130H	6000	190-200	5
HC-130P	500-1000	210-220	5
HH-53H	50-500	60-130	4
HH-53B/C	50-500	60-130	4
UH-60A	50-500	60-150	2

SPECIAL MISSION REQUIREMENTS

- Air Drops
- Blackout Landings*
- Hover Operations
- Aerial Refueling
- Full Moon to No Moon Conditions
- 3000-Foot Ceiling, 3 nm Visibility Minimums
- Covert Operations, Operating With Minimum Number of Internal and External Lights Set at Lowest Intensities

*Excludes hover airspeeds.
**Excludes in-flight refueled sorties.

NVG/HUD EQUIPMENT

The equipment configuration designed for the flight demonstration is shown in Figure 3 and is described in more detail in Appendix A. The symbols used for each aircraft evaluation are shown in the questionnaires (Appendix B) and drawings of the final symbol sets proposed for fixed-wing and rotary-wing aircraft are shown in Figures 20, 21, 22, and 23.

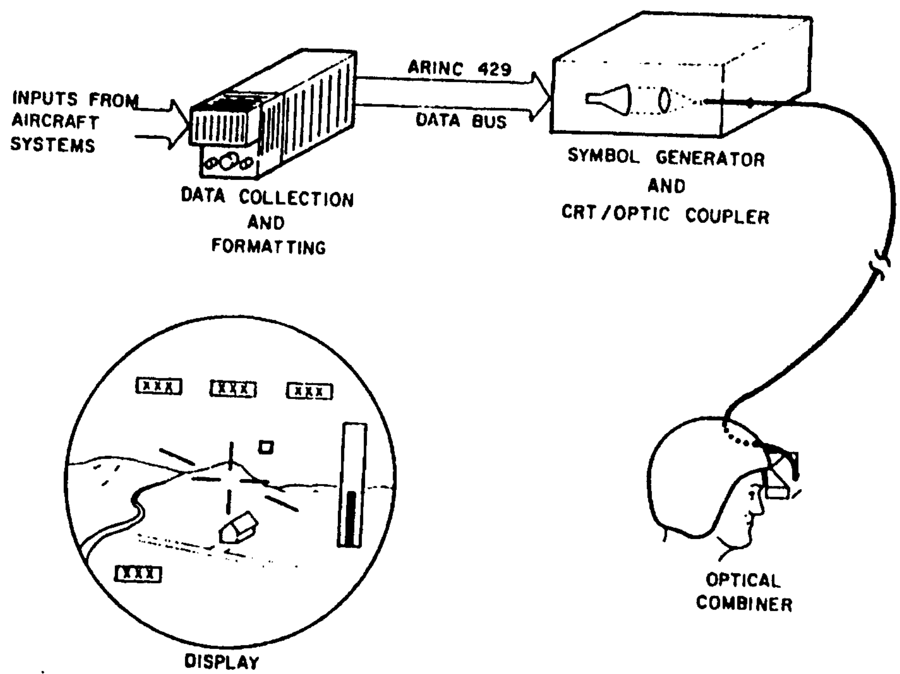


Figure 3. NVG/HUD Configuration

The flight instrument raw signal information was collected by the aircraft's signal processing computer, converted into Arinc 429 formatted data, and transmitted to the display. The display unit converted the data to a symbolic display on a cathode-ray tube format. The symbology display was reflected from a front surface mirror to a relay lens which focused the image onto a flexible fiber optic bundle. The bundle transmitted the image to the NVG where a collimating lens moved the symbol image to optical infinity. This image was then reflected from a beam splitter into the NVGs. The observer viewed the image of the HUD symbols superimposed over the outside view.

Several modes of mission oriented information were included as pilot options. Figures 4 and 5 shows the HUD symbols selected for the transport and helicopter flights. Generally, for modes such as SEARCH and LANDING, the number of symbols was reduced to avoid cluttering the center of the IR image when the pilot is concentrating on ground patterns and landmarks.

Some examples of special features of the symbology are listed in Table 3 and were varied for several of the aircraft.

The final control panel used by the pilots is shown in Figure 6. The panels were positioned at various cockpit locations, depending on the type of aircraft. A design goal was to include only critical pilot control functions and automate other functions (e.g., focus, contrast).

CREW EXPERIENCE

Table 4 summarizes the flight experience level of the pilots used in the study. The data are incomplete because of incompleted questionnaires.

The number of pilots fully qualified in several MAC special operations units is very small. For example, the six C-141B aircraft commanders (ACs) listed in Table 4 represented the majority of the total C-141B ACs qualified for this mission. In general, the pilot population was highly experienced in total flight time, time in the aircraft, and (except for combat) time with the mission.

QUESTIONNAIRES

The same MAC questionnaire (Appendix B) was used to obtain pilot experience and comments on mission adequacy and training requirements. Several AAMRL developed questionnaires (Appendix B) were used to obtain five-point ratings and comments on symbols, symbol characteristics, symbol modes and controls, and was tailored, where appropriate, for each aircraft. [For this report, the term "mode" means the display of a symbol set for a portion of a mission (e.g., enroute mode, landing mode)]. The results from the questionnaires

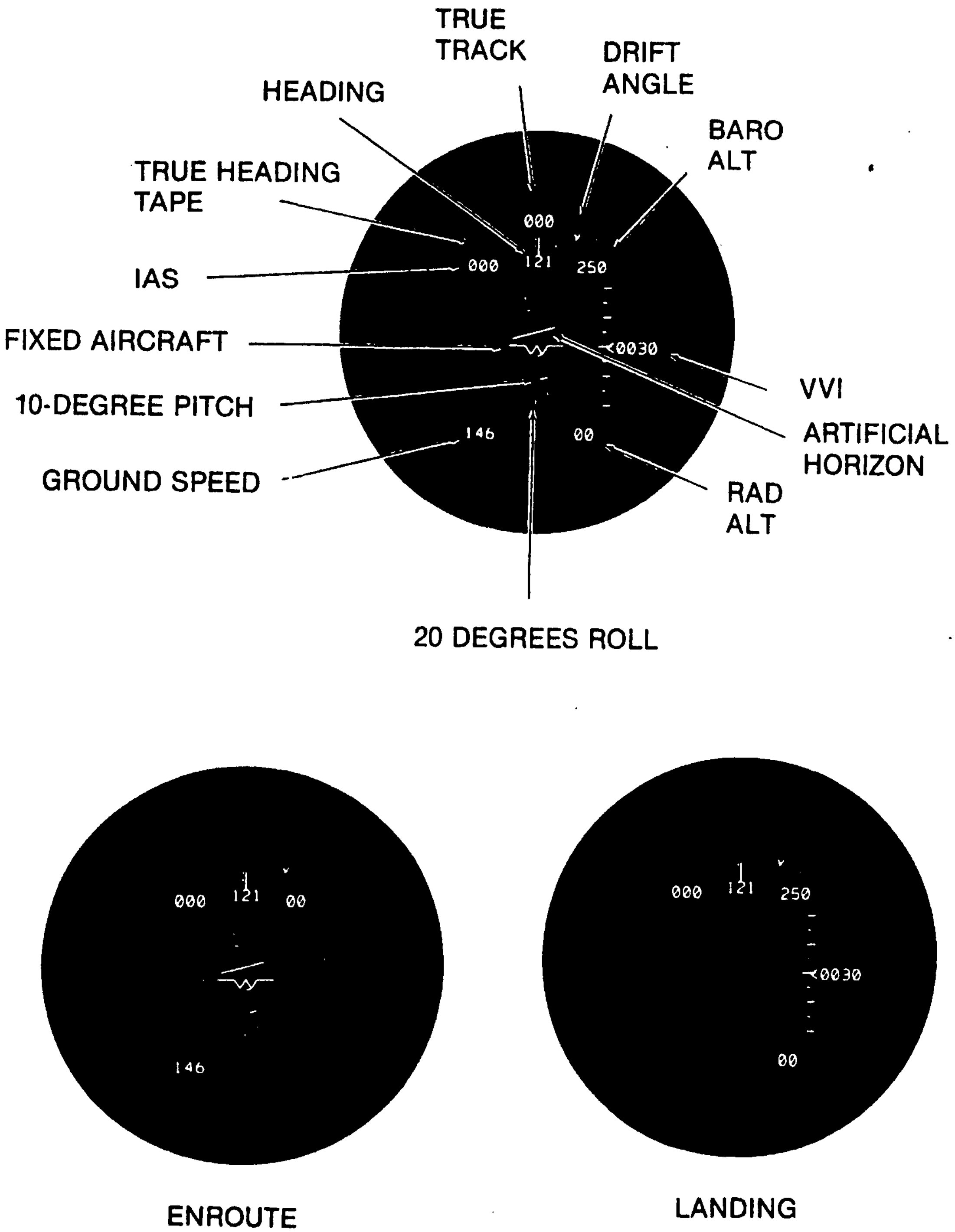


Figure 4. HUD Symbols Used for Fixed-Wing Flights

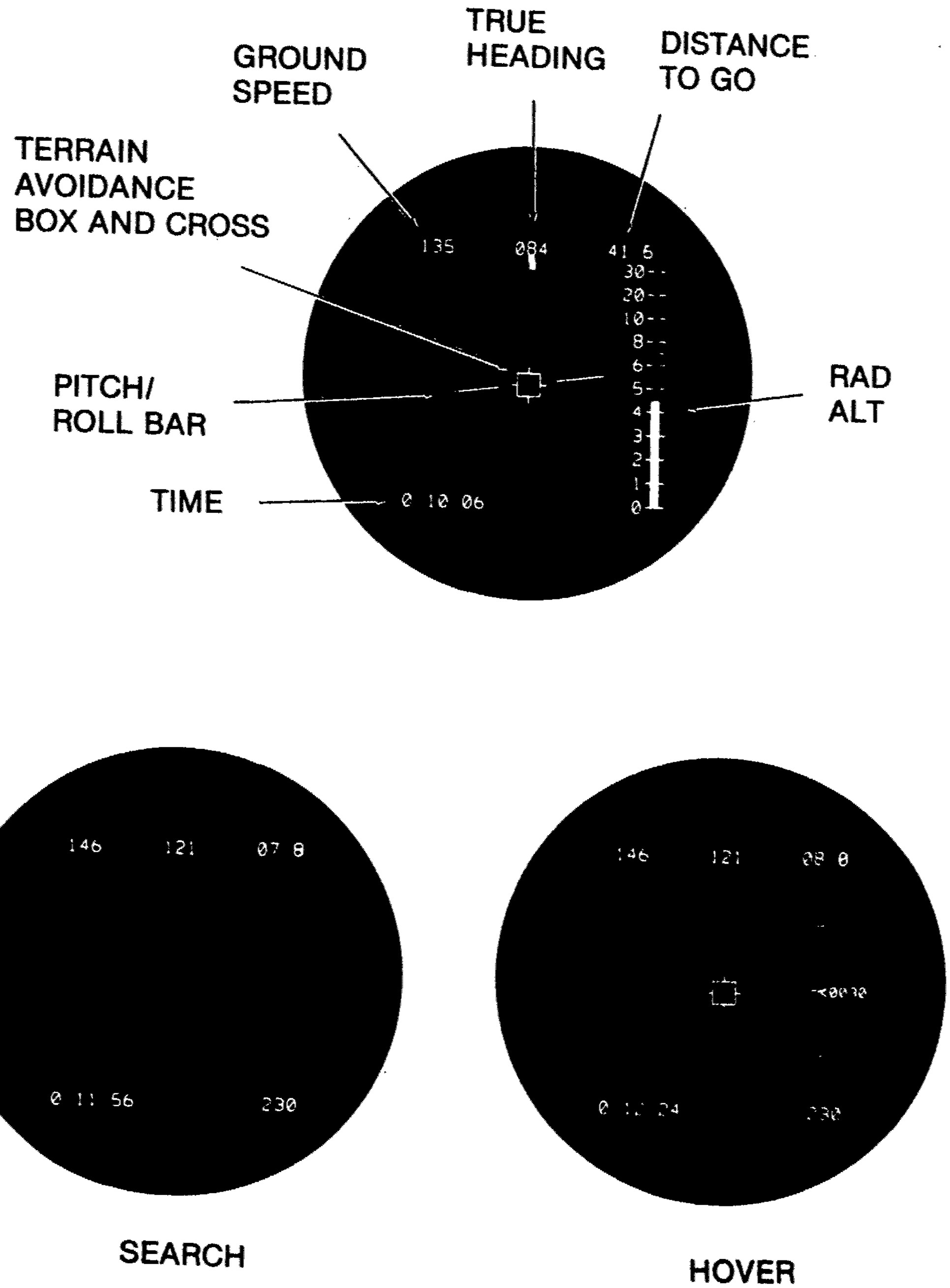
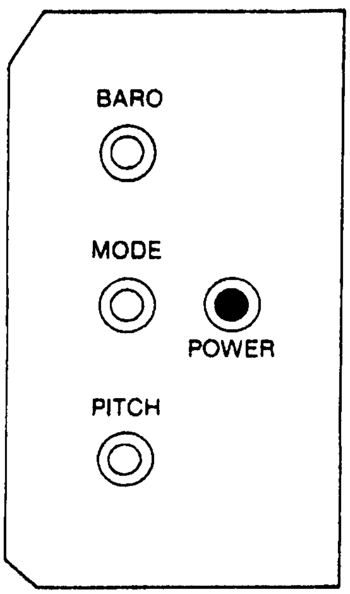


Figure 5. HUD Symbols Used for Rotary-Wing Flights

TABLE 3. SPECIAL SYMBOL FEATURES

Altitude	Displays barometric or radar altitude, radar changes in 10-foot increments below 1000 feet, 100-foot increments above 1000 feet.
Fixed Digit	The last zero for altitude and vertical velocity is an unchanging zero (0) to reduce distraction of a fast changing digit.
Pitch	Over 10 degrees of pitch, a 10's digit is displayed to the left of the aircraft and 1's unit to the right.



4 PUSHBUTTONS

BARO - Selects barometric pressure

MODE - Selects symbol set for mission segment

POWER - Turns HUD equipment ON

PITCH - Trims the aircraft symbol to horizon bar for pitch reference

1 RHEOSTAT (not shown, mounted on helmet)

BRIGHTNESS - Changes symbol brightness

Figure 6. NVG/HUD Controls

are presented in Table 4 (Pilot Experience), for each type of aircraft in Section 3 (Results), and in greater detail in Appendix C.

TABLE 4. PILOT EXPERIENCE

	C-141B	C-130E	MC-130E	AC-130	HC-130P	HH-53H	HH-53B/C	UH-60A
Number of Pilots	6	5	7	1	2	5	2	2
Crew Positions								
FEAC		2				1		
IP		2	2			1		
Pilot		1	3			3		
Total Flight Hrs (mn)*		2350	1866		950			
Months NVG Qualified (mn)			20					
**SOLL II Flight Hrs (mn)		250						
Months SOLL II Qualified (mn)		21						

* (mn = average mean)

**Special Operations Low Level II includes the use of NVGs for night airdrops and landings under blackout conditions.

Section 3
RESULTS

This section summarizes the pilots' comments on the NVG/HUD system and their recommendations for system modifications and procedures for operating the equipment. The data are presented as average ratings (mean = sum of ratings/n of respondents) individually for each aircraft, in the order the aircraft were flown.

For purposes of brevity, the crew's comments on symbol characteristics have been summarized in Figure 9. Additional pilot ratings and comments have been included in Appendix C. The crew's terms for symbols (e.g., heading, track, and mag heading) were retained for the report.

Generally, the fixed-wing and rotary-wing pilots use NVGs to maintain an outside scan while the copilots scan inside and ensure the integrity of aircraft velocity and attitude. Navigators and third pilots may share inside and outside vigilance duties in fixed-wing aircraft and verbally provide critical airspeed, altitude, and range values to the pilot.

C-141B FLIGHTS

The four-engine C-141B heavy jet transport flies Special Operations Low Level II (SOLL II) missions that include night, blacked-out airdrops or landings, and takeoffs from remote fields with three pilots, two of them wearing NVGs.

The fixed-wing questionnaire (Appendix B) was used to obtain the pilot ratings shown in Figure 7.

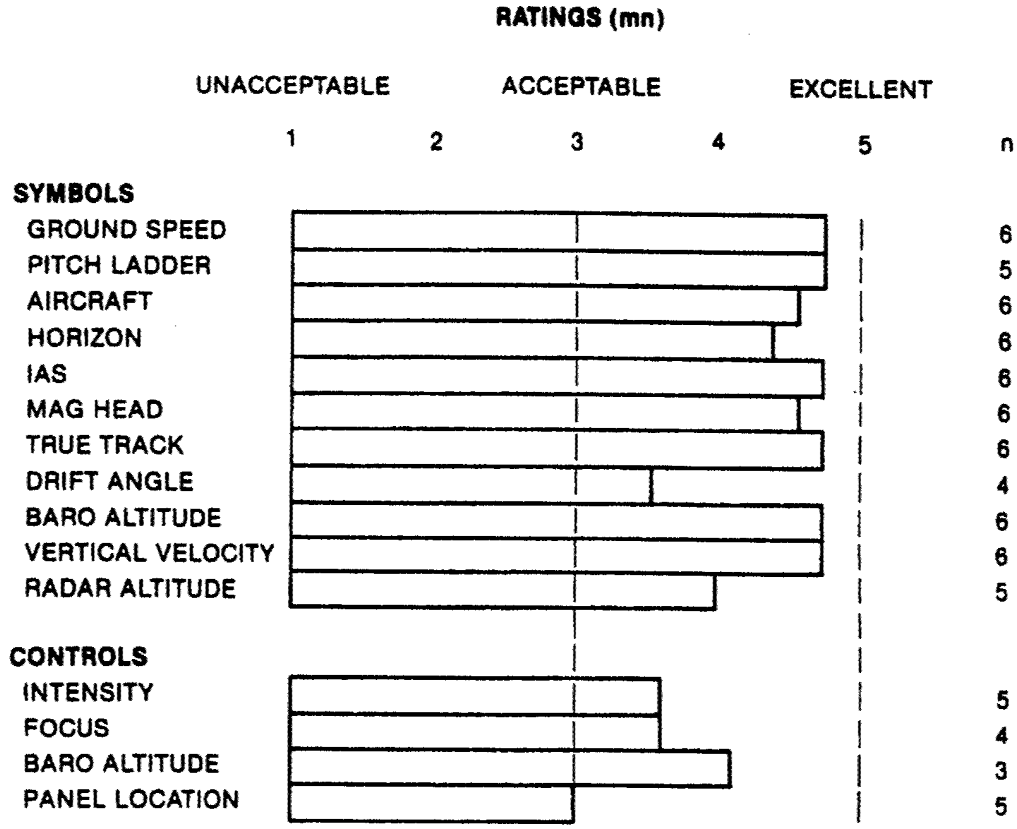


Figure 7. C-141B Pilot Ratings of Symbols and Controls (Total n=6)

Using the five-point rating scale, the HUD symbols were rated as being between "more acceptable" and "excellent" except for the drift angle symbol. The three system controls (to adjust intensity and focus and to reset the barometric altimeter) were rated as more than acceptable. The location of the control panel was rated acceptable; however, its relocation was also recommended. Visual fatigue was rated as below average to none and display contrast as being adequate for most night sky conditions under various levels of illumination. In terms of the system's contribution to mission success, the pilots generally agreed that the NVG/HUD enhanced control of the aircraft, reduced interphone communication and increased flight safety (terrain clearance).

C-130E FLIGHTS

The C-130E is an extended range version of the C-130B with large underwing fuel tanks and is equipped with an Adverse Weather Aerial Delivery System (AWADS).

In addition to ratings on symbols and controls, ratings were obtained on symbol sets for three mission modes for the rest of the aircraft in this report. Figure 8 presents the ratings of adequacy of NVG/HUD symbols and controls and Figure 9 presents the ratings on mode symbols.

Four pilots rated the drift angle symbol as acceptable but did not use it and recommended deleting it in the operational system. The aircraft symbol size was considered too small to be seen separate from the horizon symbol and preferred a new shape (or) that was closer to the ADI symbol. The vertical velocity symbol was rated as desired but its movements during the flight were erratic and unreliable. For the standard and enroute modes, the sky pointer was considered superfluous, and IAS was recommended to replace TAS. Critique of the landing mode included comments on deleting the mode, replacing it with the normal mode, and deleting mag heading and the lubber line. Two pilots recommended enlarging the symbol area ("doubling it") for easing readablilty. Control panel location in the cockpit was considered acceptable; however, one pilot suggested moving it to the forward end of the pilot's left control panel. All of the controls were rated near excellent, and one pilot recommended moving the mode pushbutton to the top of the panel because it is the most used control.

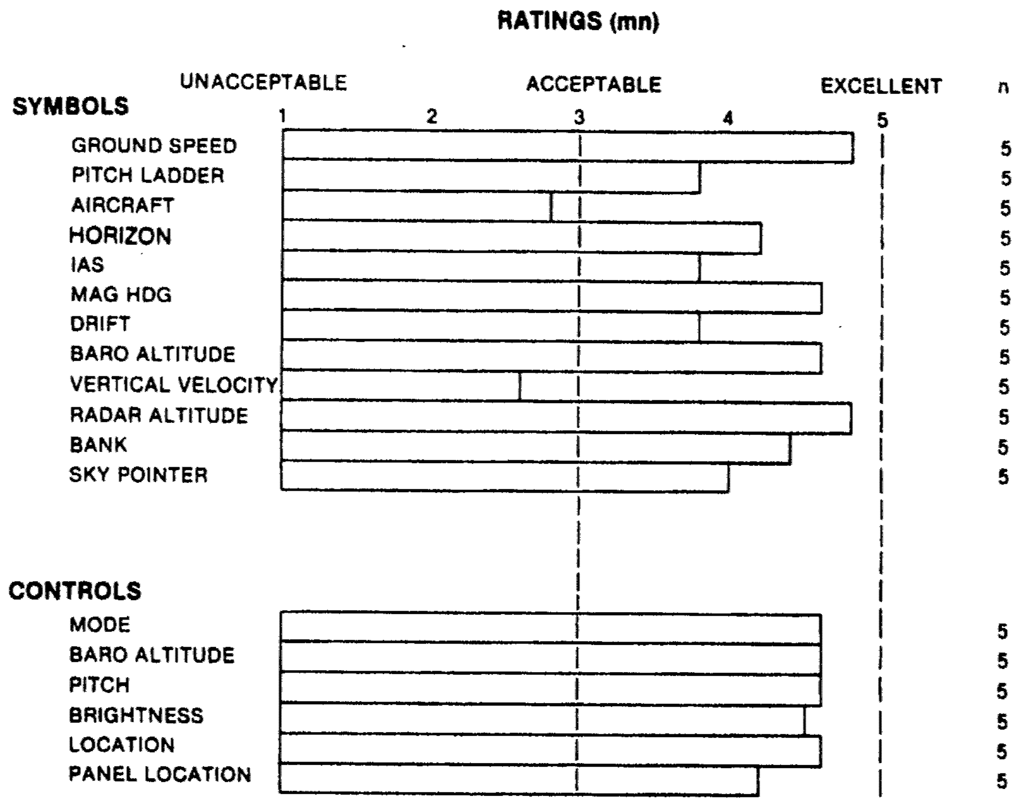


Figure 8. C-130E Pilot Ratings of Symbols and Controls (Total n=5)

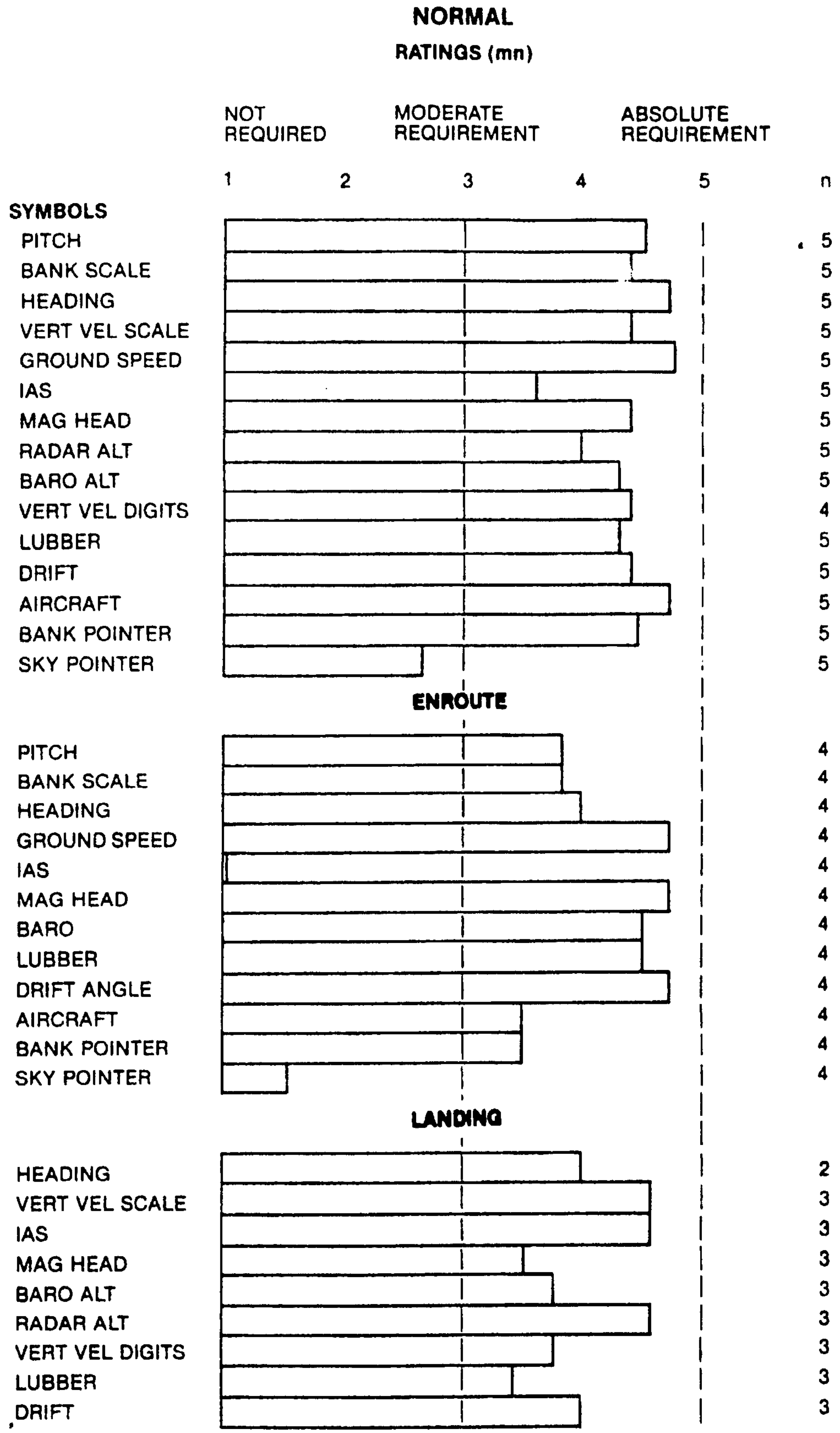


Figure 9. C-130E Pilot Ratings of Symbol Modes (Total n=5)

MC-130E FLIGHTS

The MC-130E (Combat Talon) aircraft is a low level penetration version of the C-130E. The fifteen aircraft are flown by special operations squadrons based in the Philippines, West Germany, and Florida.

Figures 10 and 11 present the MC-130E pilot ratings on symbols, modes, and controls. The MC-130E pilots rated symbol, symbol sets, and controls lower than the other aircraft pilots in this study. Several pilots suggested deleting the drift, sky pointer, lubber line, baro alt, vertical velocity, and bank angle scale symbols. The enroute mode was recommended for deletion and AGL replaced with the MSL symbol. Magnetic heading, lubber line, baro alt, and vertical velocity symbols were recommended for deletion in the landing mode. The control panel (and particularly the mode control) was recommended for placement nearer to or on the control yoke. The need for a pushbutton method of controlling baro alt and pitch were rated low. The location of the brightness control (on the helmet) was a problem for some pilots. Washout of the image from ground lights during a short final; excessive eye fatigue from changing focus between symbols and field; some restraint of head movement from the helmet; integration of INS inputs for navigation; and possible body movement problems in an emergency were mentioned by the pilots.

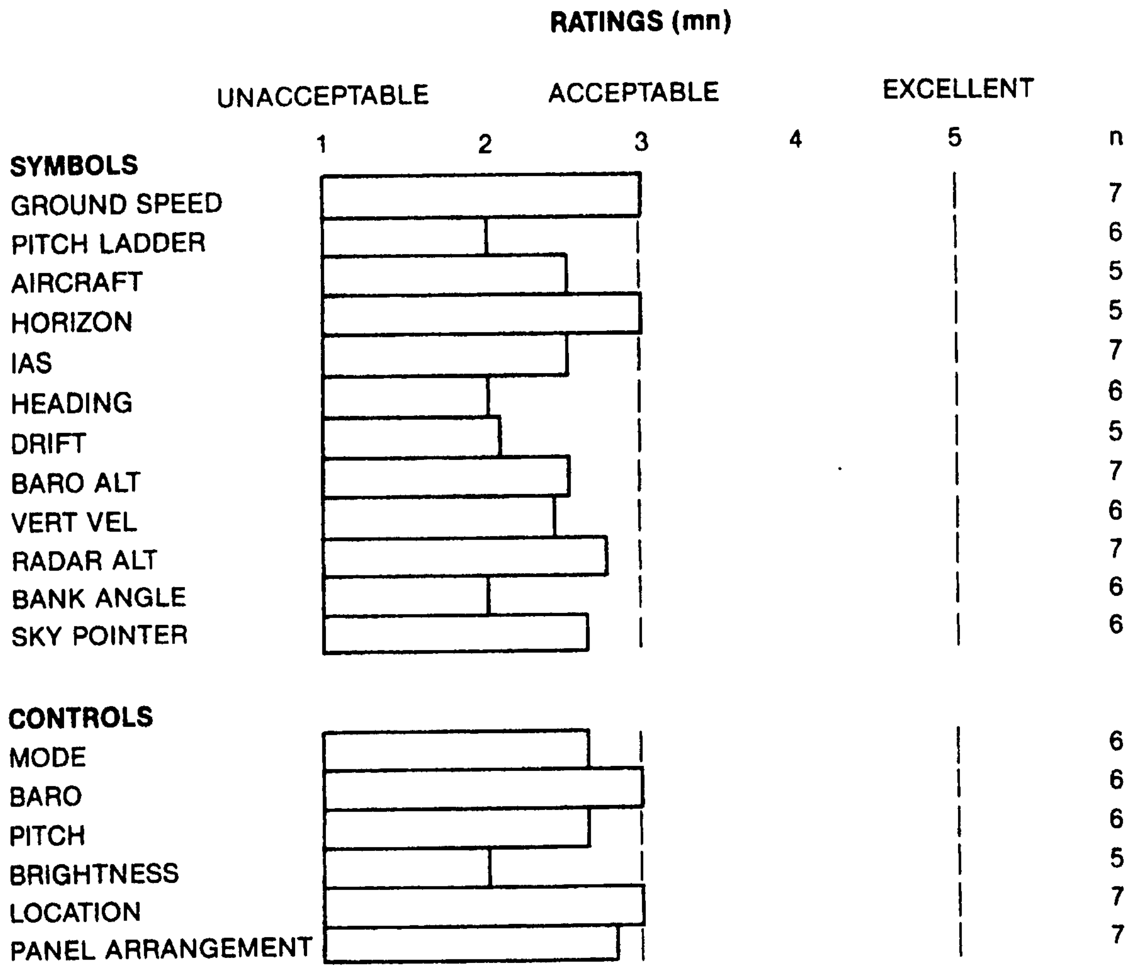


Figure 10. MC-130E Pilot Ratings of Adequacy of Symbols and Controls (Total n=7)

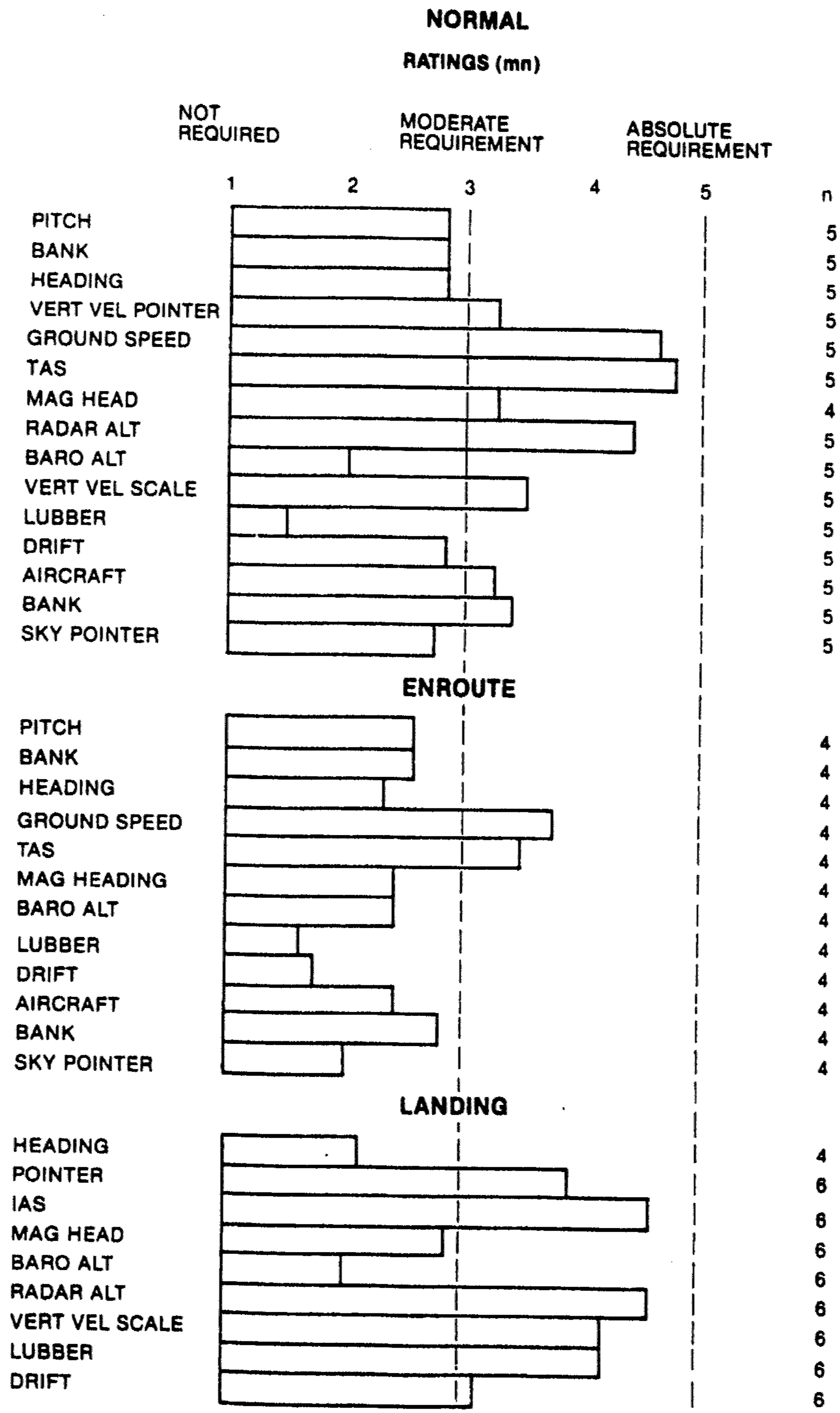


Figure 11. MC-130E Pilot Ratings of Symbol Modes (Total n=7)

AC-130 FLIGHTS

The data from these flights were not available and are not reported in this study. Queries for these data should be addressed to Jeffrey Craig, AAMRL.

HC-130P FLIGHTS

The HC-130 is an extended range version of the C-130 with upgraded engines and specialized search and rescue equipment for the recovery of aircrews. Twenty HC-130s were modified to HC-130Ps for refueling helicopters in flight.

Figures 12 and 13 present the HC-130P pilot ratings on symbols, modes, and controls. The sky pointer and lubber line were recommended for deletion and increased size recommended for the bank angle, horizon, and drift symbols. Triangles (▲) were suggested for the sky pointer and bank angle symbols. One of the two pilots did not use the mode, baro, or pitch pushbuttons and both pilots recommended dual controls for brightness.

Possible problems in moving around the cockpit in an emergency, the need for checklist calls for mode selection, and display tuning problems were mentioned by the pilots.

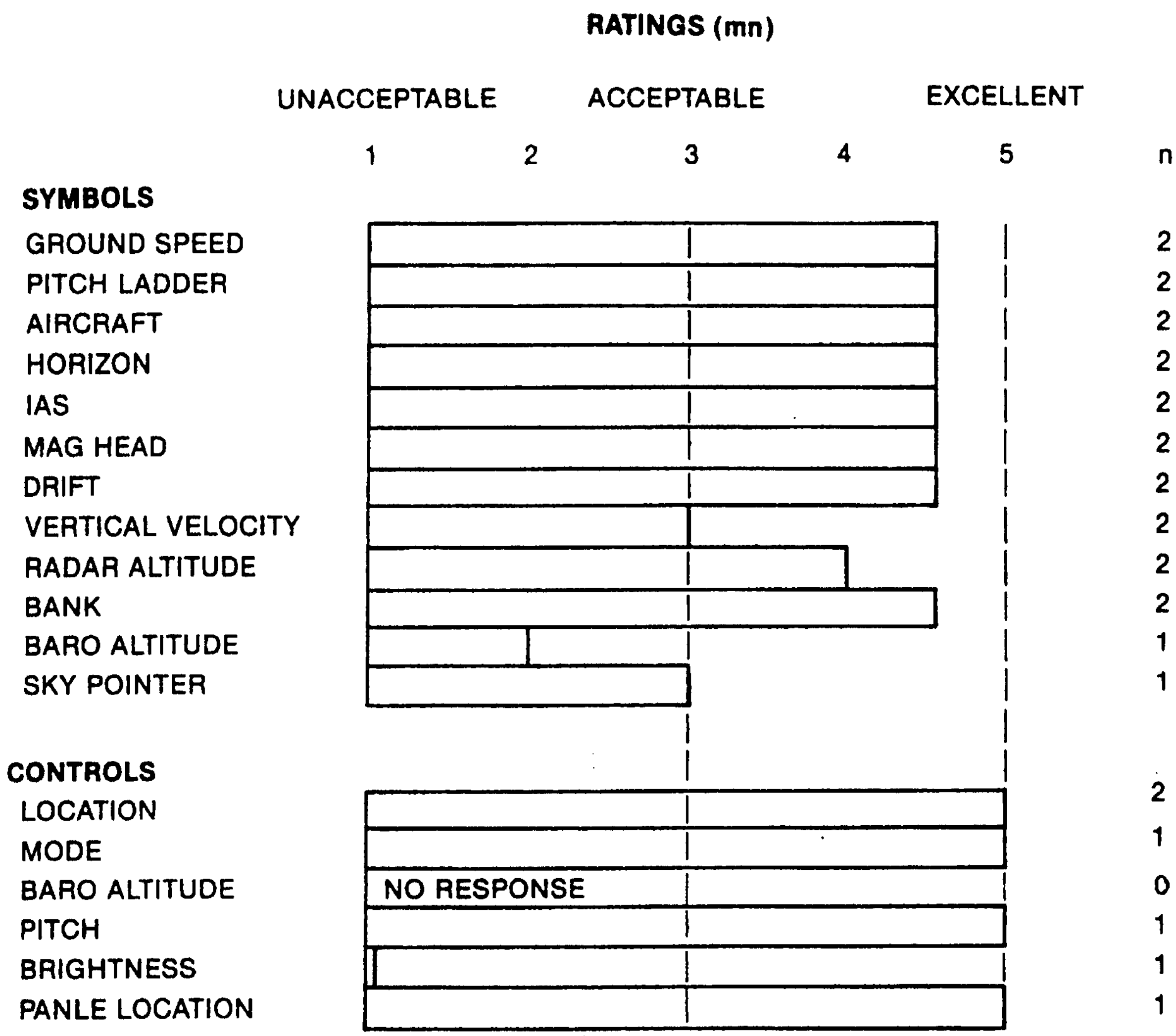


Figure 12. HC-130P Pilot Ratings of Symbols and Controls (Total n=2)

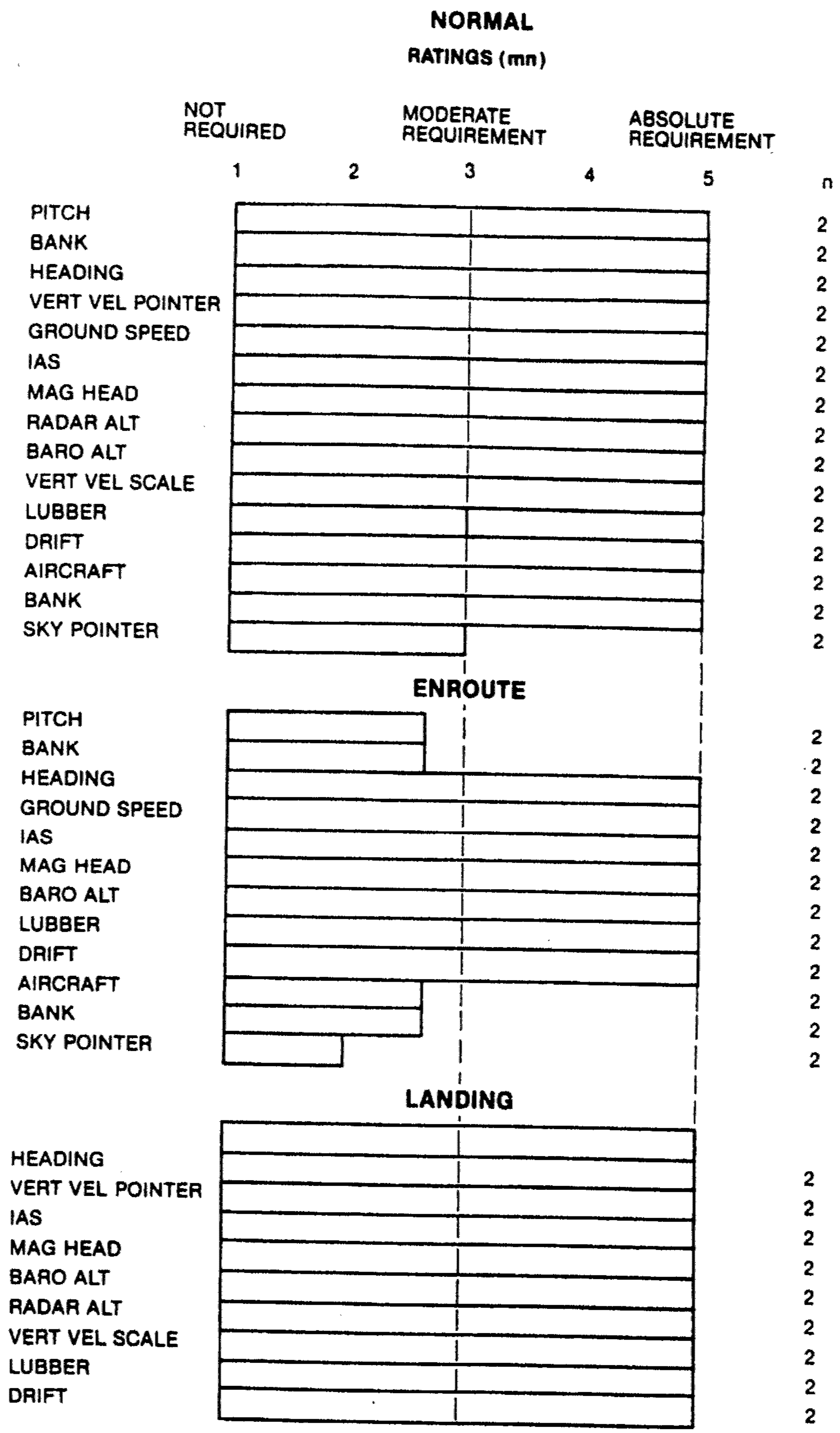


Figure 13. HC-130P Pilot Ratings of Symbol Modes (Total n=2)

HH-53H FLIGHTS

Nine HH-53Cs were modified to HH-53H aircraft (PAVE LOW) for night and adverse weather operations. Their equipment includes a stabilized forward-looking infrared (FLIR) system, an inertial navigation system, a new Doppler navigation system, and a computer projected map display and radar from the A-7D.

Figures 14 and 15 present the HH-53H pilot ratings of symbols, modes, and controls. The time-to-go, ground speed, true heading, and distance-to-go were rated as being too small. Again, for all of the modes, many of the symbols were rated as being too small in size. Ground speed, true heading, steering, and radar altitude were rated as the most required symbols. Inadequacy of display when looking toward brightly lighted areas; relocation of symbols to edge of display; need for symbols focused at infinity; eye strain helped by changing intensity, relief of workload; being able to turn off the bright FLIR display and reduce cockpit illumination; rotation of the NVG tube in the direction of the hanging bundle; and location of the mode select on the cyclic stick were reported by the pilots.

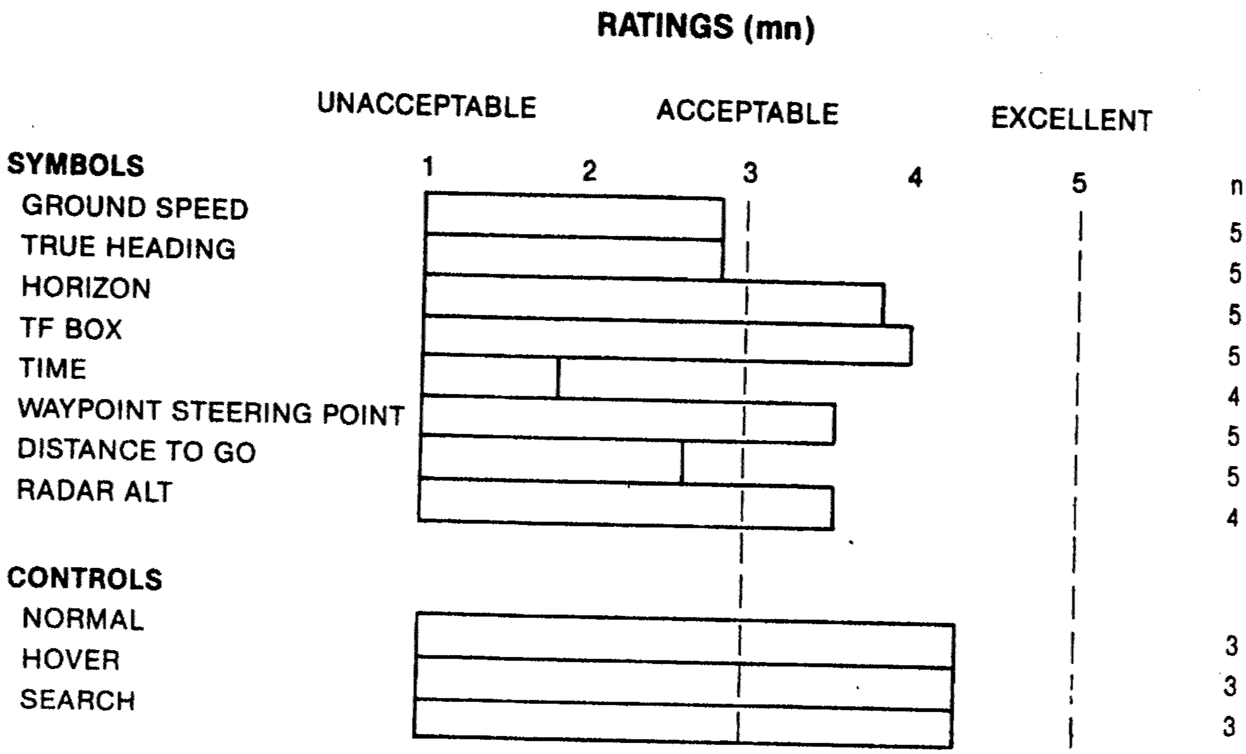


Figure 14. HH-53H Pilot Ratings of Adequacy of Symbols and Controls (Total n=5)

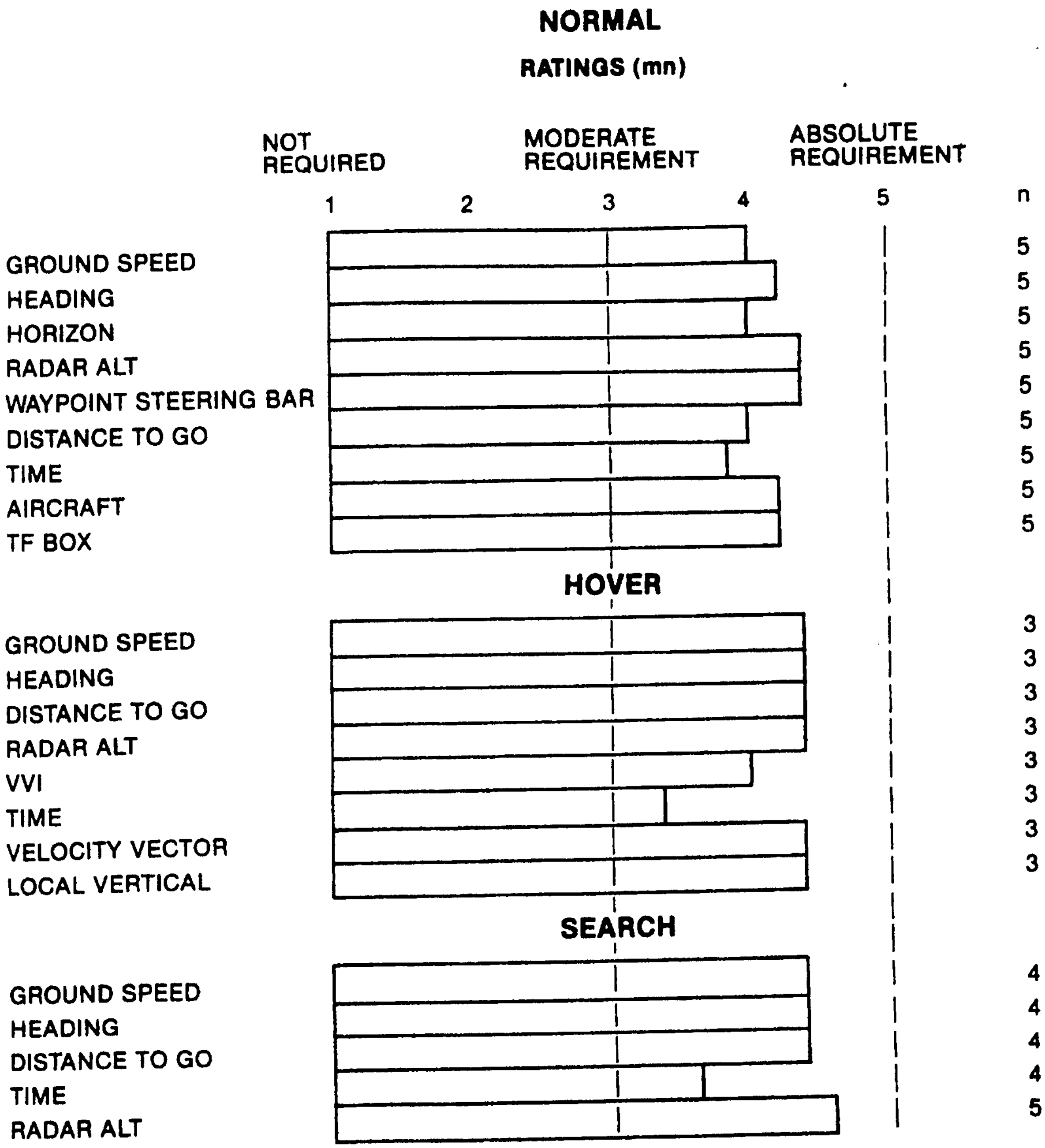


Figure 15. HH-53H Pilot Rating Symbol Modes (Total n=5)

HH-53B/C FLIGHTS

The HH-53B twin turbine heavy lift helicopter was ordered for the rescue and recovery service. It has all-weather avionics and armament and is faster and larger than the Jolly Green HH-3Es. The helos can carry 38 passengers at 170 knots.

Figures 16 and 17 present the HH-53B/C pilot ratings on symbols, modes, and controls. Based on two pilot subjects, the ground speed, mag heading, distance-to-go, and radar altitude symbols were rated as being too small in vertical size. The velocity vector and steering bar symbols were inoperative and not rated. Time-to-next-waypoint was rated as not needed in the hover mode. The mode pushbutton was recommended for a yoke location. Magnetic heading and radar altitude were rated as the most required symbols.

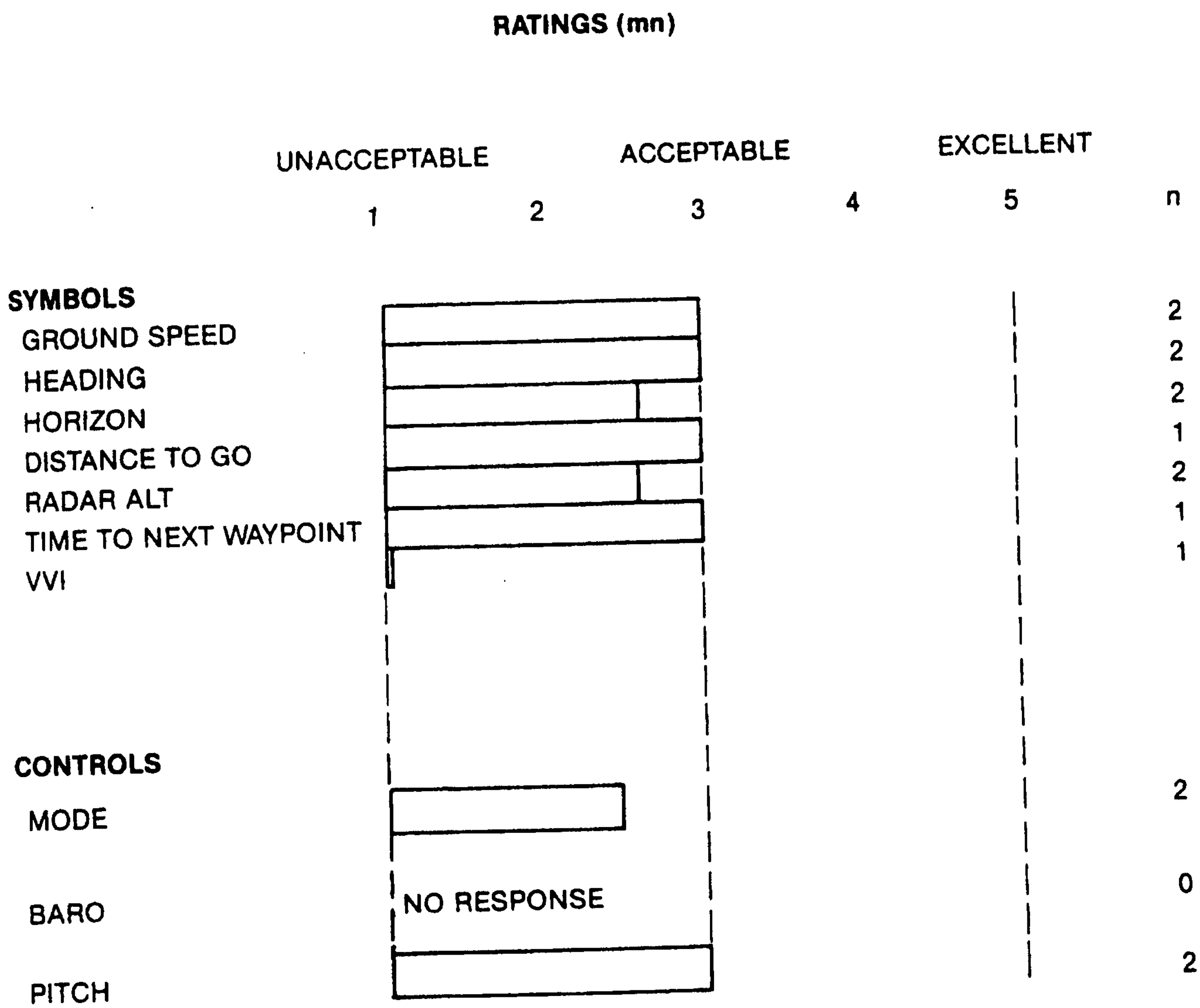


Figure 16. HH-53B/C Pilot Ratings of Adequacy of Symbols and Controls (Total n=2)

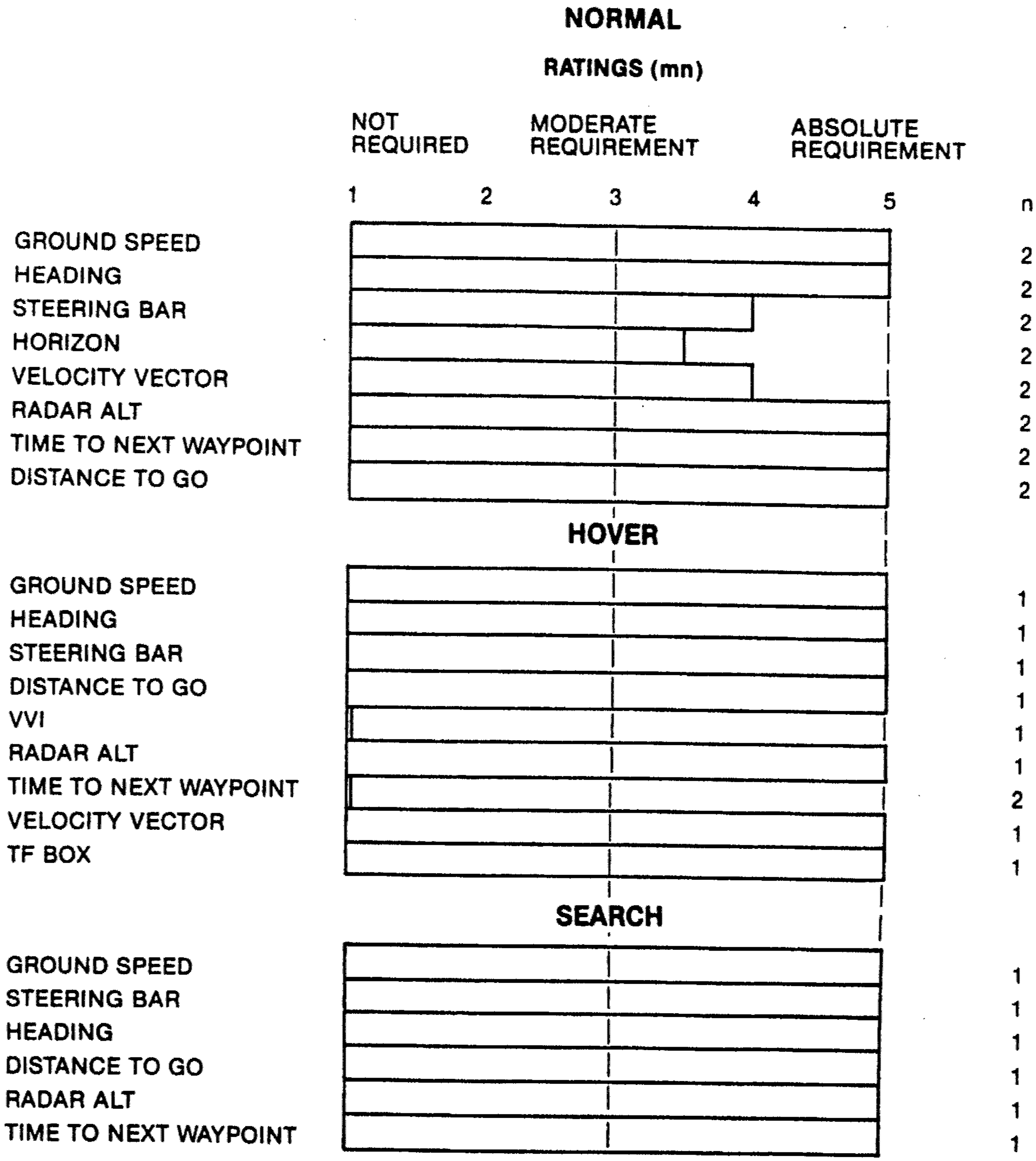


Figure 17. HH-53B/C Pilot Ratings of Symbol Modes (Total n=2)

UH-60A FLIGHTS

The Blackhawk is a twin turbo powered, 184 mph, 11 passenger helo equipped with standard U.S. Army configurations for conducting special operations missions deep behind enemy lines, in darkness or bad weather, and at treetop level.

Figures 18 and 19 present the UH-60A pilot ratings on symbols, modes, and controls. Both of the UH-60A pilots recommended larger ground speed, time, and distance-to-go symbols. Scale changes of radar altitude were suggested for hover and search modes. IAS was recommended rather than ground speed for normal and search modes and not required for the hover mode. Real-time in Zulu and deletion of VVI in hover were suggested. Heading, distance-to-go, and the steering bar were rated as the most required symbols. Slight eyestrain; need for VVI information; movement of the power cord; lag in bank angle response of the symbol; and "spreading out" of the symbol array was mentioned by the pilots.

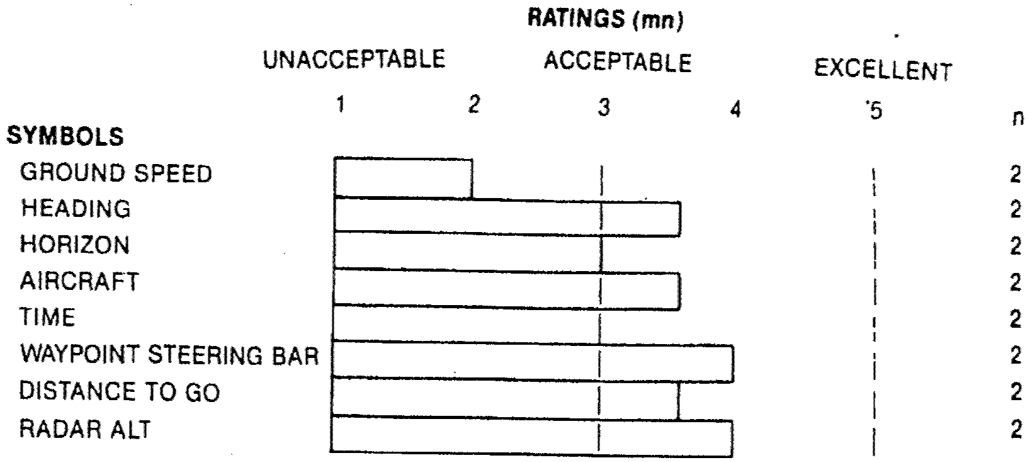


Figure 18. UH-60A Pilot Ratings of Symbols and Controls (Total n=2)

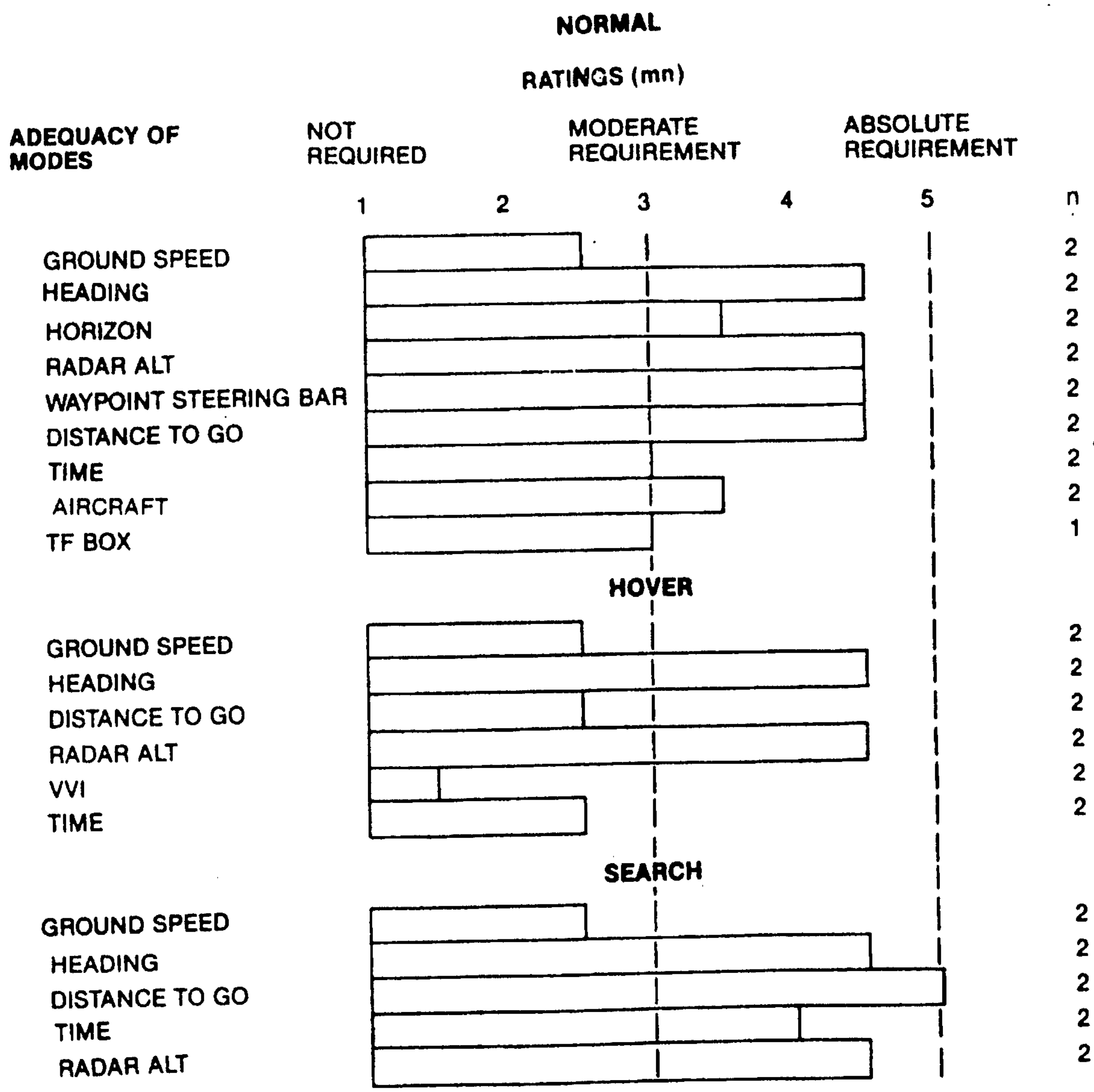


Figure 19. UH-60A Pilot Ratings of Symbol Modes (Total n=2)

SYMBOL CHARACTERISTICS FOR ALL FLIGHTS

For brevity and comparisons, ratings on symbol characteristics for all of the aircraft are included in Table 5. Symbol characteristic ratings were not obtained for the first aircraft, the C-141B, and the data were not available for the AC-130 aircraft.

Insufficient size of some symbols (e.g., ground speed, drift), deletion of some symbols for some modes (e.g., vertical velocity, sky pointer), shape and size of the fixed aircraft symbol, size and location of the distance-to-go symbol, and shape/size/scale rate of movement for the bank angle symbol were rated for changes. However, such recommendations may be specific to the type of aircraft and its special mission requirements, as well as differences between the visual information requirements for fixed-wing and rotary-wing aircraft at various airspeeds (0 to 300 knots). A high number of "no change" responses can be interpreted as being firm symbol requirements for an aircraft.

TABLE 5. RATINGS ON SYMBOL CHARACTERISTICS (ALL AIRCRAFT)

	C-130E		MC-130E		HC-130P		HH-53H		HH-53B/C		UH-60	
(Total n)	(5)		(7)		(2)		(5)		(2)		(2)	
Would You Change	Yes	No	Yes	No	Yes	No	Yes	No	Yes	No	Yes	No
Ground Speed												
Size		5		6		2	3		1	1	2	
Location		5	2	4		2		2	1	1	1	1
Width							1	1		2		1
Movement		5		6		2	1			2		1
Add a Scale		5		6		2		2		2		1
Delete		5	1	4		1		2		2		2
Mag Heading												
Size		5	2	4		2			1	1		
Location		5	3	3		2			1			
Width										1		
Delete		5	1	4		2				1		
Scale Movement		5	1	5		2						
Delete the Scale or			4	2		2						
Lubber Line		5										
Add a Label	1	4	1	3		2						
Heading												
Size							4				2	
Location							1	1			1	1
Width								2				1
Delete								2				2
Pitch Ladder												
Internal		5	1	2		2						
Length of Steps		5	1	2		2						
Number of Steps		5	1	2		2						
Label Steps	2	3		3	1	1						
Aircraft												
Change Shape To												
	1	5										
		5										
		5										
		5										
	1	5	1									
	4	1	2			2						
Horizon												
Size								1		2	1	1
Width	1	4		3	2			1		2	1	1
Location								1	1	1	1	1
Movement		4	1	2		1			1	1		2
Delete								1		2		

TABLE 5. RATINGS ON SYMBOL CHARACTERISTICS
(ALL AIRCRAFT) (continued)

	C-130E		MC-130E		HC-130P		HH-53H		HH-53B/C		UH-60	
(Total n)	(5)		(7)		(2)		(5)		(2)		(2)	
Would You Change	Yes	No	Yes	No	Yes	No	Yes	No	Yes	No	Yes	No
TF Command												
Size								1				
Shape								1				
Location								1				
Movement								1				
Delete								1				
IAS												
Size		5				2						
Location		5				2						
Add a Scale		5				2						
Movement		5			1	1						
Add a Label	1	4				1						
Delete	1	4				2						
TAS Symbol												
Size			1	3								
Location			3	1								
Add a Scale			2	4								
Movement				3								
Add a Label			1	3								
Delete				3								
Add a Scale												
Movement												
Add a Label												
Delete												
Drift												
Shape		5	1	2		2						
Size		5	1	2	1	1						
Scale		5	1	2		2						
Movement		4	1	2		2						
Delete		4	1	2		2						
Distance to Go												
Size							4			1	2	
Shape								2	1			2
Location							2	1			2	
Width								2				2
Delete								2		1		2

TABLE 5. RATINGS ON SYMBOL CHARACTERISTICS (ALL AIRCRAFT) (continued)

	C-130E		MC-130E		HC-130P		HH-53H		HH-53B/C		UH-60	
(Total n)	(5)		(7)		(2)		(5)		(2)		(2)	
Would You Change	Yes	No	Yes	No	Yes	No	Yes	No	Yes	No	Yes	No
Bar Altimeter												
Size		5		4		1						
Location		5	2	3		1						
Movement		5		3	1							
Add a Scale		5	1	3		1						
Add a Label	1	4	1	3		1						
Delete		5	1	3		1						
Vertical Velocity												
Scale	1	4	2	1		2						
Pointer		5	2	1		2						
Digit Size		5	2	1		2						
Location		5	2	1		2						
Digit Movement	2	3	1	2	1	1						
Pointer Movement	3	2	3			2						
Delete Decimal	2	2	3		1	1						
Delete Heading	2	2	2			2						
Velocity Vector												
Size												
Shape												
Location												
Box Movement												
Delete Vector												
Delete Box												
Radar Altimeter												
Size		5	1	5		2	1			2		2
Location		5	3	4		2			1	1	1	1
Width										2		2
Add a Scale		5	1	5		2			2		1	1
Movement		5	3	3	2					1		2
Add a Label	1	4	1	5		2				1		2
Delete		5		5		2		1		2		2
VVI												
Size												
Location												
Delete												
Time to Next Waypoint												
Size										1		
Location									1			
Delete										1		

TABLE 5. RATINGS ON SYMBOL CHARACTERISTICS (ALL AIRCRAFT) (continued)

Would You Change (Total n)	C-130E (5) Yes	C-130E (5) No	MC-130E (7) Yes	MC-130E (7) No	HC-130P (2) Yes	HC-130P (2) No	HH-53H (5) Yes	HH-53H (5) No	HH-53B/C (2) Yes	HH-53B/C (2) No	UH-60 (2) Yes	UH-60 (2) No
Time												
Size							3				2	
Shape								1				2
Location							1	1			2	
Width								2				2
Delete								2				2
Aircraft												
Size											1	1
Shape											1	1
Location											1	1
Movement											1	1
Delete												2
Waypoint Steering Point												
Size								2				1
Shape								2				2
Location								1				2
Movement								2				2
Width							1	1				2
Delete								2				2
Bank Angle												
Shape		5	1	2	1	1						
Size		5	2		2							
Scale		5	3			2						
Rate of Movement		5	1	2		2						
Add a Label	1	4		3		2						
Delete		5	1	2		2						
Sky Pointer												
Shape		5		2	1							
Size		5		2	1							
Scale		5		2								
Movement		5		2								
Delete	2	3	2	2	1							

Section 4
CONCLUSIONS

This section addresses the fulfillment of the seven test objectives listed in Table 1. Also, some recommendations are made for considering the use of the device for other aircraft and missions.

In general, the pilots accepted the device as favorably affecting mission success, wanted larger symbols, recommended relocating the symbols to the edge of the field-of-view, and changing the symbol focus to infinity; and some fixed-wing and rotary-wing pilots suggested a two-mode rather than three-mode concept. The two-mode concept (Figures 20 through 23) were proposed as final prototypes for fixed-wing and rotary-wing aircraft.

USEFULNESS OF NVG/HUD FOR SPECIAL OPERATIONS (OBJECTIVE 1)

The pilots rated the NVG/HUD as being useful for improving mission performance as follows;

	IMPROVING MISSION PERFORMANCE	
Aircraft	Yes	No
Fixed-Wing	8	1
Rotary-Wing	7	0
	15	1

and included the major advantages and disadvantages shown below (rank ordered for frequency of response):

Advantages of Using NVG/HUD	Fixed-Wing (n)	Rotary-Wing (n)
Approaches and Landings	8	1
Night Navigation	5	2
Increases Safety	4	1
Better Control of Aircraft	3	
Everything		3
Air Drops	1	
Hover		1

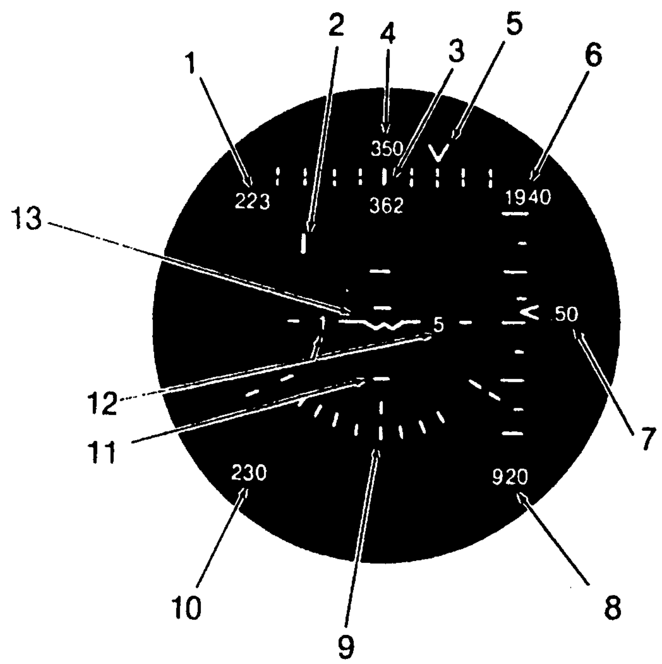
Disadvantages of Using NVG/HUD	Fixed-Wing (n)	Rotary Wing (n)
Makes Runway Acquisition Difficult	1	
Degrades Map Reading	1	
Landing Pilot has to Refocus	1	

The majority of the pilots who responded (94 percent) recommended the NVG/HUD as being useful for improving their mission performance.

PROPOSED SYMBOLS, SYMBOL MODES (OBJECTIVE 2)

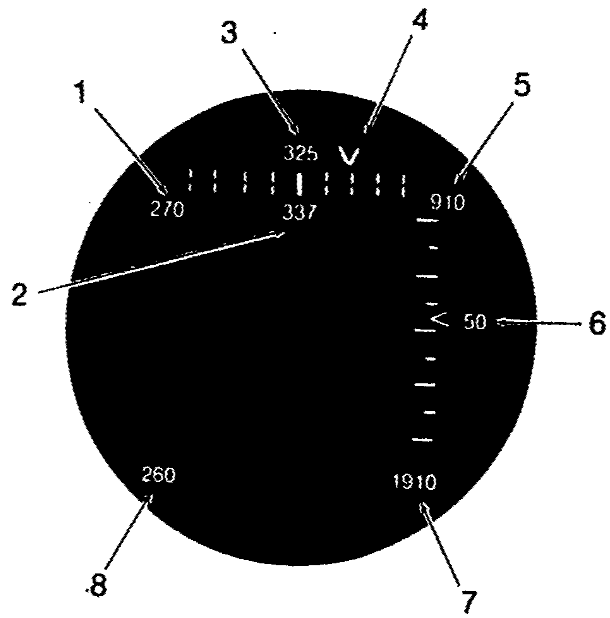
A majority of the pilots recommended expanding the HUD 14-degree instant field-of-view (IFOV) within the 40-degree IFOV of the NVG goggle. This section includes AAMRL's proposed symbols for fixed-wing and rotary-wing aircraft and includes a two-mode concept for symbol modes.

The symbols and symbol modes, shown in Figures 20 and 21, are proposed as test candidates for fixed-wing and rotary-wing aircraft. Differences in symbol scaling or movement for each aircraft are indicated in parentheses (e.g., HH-53H), where appropriate. The selections were based on pilot debriefs, questionnaire responses, and consultations with MAC personnel. Individual aircraft with unique symbol requirements were reported in summary form (Section 3) and for each pilot participant (Appendix C). Each NVG/HUD application may have to be tailored to unique signal interface and maneuvering requirements, and these data may serve as a source for selecting symbol and symbol mechanization requirements.



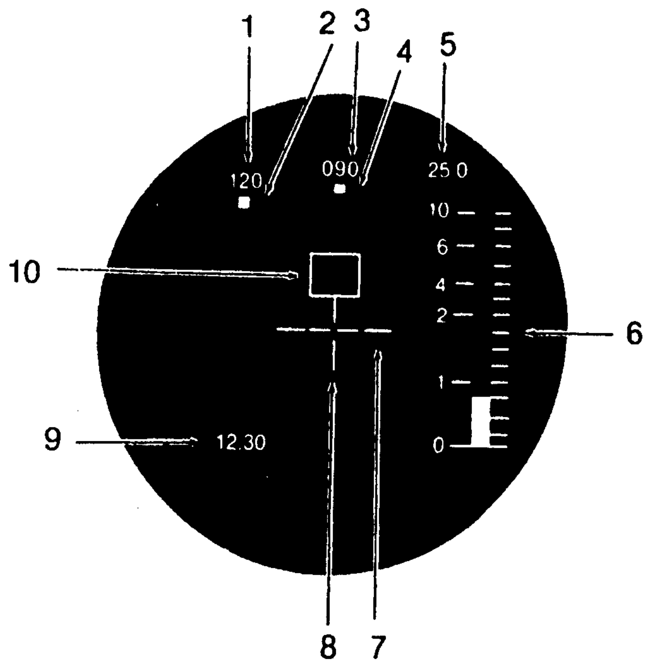
Index	Symbology	Function
1	Indicated Airspeed	Displays airspeed in 1 knot increments for full range of aircraft airspeeds.
2	Course Steering Bar	Provides left/right waypoint steering areas in relation to the course steering index. Full scale displacement is 40 degrees.
3	Magnetic Heading	Displays aircraft heading in 1-degree increments from 000 degree to 360 degrees.
4	True Track (C-141B Only)	Displays desired true track in 1-degree increments from 000 degree to 360 degrees.
5	Drift Angle	Displays left/right drift against fixed scale of 10-degree increments.
6	Barometric Altitude	Displays altitude in 10-foot increments from 0000 feet to 9990 feet.
7	Vertical Velocity	Displays velocity in 10 feet per minute increments in thousands fpm (750 fpm is displayed as .75).
8	Absolute Altitude	Displays radar in 10-foot increments at or below 300 feet and 20-foot increments above 300 feet from 000 feet to 999 feet.
9	Bank Angle	Displays 10, 20, 30, and 60 degrees of bank.
10	Ground Speed	Displays speed in 1 knot increments for full range of aircraft speeds.
11	Pitch Ladder Graduations With Artificial Horizon	Displays horizontal pitch graduations in 5-degree increments from 0 to 90 degrees.
12	Numeric Pitch	Displays pitch at 10 degrees and, thereafter, in 1 degree increments from 10 degrees to 90 degrees.
13	Aircraft Symbol	Fixed symbols.

Figure 20. Proposed Symbol Sets for Fixed-Wing Aircraft, Mode 1



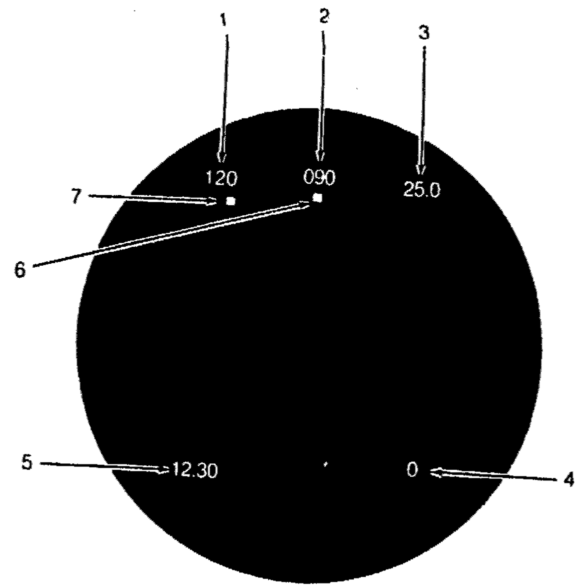
Index	Symbology	Function
1	Indicated Airspeed	Displays airspeed in 1 knot increments for full range of aircraft airspeeds.
2	Magnetic Heading	Displays aircraft heading in 1-degree increments from 000 degree to 360 degrees.
3	True Track (C-141B Only)	Displays desired true track in 1-degree increments from 000 degree to 360 degrees.
4	Drift Angle	Displays left/right drift against fixed scale of 10-degree increments.
5	Barometric Altitude	Displays altitude in 10-foot increments from 0000 feet to 9990 feet.
6	Vertical Velocity	Displays velocity in 10 feet per minute increments in thousands fpm (750 fpm is displayed as .75).
7	Barometric Altitude	Displays altitude in 10-foot increments from 0000 feet to 9990 feet.
8	Ground Speed	Displays speed in 1 knot increments for full range of aircraft speeds.

Figure 21. Proposed Symbol Sets for Fixed-Wing Aircraft, Mode 2



Index	Symbology	Function
1	Groundspeed	Displays groundspeed in 1 knot increments.
2	Course Steering Bar	Provides left/right waypoint steering cues in relation to the course steering index. Full scale displacement is ± 20 degrees.
3	Heading	Displays aircraft heading in degrees true (HH-53H) or magnetic (UH-60A and HH-53B/C) in 1 degree increments.
4	Course Steering Index	Provides a center index for the course steering bar.
5	Distance to Next Waypoint	Displays the distance to go to the next selected waypoint in 0.1 nautical mile increments.
6	Radar Altitude Tape	Displays the radar altitude in 25 feet increments from 0 to 200 feet, 100 feet increments from 200 to 600 feet, and 200 feet increments from 600 to 1,000 feet.
7	Horizon Bar	Provides an artificial earth horizon reference.
8	Aircraft Reference	(HH-53H) Represents the aircraft flight path vector or aircraft velocity vector and is fixed at the center. (UH-60A and HH-53B/C) Represents the aircraft attitude and below 30 nautical miles-per-hour also represents the aircraft drift with respect to the box reference. The aircraft reference is fixed at the center.
9	Time to Next Waypoint	Displays the time in minutes and seconds to the next selected waypoint based on the existing groundspeed.
10	Box Reference	(HH-53H) Represents the terrain following climb/dive command or the computed local vertical. (UH-60A and HH-53B/C) Below 30 nautical miles-per-hour groundspeed the box represents a drift reference for the aircraft symbol. Above 30 nautical miles-per-hour the box disappears.

Figure 22. Proposed Symbol Sets for Rotary-Wing Aircraft, Normal Mode



Index	Symbology	Function
1	Groundspeed	Displays groundspeed in 1 knot increments.
2	Heading	Displays aircraft heading in degrees true (HH-53H) or magnetic (UH-60A and HH-53B/C) in 1 degree increments.
3	Distance to Next Waypoint	Displays the distance to go to the next selected waypoint in 0.1 nautical miles increments.
4	Radar Altitude	Displays the radar altitude in 1 foot increments from 0 to 50 feet, 5 feet increments from 50 to 100 feet, and 10 feet increments above 100 feet.
5	Time to Next Waypoint	Displays the time in minutes and seconds to the next selected waypoint based on the existing groundspeed.
6	Course Steering Index	Provides a center index for the course steering bar.
7	Course Steering Bar	Provides left/right waypoint steering cues in relation to the course steering index. Full scale displacement is ± 20 degrees.

Figure 23. Proposed Symbol Sets for Rotary-Wing Aircraft, Search Mode

Symbol Requirements for All Aircraft

Figures 24, 25, and 26 include pilot responses averaged (means) for each type of aircraft. These data are not included for design decisions which are considered to be aircraft specific but rather for research personnel examining visual information requirements for night, VFR, low altitude flight.

Figure 24 presents the adequacy of the HUD symbols for both classes of aircraft. The presentation of baro altitude, bank angle, and vertical velocity in fixed-wing aircraft and ground speed, real-time (clock time), and vertical velocity were considered marginal and in need of change of shape, movement, or deletion.

Figures 25 and 26 present pilot ratings for symbol requirements for low level, night VFR flight. For fixed-wing aircraft (Figure 25), true with mag heading and lubber line symbols for the normal mode; bank angle, true with mag heading, drift, and sky pointer symbols for the enroute mode; and baro alt and the lubber line symbols for the landing mode may not be significant requirements. For rotary-wing aircraft (Figure 26), only VVI and time to next waypoint symbols in the hover mode were rated below moderate requirement. An engineer selecting symbols for new devices might consider the symbols rated as absolute requirements as being a minimum symbol set and the priorities between moderate and absolute requirements for selecting a mode oriented set of symbols.

ADEQUACY OF DEVICE FOR LEVELS OF NIGHT ILLUMINATION (OBJECTIVE 3)

Moon disc size for the flights was estimated by the pilots to average 45 percent (range = no moon to 98 percent, n = 10) and effective ground illumination from moonlight to average 40 percent (range = 10 to 100 percent, n = 13). Visibility for all of the flights was reported as clear (unlimited) with high scattered clouds from 10 to 25,000 feet.

The majority of the pilots considered the HUD display as being adequate for all night sky illumination conditions (overcast to full moon).

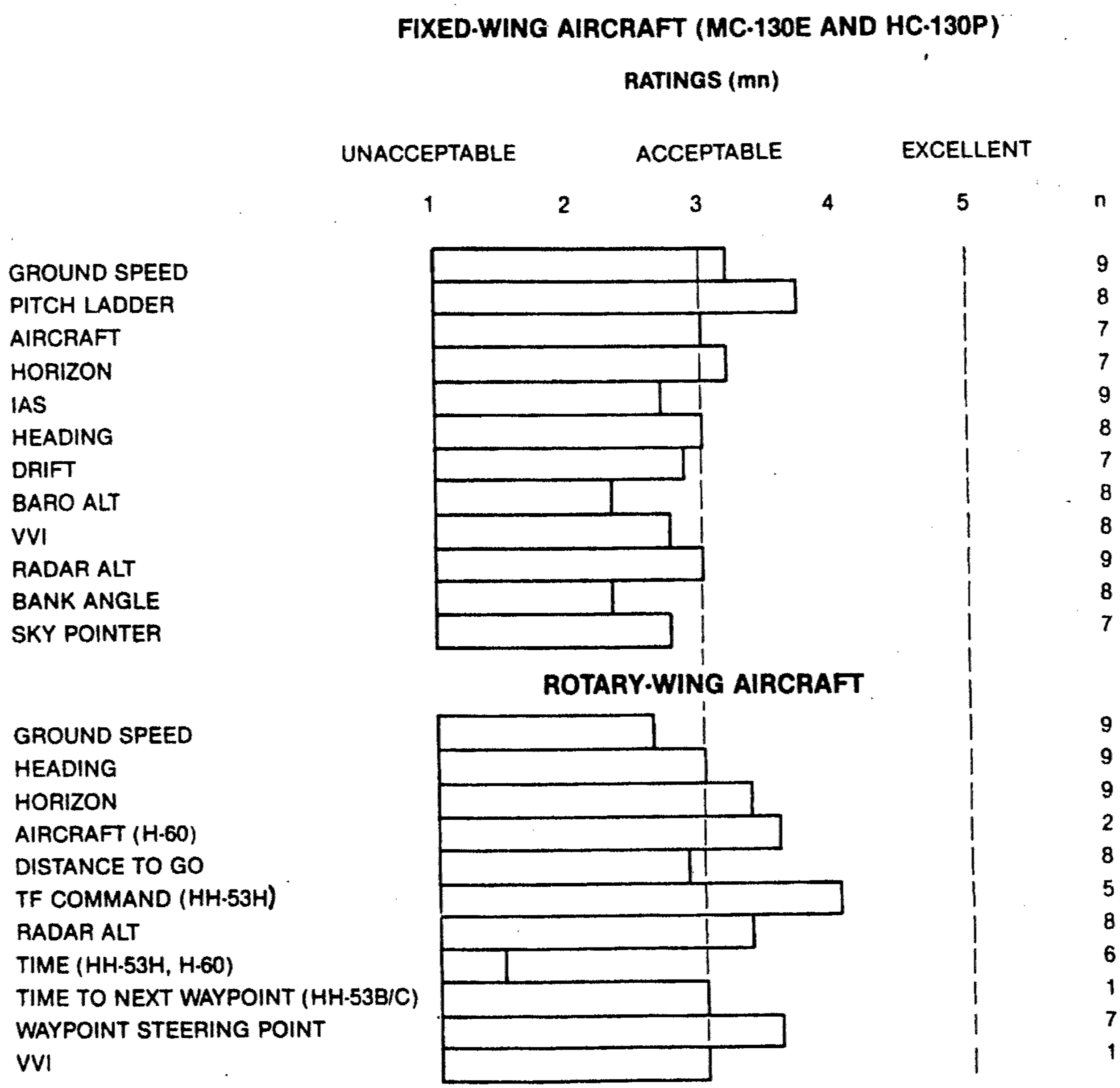


Figure 24. Adequacy of HUD Symbols

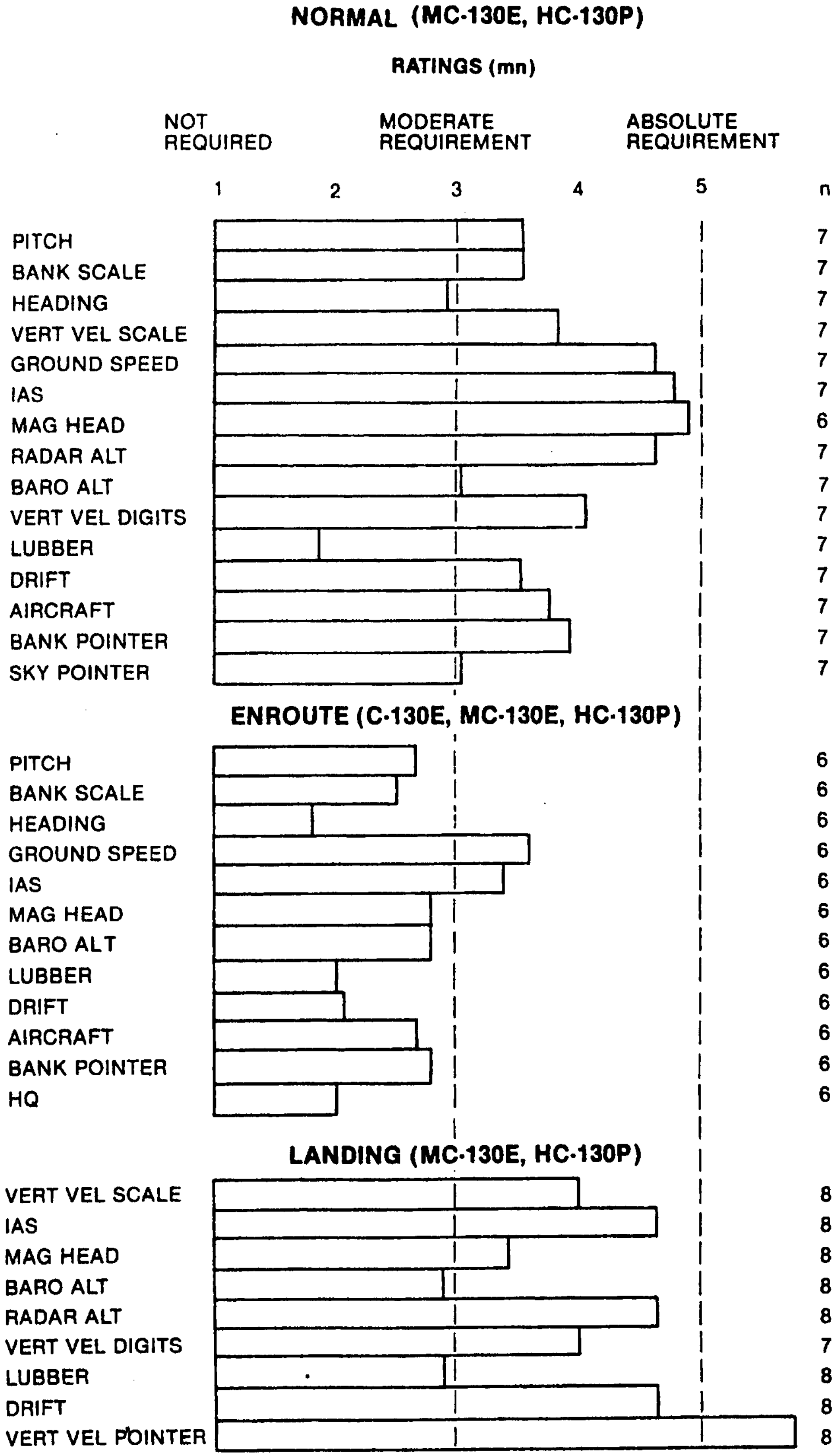


Figure 25. Symbol Requirements for Fixed-Wing Aircraft

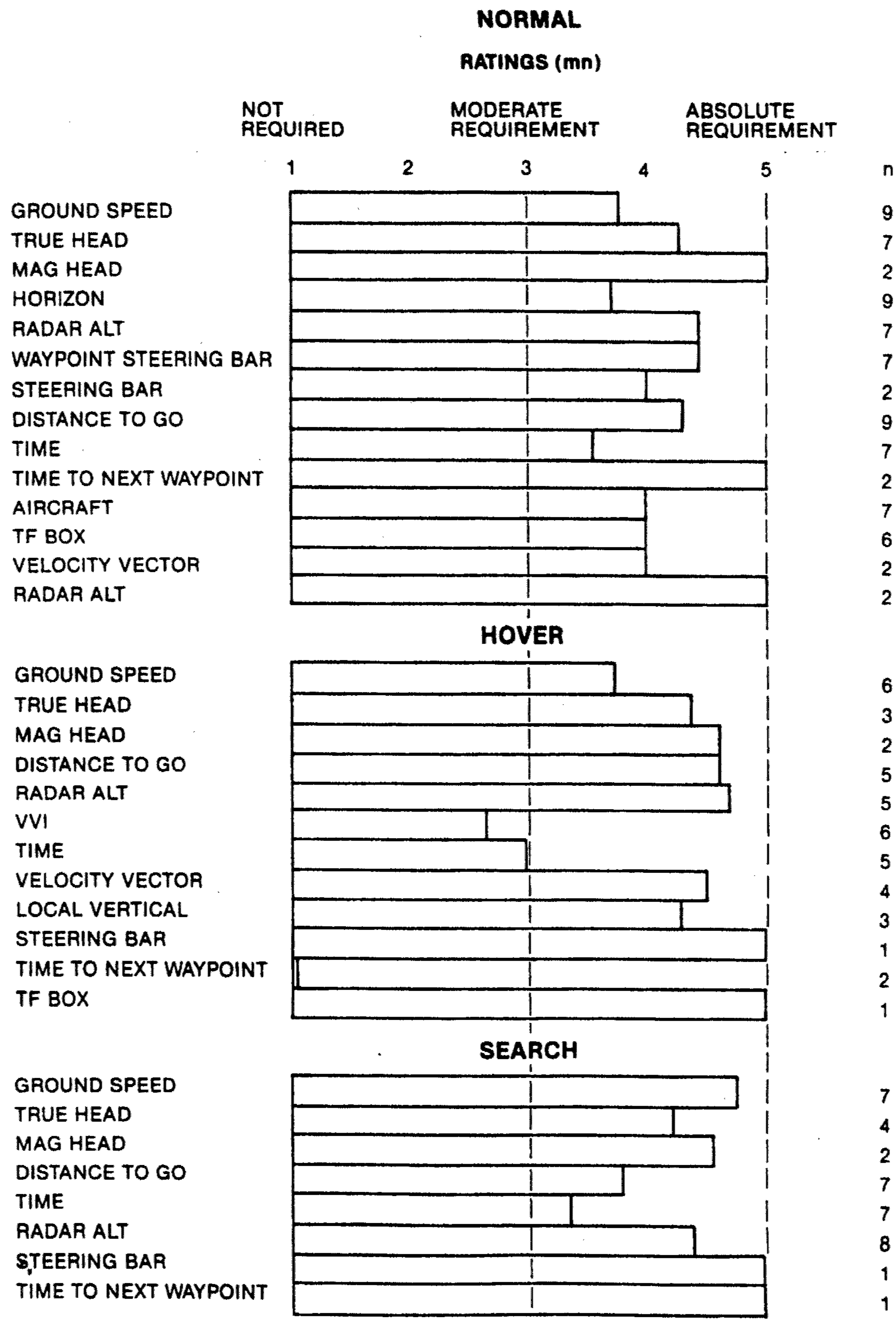


Figure 26. Symbol Requirements for Rotary-Wing Aircraft

CONTROL REQUIREMENTS (OBJECTIVE 4)

The five controls shown in Figure 6 (for power, pitch adjust, mode select, barometric adjust, and brightness adjust (on the helmet) are proposed for an NVG/HUD specification. On a vertically aligned panel, the mode button was recommended for the top position (unless the panel is overhead) and for the nearest position to the pilot for horizontally aligned buttons. Individual pilots recommended the mode button be installed on the cyclic, run the optic cable on top of the helmet, and add a control for symbol intensity. All of the eight rotary-wing pilots said that operation of the NVG/HUD controls did not interfere with any other equipment nor did the operation of other equipment interfere with operation of the NVG/HUD. The optic bundles might impede movement in the cockpit in an emergency.

COMPATIBILITY WITH CURRENT EQUIPMENT (OBJECTIVE 5)

A microprocessor based data collection and formatting unit was developed to provide interfaces to all of the required sensor data. Signals were scaled and formatted to an ARINC 429 standard for transmission to a symbol generator. Software was prepared using assembly language for each aircraft. Generally, pitch and roll signals were derived from attitude gyros; heading from a directional gyro; radar altitude from a radar altimeter; navigation data from a doppler radar; and attitude, airspeed, and vertical velocity from pitot-static systems. Installation downtimes were minimized by the introduction of a common data collection and formatting unit.

OPERATIONAL PROCEDURES (OBJECTIVE 6)

The fixed-wing pilots commented on the probable elimination of communication from the copilot and radar navigator to the pilot (especially concerning airspeed and altitude) (MC-130E); both pilots could simultaneously use goggles on the entire mission (HC-130P) and its use would promote more aggressive flying (HC-130P). The rotary-wing pilots also commented on the reduction of communication requirements, the reduction of light in the cockpit by turning off the bright FLIR display, and its aid as an instructors' device; however, crew coordination would have to be increased for

Night Recover System (NRS) equipped aircraft that requires the flight engineer to operate a camera. Formal checklist requirements for tuning and checking the device and copilot calls to the pilot to change modes ("before takeoff, before landing") were recommended.

TRAINING REQUIREMENTS (OBJECTIVE 7)

Table 6 summarizes pilot recommendations for training requirements (one to three flights) for NVG qualified pilots.

TABLE 6. TRAINING REQUIREMENTS

Aircraft	Pilot Comments	n
MC-130E	One ride (one low approach or until comfortable, one flight of 2 hours).	3
	Two rides (minimum of four landings and one go-around each ride).	1
HC-130P	No special requirement.	1
	Two rides (with an IP).	1
Rotary	One ride [2-hour sortie after a training session, include a new sortie with approaches and hovering over a landing zone (LZ)].	2
	One to two rides (include terminal operations, low level formation, terrain masking, and refueling).	2
	Two to three rides.	2

NVG/HUD APPLICATION CONSIDERATIONS

The impetus for the use of night vision optics started with the use of handheld starlight scopes with the U.S. Army ground and air forces in Vietnam. The Air Force soon adopted handheld and gimballed TV and IR devices in a variety of recon and strike aircraft. The astonishing success of side-firing aircraft in Vietnam (Ballard, 1982) and later in Grenada, confirms the necessity for having a night VFR target detection and strike capability. The requirement for penetrating a high threat, night, Warsaw Pact conflict with low level tactics has been well documented and will doubtless proliferate the use of night optics into future systems.

Future developers should consider the NVG factors listed in Table 7 as the three services move into airborne low level night operations.

TABLE 7. NVG/HUD APPLICATION CONSIDERATIONS

Factors	Comments
Field of View	Restrictions of FOV (40 degrees for Generation III NVG) may affect scanning patterns and target acquisition capabilities. Any restriction of the aft or high scan envelope may directly affect formation, refueling, or air combat maneuvers.
Visual Fatigue	Anticipate visual fatigue problems because of the monocular presentation and close focused symbols superimposed over an image at infinity. Some pilots may reduce cross checks and tend to focus on the close symbols.
Helmet Weight	Physiological fatigue for some pilots is increased with increased helmet weight and type of weight distribution.
Optics Bundles	The bundles may limit head movements and body movements.

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NIGHT VISION GOGGLE (NVG) HEADS-UP DISPLAY (HUD)

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SUMMARY

Standard night vision goggles were modified to accommodate a visual display similar to that employed in aircraft Heads-Up Displays (HUDs). Primary users of this device are Military Airlift Command (MAC) pilots flying low level special operations. During use, the pilot sees a thermal image of the ground, with critical flight path and attitude information symbolically displayed on the scene. This modification allows the pilot to fly at very low levels at night without having to look inside in the cockpit. This paper relates the process of design and fabrication of the HUD optics and the selection of the heads-up symbols (e.g., airspeed, altitude, heading) for transports and helicopters. It also reports the first successful trials on a C-141B jet transport.

INTRODUCTION AND BACKGROUND

This report documents the development and first application of NVGs modified with HUD symbols for flying night, visual flight rule (VFR), low level operations. The NVG/HUD combines monocularly presented flight symbology with a binocular view of the outside scene. Development and construction of the devices associated with the NVG/HUD were performed at the Air Force Aerospace Medical Research Laboratory (AFAMRL).

The NVG/HUD is presently used by pilots flying jet and turbo-powered cargo aircraft, as well as pilots of conventional helicopters. Flight testing was performed during night sorties in South Carolina and Florida. Structured questionnaries and interviews are used to guide design changes, suggest training requirements, and assess pilot acceptance.

Characteristics and use of NVGs

Godfrey (1982) described the development and use of NVGs in military crewstations.

> "NVGs have now attained a level of sophistication such that aircraft can be safely and comfortably flown using these devices. NVGs operate by amplifying reflected low intensity visible and near infrared (invisible) light. The goggles most commonly referred to are AN/PVS-5 (Generation II) and ANVIS (Generation III) (Aviators Night Vision Imaging System). Generation II goggles can be helmet-mounted

but are rather heavy and awkward. The user must see everything through them including cockpit instrumentation. The Generation II produces a bright target image at light levels as low as quarter moon illumination. The latest NVGs (Generation III) are helmet-mounted, lightweight, and well balanced so that the person wearing them can operate unhindered. The design permits use of the goggles to produce a clear green picture of the world around, while at the same time permitting use of the naked eye to look under the goggles and read instrumentation or other information. Generation III NVGs produce a bright target image at light levels as low as starlight illumination."

As with any new technology introduced into areas as complex as an aircraft crewstation, there are a number of problems which must be resolved. The most significant problem is the light which is enhanced to produce a picture of the outside world. The wavelength of this light is between 600 to 900 nm. This means that incandescent lamps or any other light whose wavelength is longer than approximately 525 nm (green light output) will also be amplified and interfere with the image of the outside scene. Yellows, reds, and infrared either "blind" the goggles or cause them to protectively shut down much as the unaided eye adapts to very bright light. The response of these goggles is shown in Fig. 1.

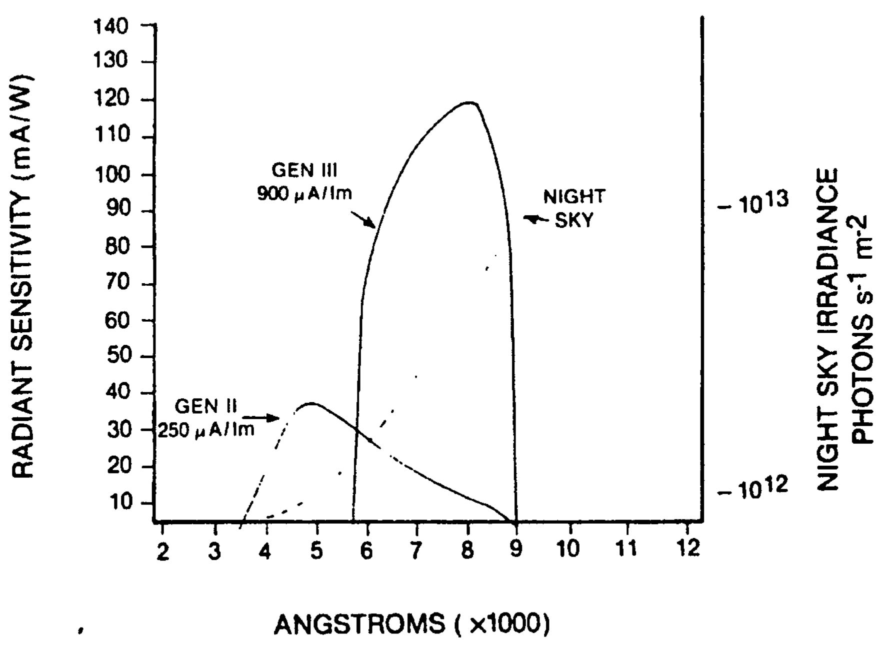


Figure 1. Response of night vision goggles.

Characteristics of the NVG/HUD

AFAMRL solved the problem of flying very low levels, at night, by providing HUD symbols on a combining glass over one of the goggle eyepieces. The concept was to provide sufficient position and attitude information to the pilot during enroute, air drop, and landing operations to allow an "eyes-out" orientation during the complete operation.

Several modes of information display are available. Fig. 2 shows the HUD symbols selected for one mode (normal) of the transport and helicopter mission. Generally, for other models such as SEARCH and LANDING, the number of symbols was reduced to avoid cluttering the center of the IR image when the pilot is concentrating on ground patterns and landmarks.

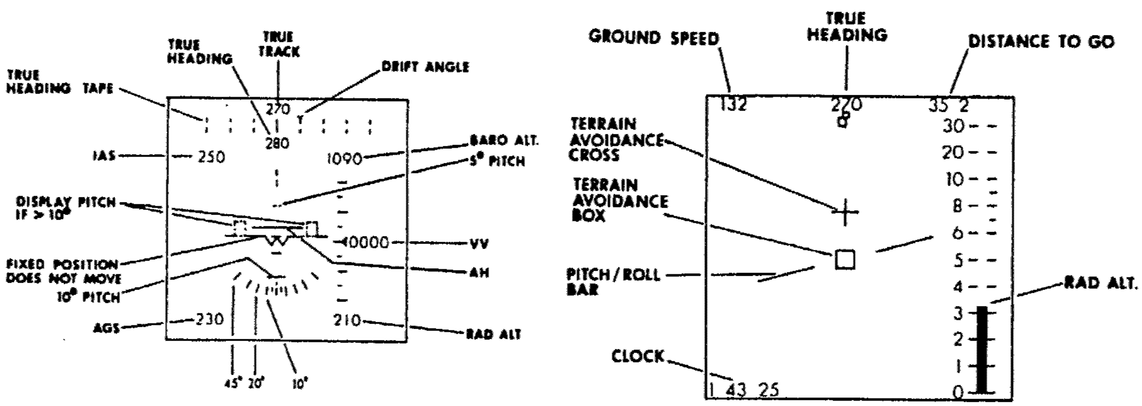


Figure 2. HUD symbols for transport and helicopters. Several special features of the symbology are indicated in Table 1.

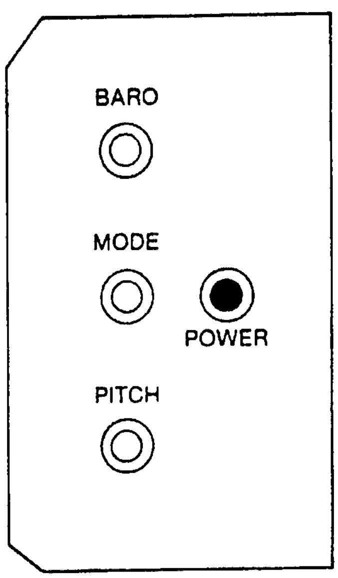
TABLE 1. Special control/display features.

Altitude	Displays barometric or radar altitude, radar changes in 1Ø-foot increments below 1ØØØ feet, 1ØØ-foot increments above 1ØØØ feet.
Fixed Digit	The last zero for altitude and vertical velocity is an unchanging zero (Ø) to reduce distraction of a fast changing digit.
Pitch	Over 1Ø degrees pitch, a 1Ø's digit is displayed to the left of the aircraft and 1's unit to the right.

The flight instrument raw signal information is collected by the aircraft's signal processing computer and converted into Arinc 429 formatted data. The data are transmitted to the AFAMRL display unit across the Arinc 429 bus.

The data unit converts the data to a symbolic display on a cathode-ray tube format. The symbology display is reflected from a front surface mirror to a relay lens which focuses onto a flexible fiber optic bundle. The bundle brings the image up to the NVG where a collimating lens moves the image or the symbology to optical infinity. This image is then reflected from a beam splitter into the NVGs. The observer sees the image of the HUD symbols superimposed over the outside view.

The controls for the HUD portion of the system are shown in Figure 3. The control panels are positioned at various locations, depending on the type of aircraft. The design goal was to include only critical pilot control functions and automate other functions (focus, brightness, contrast).



4 PUSHBUTTONS

BARO - Changes readout to match aircraft altimeter

MODE - Selects symbol set for mission segment

POWER - Turns HUD equipment ON

PITCH - Trims the aircraft symbol to horizon bar for aircraft attitude

Figure 3. Pilot's controls for transport and helicopters (tentative).

Evaluation of the NVG/HUD

Evaluation and modification of the device was iterative. The approach was to use actual flight experience to modify user HUD symbol requirements, obtain acceptance ratings for the device, and identify problems. For each aircraft, pretest discussions were held with MAC personnel to derive a symbol set that appeared to satisfy the aircraft mission requirements. Throughout the aircraft test series, the design goal was to minimize the number of symbols, modes, and controls without compromising crew safety or adding to crew workload.

HQ MAC authorized a series of evaluations based on successful trials in preliminary C-141 flights. Over a 1-year period, MAC directed that other aircraft be evaluated for NVG/HUD use:

Aircraft Evaluated for NVG/HUD Use

C-141B	C-13ØE (AWARDS)	H-53E
	MC-13ØE	HH-53B/C
	AC-13ØH	HH-53H
	HC-13Ø	UH-6ØA

Several C-141 and C-13Ø crews have flown and endorsed the NVG/HUD for low level operations. Testing and evaluation on other aircraft is ongoing.

RESULTS

The four-engine heavy jet transport, C-141B, flies a low level mission that currently relies on the pilot looking outside and maintaining terrain clearance while the co-pilot looks inside and ensures the integrity of aircraft velocity and attitude. The missions include a blacked-out approach, landing, and takeoff from a remote field. The current concept (pre-NVG/HUD) is for the co-pilot and two navigators to verbally provide critical information to the pilot throughout the operation. Six C-141B pilots flew night approached and full-stop landings with the NVG/HUD. A structured questionnaire was used to obtain the pilot ratings shown in Table 2.

Using a five point scale (Ø=unacceptable, 3=acceptable, and 5=excellent), all HUD symbols were rated between "more acceptable" and "excellent" except for the drift angle symbol. The three system controls (to adjust intensity and focus and to reset the barometric altimeter) were rated as more than acceptable. The location of the control panel was rated acceptable; however, its relocation was recommended. Visual fatigue was rated as below average to none and display contrast as being adequate for most night sky conditions under various levels of illumination. In terms of the systems contribution to mission success, the pilots generally agreed that the NVG enhances control of the aircraft, reduces interphone communication and increases flight safety (terrain clearance).

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Marasco, P. L., & Task, H. L. (1998). Examination of a method for improving night vision device depth of field. *SAFE Journal 28(3)*, 94-100.

Examination of a Method for Improving Night Vision Device Depth of Field

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ABSTRACT
Night Vision Device (NVD) depth of field is extremely small when viewing objects close to the observer. An optical system's depth of field can be increased by reducing, or slowing, the system's f-number (*f/#*) which can be accomplished by adding restrictive apertures onto the front of the objective lens. This noticeably increases NVD depth of field but causes a significant reduction in the device's light gathering capability. This paper derives equations describing the phenomenon, assesses the tradeoffs that are involved in using apertures to increase depth of field, and discusses an experiment demonstrating improved depth of field resulting from decreasing the objective lens aperture.

INTRODUCTION

A problem with Night Vision Devices (NVDs) is their depth of field. When the device is focused far away, such as at infinity, objects close in are out of focus. This problem has little effect on pilots flying an aircraft, whose attention is on distant objects, but it presents a safety hazard for some crewmembers who must constantly move about the aircraft, refocusing their NVDs while trying to accomplish complicated tasks [3]. When focused close to the user, NVD depth of field is extremely small. If a user moves their head only a few inches, the image moves in and out of focus quite rapidly, complicating tasks. Frequent refocusing of the device may be unacceptable to the user who continually changes the point of their attention or has a heavy workload, such as a loadmaster, gunner, or medic [4]. This report examines one approach for improving NVD depth of field by using small apertures over the objective lens, and its potential limits of NVD performance.

Depth of field arises from the ability of an imaging device to accept defocus [5]. Ignoring objective lens aberrations, imaging array resolution is limited by the picture element (pixel) size. The pixels of the NVD under "bright" light conditions are the individual channels in the image intensifier (I^2) tube microchannel plate [2]. This paper concentrates on the bright light condition where the NVD is microchannel-plate limited. In dim light conditions where system performance is limited by the human eye, the treatment of the problem changes somewhat and will not be addressed here [2].

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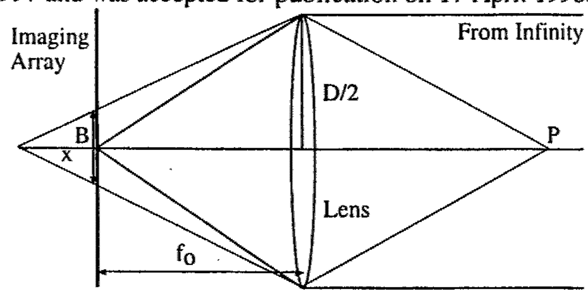

Figure 1. Geometry for derivation of hyperfocal distance.

Hyperfocal Distance

One should note that imaging system objective lenses are normally not single lenses but rather complex combinations of lens elements. For these complex lenses, the focal length of the lens, f_o, is the distance from the rear principle plane to the focal plane. To simplify the diagrams and to make the geometry more clear, complex objective lenses will be represented by a simple, single lens element.

An interesting condition can be derived from the geometry of a lens focused at infinity (Figure 1). Because it is focused at infinity, we know that the distance from the lens to the imaging array is exactly f_o, [5]. It is also known that because of the pixel size, or acceptable blur size, *B*, some points closer to the observer than infinity will be in acceptable focus. From this information, it is possible to determine the distance to the closest point that will appear in focus to an infinity-focused imaging system. From Figure 1, a point inside infinity, *P*, forming a blur circle of exactly *B* and appearing in focus to the imaging device, forms an image a distance *x* behind the photocathode. Given a lens of diameter D and a blur size B, x can be found by using basic geometry:

$$\frac{B/2}{x}=\frac{D/2}{f_o+x} \qquad (1)$$

Solving for x:

$$x=\frac{Bf_o}{D-B} \qquad (2)$$

Once x is known, the near edge of the depth of field for an infinity focused lens can be found by determining the plane in object space that is conjugate to the image distance $(f_o + x)$. This can be calculated by using the thin lens equation [5]:

$$\frac{1}{s}+\frac{1}{s'}=\frac{1}{f_o} \qquad (3)$$

Where, s is the distance from the lens to the object and s' is the distance from the lens to the image. For this derivation, s' is equal to $f_o + x$. Substituting this into the thin lens equation and solving for s yields:

$$s=\frac{f_o(f_o+x)}{x} \qquad (4)$$

Substituting the expression for x, Equation 2, into Equation 4 and simplifying yields an expression for the lens-to-object distance of:

$$HFD=s=\frac{f_oD}{B} \qquad (5)$$

Where HFD is the hyperfocal distance. Objects beyond this distance are in focus for an infinity-focused lens. Note that the HFD is directly proportional to the diameter of the lens.

Depth of Field

Calculating HFD is not ideal for determining the largest potential NVD depth of field. It should be easy to see that when focused well inside infinity, an optical device's depth of field will have limits on both sides of best focus. Since the model in the previous derivation is already focused on infinity, it only exhibits a near side. There can be no far side when focused at infinity since it is impossible to have real objects farther away than infinity. Conceptually, the infinity focus condition only uses part of the viewing device's potential depth of field. Derivation of the equations locating the near and far edges of the depth of field is more involved than for HFD.

The lens in Figure 3 is focused on an object at some distance, placing a sharp image in the image plane. Points closer to the observer than the object whose

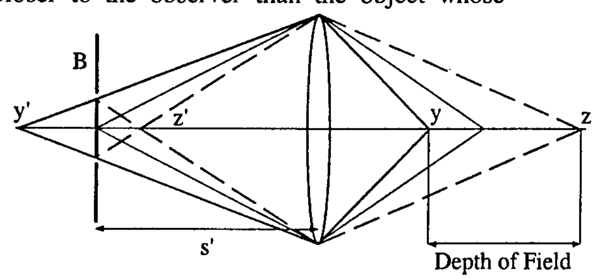

Figure 2. Basic depth of field geometry.

images are at the threshold for acceptable blur, image to a plane a distance y' behind the image plane. Points further from the observer than the object whose images are at the threshold for acceptable blur, image to a plane a distance z' in front of the image plane. Images that form anywhere up to a distance y' behind or a distance z' in front of the imaging array will appear in sharp focus to the observer. The longitudinal distance in object space from which these images come is the device depth of field, as in Figure 2.

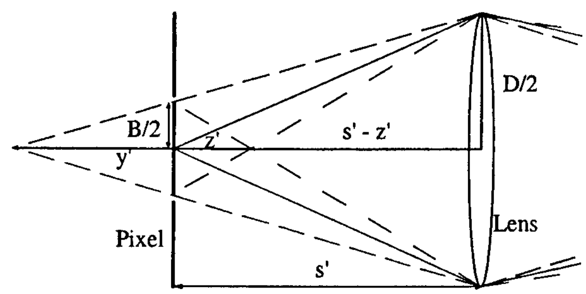

Figure 3. Geometry describing depth of field boundaries.

Two equations can be derived using the geometry of Figure 3: one for the depth of field's near edge and one for its far edge. Objects closer to the imaging system than the plane on which the imaging system is focused will form images behind the imaging array. Point objects closer to the observer than the focus distance that create blur circles with a diameter of exactly B will image a distance y' behind the imaging array. From Figure 3, it can be seen using the similar triangle approach that:

$$\frac{B/2}{y'}=\frac{D/2}{s'+y'} \qquad (6)$$

And therefore:

$$y'=\frac{Bs'}{D-B} \qquad (7)$$

Remember that s' is the distance from the lens to the image for a given focus distance. Using the thin lens equation, Equation 3, where the lens of focal length is f_o, and the focus distance is f_d. Solving for s' yields:

$$s' = \frac{f_o f_d}{f_d - f_o} \quad (8)$$

Now, the location of objects that image to the plane y behind the imaging array must be determined. Rewriting the thin lens equation so that S' is the image distance and S is the object distance gives:

$$\frac{1}{S} + \frac{1}{S'} = \frac{1}{f_o} \quad (9)$$

Solving for the object distance yields:

$$S = \frac{f_o S'}{S' - f_o} \quad (10)$$

It is known that S' is equal to the image distance created by the lens for a chosen focus, s', plus the extra distance behind the imaging array at which acceptable images would form, y'. Therefore:

$$S' = s' + y' \quad (11)$$

Substituting Equation 11 into Equation 10 yields:

$$S = \frac{f_o(s' + y')}{(s' + y') - f_o} \quad (12)$$

Substituting Equation 7 for y' into Equation 12 and simplifying yields:

$$S = \frac{f_o D s'}{s' D - f_o D + f_o B} \quad (13)$$

Substituting Equation 8 for s' and simplifying yields the equation for the near side of the depth of field.

$$S = DOF_N = \frac{f_o f_d D}{f_o(D - B) + f_d B} \quad (14)$$

The derivation of the equation for the far edge of the depth of field closely follows the one for the near edge. Objects farther from the imaging system than the plane of best focus will come into focus in front of the imaging array. Those whose point objects create blur circles of exactly diameter B form images a distance z' in front of the imaging array. Using geometry and the first order imaging technique, it can be shown that the location of the far edge of the depth of field, $\mathrm{DOF_F}$, is [6]:

$$DOF_F = \frac{f_o f_d D}{f_o(D + B) - f_d B} \quad (15)$$

One should notice that the equation for the far edges of the depth of field can generate negative numbers if f_d gets large enough, implying that $\mathrm{DOF_F}$ is beyond infinity. These results should simply be ignored since in the real world, distances cannot be negative and objects cannot be located farther away than infinity. Negative $\mathrm{DOF_F}$ values should be treated as an infinity result.

Limits

Notice what happens to the near edge of the depth of field when focus goes to infinity. This can be determined mathematically by evaluating the limit of the above $\mathrm{DOF_N}$ equation as f_d gets very large using L'Hôpital's Rule.

$$\lim_{f_d \to \infty} \frac{f_o f_d D}{f_o(D - B) + f_d B} = \frac{f_o D}{B} \quad (16)$$

This shows that for large focus distances;

$$DOF_N = \frac{f_o D}{B} = HFD \quad (17)$$

When the imaging system lens is focused at true infinity, the near edge of the depth of field should converge to the system's hyperfocal distance.

Another important condition to note is the focus distance, f_d, at which the far edge of the depth of field goes to infinity. Mathematically, this happens when the denominator of Equation 15 goes to zero. Setting the denominator to zero and solving for f_d yields:

$$f_d = \frac{f_o(D + B)}{B} \approx \frac{f_o D}{B} \quad (18)$$

Since D is much larger than B, this is essentially the hyperfocal distance. Therefore, when the imaging device's objective lens is focused at the device's HFD, the depth of field's far edge extends approximately to infinity. Recall that the near edge of its depth of field falls closer to the observer than the HFD. Since the depth of field's far edge extends to infinity for this particular focus condition, it is the condition for the maximum depth of field.

The near edge must be located to quantify the maximum depth of field. By substituting Equation 19 into the equation for the near edge of the depth of field, Equation 14, and simplifying, its position can be determined.

$$DOF_N = \frac{f_o(D + B)}{2B} \quad (19)$$

Note that this is approximately one-half the HFD. So, if the device is focused at the HFD, the depth of field extends from one-half the HFD to infinity. Since DOF_N slowly converges to the HFD as f_d gets larger, focusing at the HFD will maximize device depth of field. This condition is the maximum depth of field for a particular imaging system since objects cannot be located beyond infinity. Focusing an NVD in any other plane will yield a smaller depth of field.

PROCEDURES

A brief experiment was conducted to examine the practicality of the concept. Apertures were placed over an NVD objective lens. Several subjects' visual acuities were measured at discrete distances without refocusing the NVD. It was anticipated that stopping down an NVD objective lens, increasing depth of field, should yield a noticeable improvement in subject visual acuity at different distances without refocusing the NVD.

In this experiment each subject was placed in a light tight room and allowed to dark adapt for 15 minutes. The subject was then given an F4949 ANVIS-type (Aviator's Night Vision Imaging System) NVD focused at 30 feet and asked to read square wave acuity targets at 30 feet, 20 feet, and 5 feet from the end of the NVD without refocusing the device objective lenses. Subjects were allowed to adjust eyepiece focus to optimize their visual performance. Three different apertures were selected for the tests: 23.5 mm, which corresponds to the normal NVD objective lens aperture, 7 mm, and 3 mm. Each subject was asked to read the targets once for each aperture.

The square wave acuity targets used in this research were modified versions of the NVD focusing target originally designed and fabricated by Armstrong Laboratory personnel for the aviators of Desert Shield [3]. Modifications were limited to changing the frequency of the target square waves to enable the technicians to make the anticipated measurements.

Light levels used in the tests were chosen to maximize luminance out of the NVD, thereby maximizing NVD aided human visual performance. For these tests, the luminance level was chosen between quarter and half moon, approximately $8.0X10^{-3}$ footLamberts (fL) for the open aperture, $9.0X10^{-2}$ fL for the 7 mm aperture, and 0.5 fL for the 3 mm aperture. This ensured constant NVD photocathode illumination for all three trials. The higher light levels for the 3 mm and 7 mm apertures were calculated by taking the ratio of the NVD lens area to the aperture area and multiplying by $8.0X10^{-3}$ fL.

RESULTS

Theoretical

Example calculations are helpful in emphasizing the significance of the resultant equations from the earlier derivation. An average NVD will be used, with an objective lens focal length of 27.03 mm, an *f/#* of 1.23, and a maximum resolution of 1.0 cycles per milliradian. Its exit pupil diameter can be calculated to be 21.98 mm using Equation 20 where f_o is the lens focal length and D is the lens diameter [5]:

$$f/\# = \frac{f_o}{D} \qquad (20)$$

If *RES* is the maximum resolution in cycles per milliradian, then the blur circle size can be found using:

$$B = f_o Tan\left[\frac{1}{2000 \times RES}\right] \qquad (21)$$

Where f_o is the objective lens focal length and B is the blur circle size. Substituting the appropriate values into Equation 21 yields a blur size, B, of 0.01352 mm.

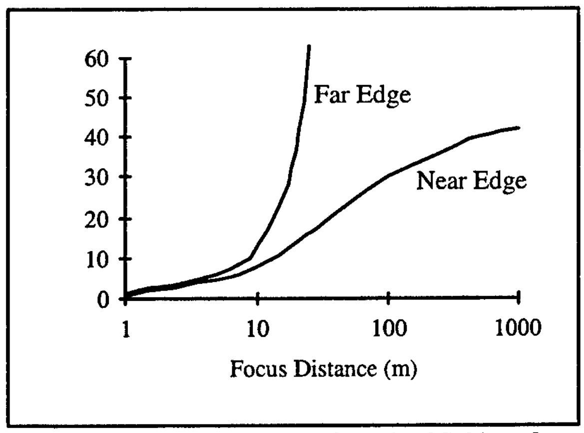

Figure 4. Near and far edges of depth of field vs. focus distance.

Now, recall Equation 5, the equation for the hyperfocal distance. For this system, f_o = 27.03 mm, D = 21.98 mm, and B = 0.01352 mm. Applying Equation 5 yields a HFD of 43.56 m. It should be noted that many systems available today exhibit resolution performance better than 1.0 cycles per milliradian. Improved resolution reduces B and consequently increases the HFD.

It is useful to examine how the equations behave as a function of f_d. When the location of the DOF_N and the DOF_F are plotted as a function of the focus distance, the results are shown in Figure 4. This figure has two interesting features. First, as f_d gets very large, as it would when the imaging system is focused at infinity, the near edge of the depth of field converges to the HFD. One should also note that as f_d approaches the HFD, DOF_F goes to infinity.

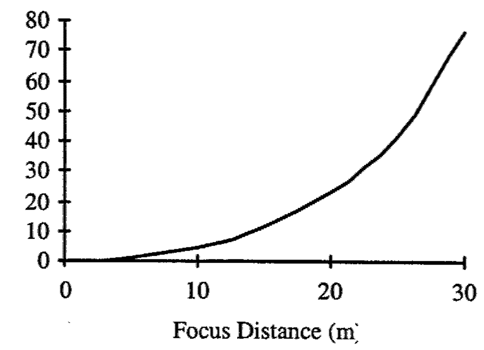

Figure 5. Depth of field vs. focus distance.

One should note that Figure 4 is a plot of the two edges of the NVD depth of field, not the depth of field itself. Calculating the difference between DOF_N and DOF_F and plotting it as a function of focus distance yields Figure 5. It is easy to see the trend that, for distances less than the HFD, the depth of field gets larger as the distance at which the NVD is focused increases.

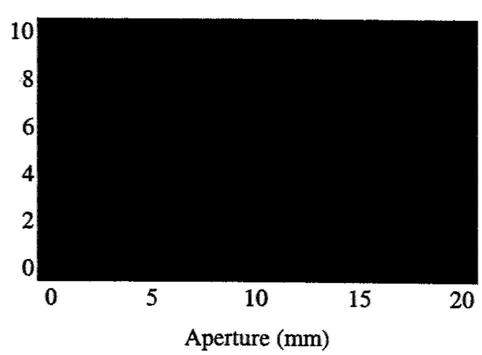

Figure 6. Depth of field vs. aperture size for various focus distances.

Figure 6 illustrates the effect of aperture size, *D*, on depth of field for several focus distances. Note that apertures above 10 mm have little effect but apertures below 5 mm show significant increases in depth of field. Also note that as focus distance gets longer, the curves move up and to the right, indicating that for longer focus distances, the user can achieve the same depth of field with a larger aperture. This effect gives rise to a significant tradeoff that will be discussed later. It should be emphasized that changing the focus distance also changes the location of the depth of field's near edge. While increasing focus distance increases depth of field, it also moves the depth of field's near edge father from the observer.

Figure 7 shows how depth of field changes with respect to NVD resolution performance for an F4949 ANVIS-type system where f_o = 27.03 mm and, without a limiting aperture, D = 21.98 mm. The trend indicates that high-resolution systems will have smaller depths of field. This is true in any two-dimensional imaging array. To achieve higher resolution, the pixels must be made smaller, making the overall system more susceptible to defocus. It should be noted that NVD HFD also increases for the same reason. A way around this effect, and recover the lost depth of field, is to shorten the objective lens focal length while maintaining a constant *f/#*. Unfortunately, this would increase the apparent angular size of the individual pixels and reduce the overall system resolution.

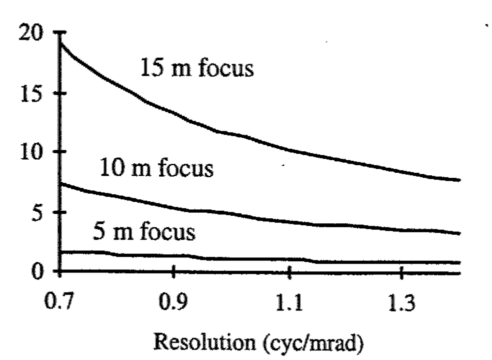

Figure 7. Depth of field vs. NVD resolution.

One can also see from Figure 7 that depth of field is larger for low resolution NVDs. If the user is willing to accept some resolution performance loss, depth of field will appear larger. If a user is trying to see large targets and adequate performance can be achieved with low resolution, user depth of field will appear to be larger.

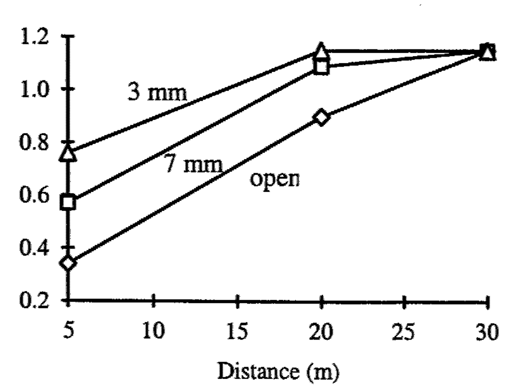

Figure 8. Resolution vs. target distance

<u>Experimental</u>

The data collected from the experiment described earlier appears in Figure 8. These data indicate that decreasing the objective lens aperture improves the subject's visual acuity as they view targets displaced from the plane of best focus. It also indicates that smaller apertures yielded greater acuity improvements than larger apertures. This is expected because of the anticipated increase in the device depth of field with a decrease in aperture size.

DISCUSSION

Radiometry of Small Apertures

As shown in Figure 6, it can be seen that depth of field increases dramatically as the limiting aperture diameter decreases. Unfortunately the light gathering capability of the device decreases as the limiting aperture gets smaller. When light is plentiful, this is not a problem. But in situations where one would use an NVD, light is scarce. The radiometry of the problem is very straight forward and described by the following equation [1]:

$$\Phi = LA\Omega \qquad (22)$$

In Equation 22, Φ is the radiant power or flux, L is the radiance of the source, A is the projected area of the detector, and Ω is the solid angle the source subtends from the point of view of the detector. The ratio of the radiant power collected by two different detectors is therefore given by:

$$\frac{\Phi_1}{\Phi_2} = \frac{L_1 A_1 \Omega_1}{L_2 A_2 \Omega_2} \qquad (23)$$

It is assumed that the two detectors are NVDs looking at the same scene, from the same point in space, but with different size apertures over their objective lenses. Therefore, they both see the same scene radiance, $L_1 = L_2 = L$, and solid angle, $\Omega_1 = \Omega_2 = \Omega$. When a lens is involved in radiometry, the area of the collecting lens is substituted for the area of the detector [1]. A_1 and A_2 now represent the areas of the two objective lens apertures. Equation 23 simplifies to:

$$\frac{\Phi_1}{\Phi_2} = \frac{A_1}{A_2} = \frac{\pi r_1^2}{\pi r_2^2} = \frac{r_1^2}{r_2^2} \qquad (24)$$

Where r is the radius of a particular aperture. Therefore, when using small apertures to increase depth of focus, device light gathering capability is reduced by the ratio of the squares of the radii of the apertures involved. For example, if a 3 mm aperture is placed over a 23.5 mm NVD objective lens, the NVD will see only 1.70% of the available light. This indicates that operations with small apertures over NVD objectives may require the use of auxiliary light sources. If such sources are not infrared, then the user may find it easier to simply take their NVD off and turn on conventional lighting. These calculations are made using the physical size of the NVD objective lens aperture, or lens entrance pupil, and not D, the exit pupil diameter, as in earlier calculations. Since the entrance and exit pupils are not necessarily the same diameter, the radiometry would not correctly describe the phenomenon if D were used.

Diffraction Limit

Even if adequate light is available for conducting NVD operations with very small apertures to increase depth of field, there is another limit that cannot be overcome: the objective lens diffraction limit. It is possible to try to operate with an aperture on a NVD that is small enough to create a diffraction spot larger than the limiting resolution of the I^2 tube. When this happens, the benefit of the larger depth of field is significantly reduced by the loss of system resolution. Theory indicates that the diffraction limited spot size, in microns, of an optical system is give by [8]:

$$\textit{Spot Size} = 2.44\,\lambda f/\# \qquad (25)$$

Where λ is the wavelength of light, expressed in microns.

Note that ANVIS-type NVDs, such as the F4949, are equipped with a minus-blue filter to shape the I^2 tube photocathode response and block most visible light. These filters pass light at numerous wavelengths. In this analysis, the filter response was reduced to a single wavelength by averaging the filter cut-on wavelength and the photocathode cut-off wavelength. Minus-blue filter cut-on wavelengths are 0.625 μm and 0.665 μm for Class A and Class B filtered goggles respectively. The cut-off wavelength of the photocathode is approximately 0.900 μm for the third generation I^2 tube's photocathode [7]. This yields average wavelengths of 0.763 μm for Class A filters and 0.783 μm for Class B filters.

Using the expression of *f/#* listed earlier, the spot size equation can be rewritten:

$$\textit{Spot Size} = \frac{2.44\lambda f_o}{D} \qquad (26)$$

Note that as the aperture becomes smaller, the diffraction limited spot size becomes larger. When the aperture is small enough, the diffraction limited spot size becomes greater than the resolution limit of the I^2 tube. When this happens, the maximum resolution of the device becomes equal to the diffraction spot size, decreasing NVD performance and reducing the benefit of a large depth of field. For the example system used earlier, (Spot Size = 13.52 μm and f_o = 27.03 mm) this happens when the lens limiting aperture shrinks below 3.7 mm with a Class A filtered response, and below 3.8 mm with a Class B filtered response. However, because of the energy distribution of the diffraction spot and an appropriate point resolution criterion, this phenomenon will not become significant until apertures about half as large as the calculated values are employed [8]. Therefore, apertures smaller than 3 mm were ignored in the experiment.

CONCLUSIONS

Objective lens focal length, objective lens diameter, system resolution, and the distance at which the system is focused all influence the depth of field of an imaging system like the NVD. Adjusting any of these parameters will yield a noticeable change. The amount of improvement possible in an application is determined by the image quality the user requires.

Adding apertures to reduce the objective lens diameter can significantly increase NVD depth of field. However, limitations reduce the usefulness of this approach. Apertures dramatically reduce the light gathering capability of the device. Supplemental illumination, such as auxiliary infrared lights, may be necessary to achieve the desired system performance. It is also possible to reduce the aperture to such an extent that imaging performance, or resolution suffers. Reducing the lens aperture slows the system *f/#* and increases the diffraction spot size. Once the minimum spot separation, determined by the diffraction spot size and the appropriate resolution criterion, exceeds the maximum resolution of the system, imaging performance starts to suffer.

Other parameters can be adjusted to increase NVD depth of field. Accepting lower system resolution performance will make device depth of field appear larger. This may be difficult to accept for some users whose duties require high resolution NVDs. Shortening the objective lens focal length while maintaining objective lens *f/#* will lead to a larger depth of field but will reduce the system's overall resolution performance. Objective lens focus distance can be optimized to yield a greater depth of field by focusing at the device's HFD. However, this is only practical when infinity focus is required. Poor objective lens positioning mechanisms make this approach difficult to implement.

Some performance characteristics can be sacrificed or traded to optimize NVD depth of field. These tradeoffs must be examined on the basis of individual situations or applications to determine the most acceptable compromise between depth of field, resolution performance, and light gathering before this idea can be implemented.

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The Impact of Helmet-Mounted Display Visor Spectral Characteristics on Visual Performance

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ABSTRACT

Visors are an important element in modern helmet-mounted displays (HMDs). In addition to their more conventional use as eye protection, they can be used as the final element in the optical system that relays visual information to the observer. To enhance their usefulness as the final optical element (as a beam splitter or image combiner), visors are sometimes coated to increase their reflectivity, improving the efficiency of the optics. However, pilots often object to the addition of reflective patches on their visors, indicating, among other reasons, that they decrease observed target contrast and, therefore, decrease target detection range. This paper will examine the impact of the additional reflective coating on visual performance through a helmet-mounted display visor. It will propose some design parameters on the spectral nature of the coating that might make it more useful to both the HMD designer and to the HMD wearer. Finally, this paper will examine visual phenomena that may affect visual performance through a coated visor.

Key Words: Helmet-mounted display, HMD, Visor, Visual performance, Coatings

1. INTRODUCTION

The visor is a critical part of the pilot's equipment. In most cases, it is one of at least two transparencies (visor and windscreen) through which they must look to see the world around him. Both transparencies can have a significant impact on the pilot's visual performance. The optical properties of both the visor and the windscreen, including transmission, reflection, distortion, and their tendency to scatter light, play an important role in the quality of image a pilot can see through them.

Visors have evolved into an important part of modern helmet-mounted displays (HMDs). To simplify the optical design, in terms of the number of optical elements needed, the helmet visor can be used as the beamsplitter, reflecting the HMD imagery into the pilot's eyes while still allowing him to see the targets of interest. This final reflection can rely on the Fresnel reflectivity inherent to the visor or can be enhanced by use of coatings. Coatings of interest can enhance the reflection of the visor as much as desired. Unfortunately, these reflection-enhancing coatings are known to have a negative impact on the pilot's visual performance. Many pilots have noticed a significant and unacceptable reduction in the distance at which they can engage a target, or "Tally Ho" distance [Kocian and Task 2000]. However, HMDs that employ uncoated visors must rely on very luminous image sources to ensure that enough light reaches the pilot's eyes. This tends to shorten image source lifetime and preclude the use of certain image sources in these HMD designs.

To examine the impact of visor coatings, one must start with the assumption that reductions in visual performance are due exclusively to a loss of target contrast. As shown in Figure 1, this paper will define L_T as the luminance of the target, L_B as the luminance of the target background, E_s as the external illumination falling on the visor, and L_H as the luminance of the HMD display that reaches the observer's eyes. Using this notation, the true contrast (Michaelson or modulation contrast) of the target, of luminance L_T, with its background, of luminance L_B, can be expressed as:

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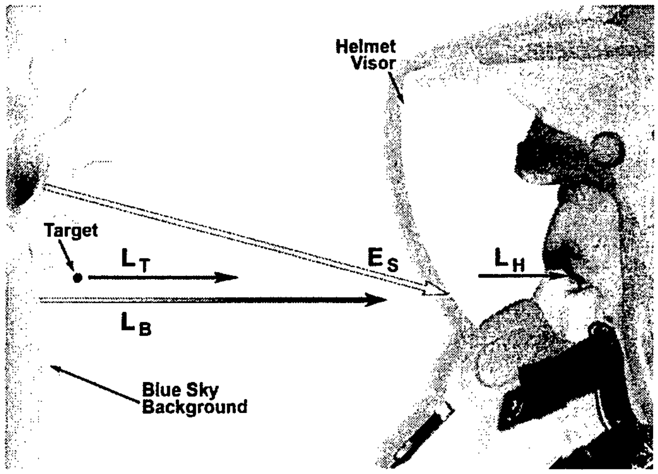

Figure 1. Graphical description of parameters affecting observed contrast.

$$C_T = \frac{|L_T - L_B|}{L_T + L_B} \qquad (1)$$

The primary reason for this loss of observed contrast is the veiling luminance stemming from scattered light from the visor and from facial reflections. To incorporate the impact of scatter and reflections on the perception of target contrast, a veiling luminance, L_V, can simply be added to the target and background luminances in Equation 1. This approach was used in other papers [Marasco and Task 2001] [Kocian and Task 2000] and treats the veiling luminance as if it originates at the visor, not propagating through it like the light from the target. Therefore, the impact of visor transmission, T_V, on perceived contrast must be included. This is achieved by multiplying L_T and L_B by T_V. These modifications of Equation 1 change the equation from one describing the true contrast of the target to an equation for the contrast seen from the observation point, or observed contrast, C_o.

$$C_o = \frac{|(T_V L_T + L_V) - (T_V L_B + L_V)|}{(T_V L_T + L_V) + (T_V L_B + L_V)} \qquad (2)$$

Assuming that L_B is greater than L_T, the above expression simplifies to:

$$C_o = \frac{C_T}{\frac{L_V (C_T + 1)}{L_B T_V} + 1} \qquad (3)$$

To maximize C_o, one has few options as shown in Equation 3. L_B can be large but not on command. The engineer cannot control the sky or ground luminance. L_V can be made small, but only so small. Recall that:

$$L_V = L_{Vs} + L_{Vf} \qquad (4)$$

Here, L_{Vs} and L_{Vf} are the veiling luminance caused by scatter from the transparency and the veiling luminance from facial reflections, respectively. The veiling luminance caused by visor scatter is a function of a number of parameters including the incident illuminance (E_s) and the sample's inherent tendency to scatter light, symbolized by a function S_v. The sample's ability to scatter has been shown to be a function of the illumination and observation geometry and the wavelength of the illumination, λ [Marasco 2000]. Stated simply, $L_{Vs} = E_s S_V$. If one assumes a Lambertian reflection and keeping in mind that $E_s = M = \pi L$ [Boyd 1985] where M is the luminous exitance and L is luminance, the luminance of the pilot's face, L_f, can be described as:

$$L_f = \frac{1}{\pi} E_s T_V R_f \tag{5}$$

Here, R_f is the reflectivity of the pilot's face. When this light is reflected back to the pilot by the visor, it contributes to L_V. The veiling luminance due to facial reflections as seen in the visor, L_{Vf}, can therefore be expressed:

$$L_{Vf} = \frac{1}{\pi} E_s T_V R_f R_V \tag{6}$$

Here, R_V is the reflection from the inside surface of the visor. Eliminating scatter from the visor and reflections from the pilot's face is difficult if not impossible. And even if scatter can be eliminated from new visors, it will increase as the visors age and become scratched from wear and handling.

The only parameter in Equation 3 that the engineer can use to improve observed contrast is the visor transmission. T_V can be made as large as possible, thus improving the target's observed contrast (Figure 2). In Figure 2, observed contrast is plotted as a function of transmission for a number of conditions described by the ratio of the veiling luminance to the background luminance (L_V/L_B). This parameter is used to indicate how much stronger than veiling luminance the background luminance is. When L_V/L_B is small, the background luminance dominates the ratio, improving visual performance by overwhelming the veiling luminance. When LV/LB is large, scattered light dominates, reducing visual performance. One should also note from Figure 2 that visor transmission can significantly influence observed contrast, especially when transmission is below 20%.

Dielectric stack coatings can be designed to build reflectors that are spectrally selective. Such coatings can be designed to reflect strongly at some wavelengths while functioning as an antireflection coating at others, reflecting nearly nothing. This property of dielectric stack coatings can be exploited to build a visor reflector for HMD applications that maximizes visor transmission, thus increasing the visibility of targets seen through the visor, while increasing the amount of light presented to the pilot by the HMD optics.

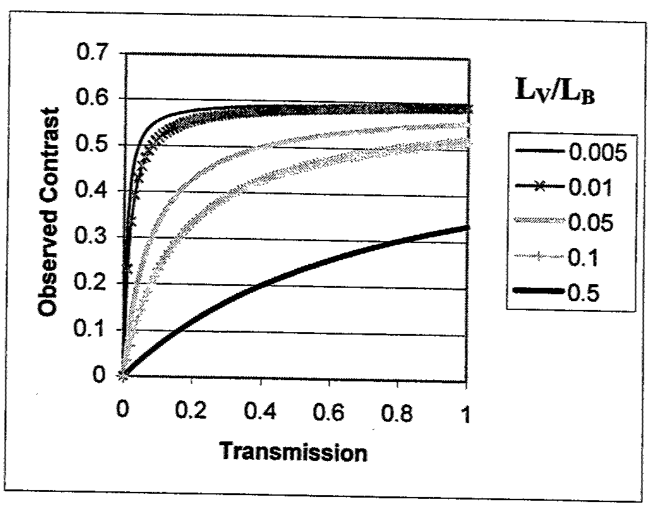

Figure 2. The effect of transmission on observed contrast for a 60% contrast target.

2. EFFECT OF SPECTRAL TRANSMISSION AND REFLECTION

Up to this point, this paper has treated many parameters as constants with respect to wavelength. However, many, if not all, parameters discussed are functions of wavelength. For example, the Fresnel surface reflections are often treated as relatively constant with respect to the visible spectrum but actually exhibit distinct wavelength dependence. Figure 3 is a plot of the index of refraction of two popular plastics as a function of the wavelength of light. Using established relationships, the Fresnel reflection for polycarbonate can be calculated (Figure 4). This is a plot of the reflectivity of a bare polycarbonate surface inclined at a number of incidence angles. One can see from Figure 4 that even an uncoated piece of plastic reflects more strongly in blue light than in red. The Fresnel reflectivity of many optical materials, including glass, is a function of wavelength and incidence angle. One should note that the reflectivities plotted in Figure 4 are the average of s and p polarized light. The reflectivity of each can be noticeably different (Figure 5). At a 45-degree angle of incidence, similar to what is used in some helmet-mounted display designs, the bare polycarbonate visor reflects predominantly s-polarized light. However, for unpolarized sources, the reflectivity of the surface is the average of the s- and p-polarized components. The resulting surface reflectivity is considerably less for unpolarized sources.

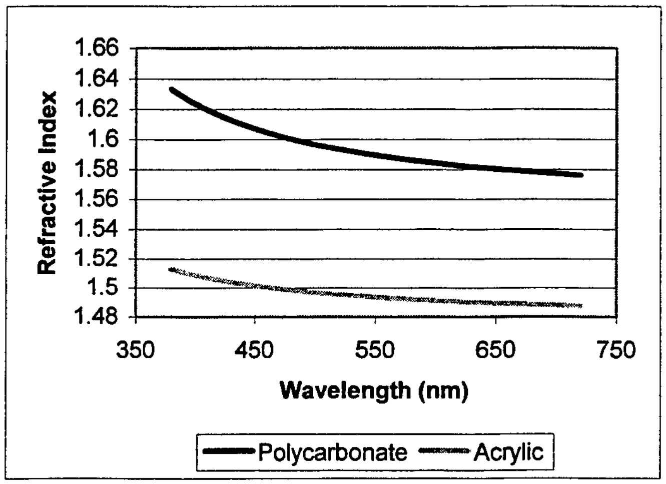

Figure 3. Index of refraction of two plastics plotted as a function of wavelength.

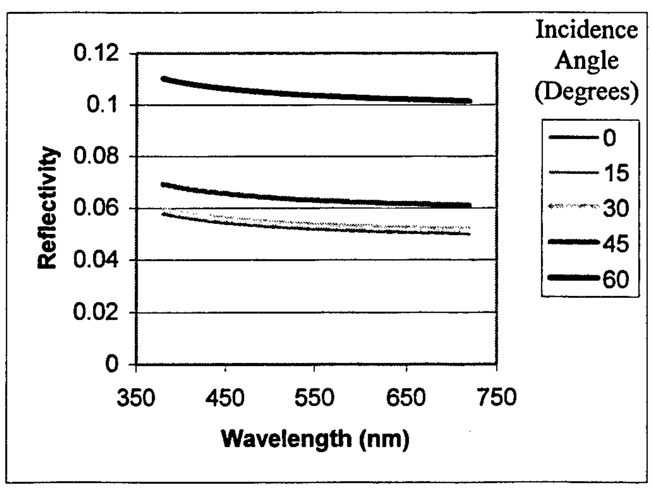

Figure 4. The reflectivity of polycarbonate plotted as a function of wavelength for five angles of incidence, in degrees.

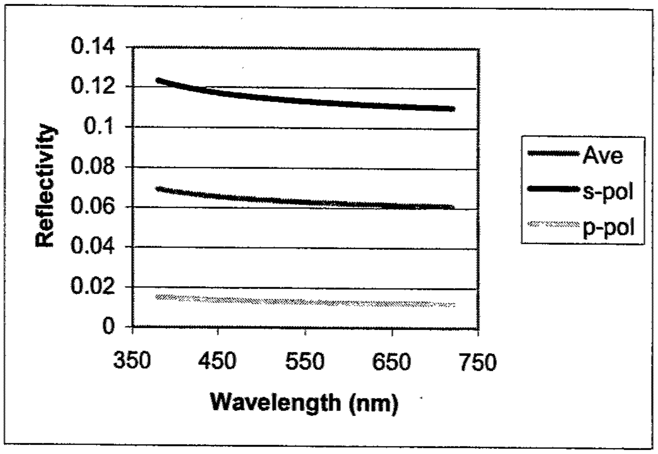

Figure 5. The average reflectivity of polycarbonate as a function of wavelength and its reflectivity for s- and p-polarized light.

Thin dielectric stacks have been used to create coatings with spectrally complex reflectivities and transmissivities. If dielectric stack reflectors are employed on the visor, this spectral complexity can be exploited to achieve several interesting results. A good coating should do more than just reflect the image source of the HMD. One could, theoretically, be tuned to give the desired reflection of the HMD while transmitting a large percentage of visible light from the target. This can be accomplished by redistributing the reflectivity inherent in the visor surface. Fresnel reflection for a polycarbonate visor is about 6% per surface (12% per visor). If the visor could be antireflection coated in parts of the visible spectrum not needed to reflect the HMD image source, this loss could be recovered for wavelengths other than those reflected for the display. One could think of the approach as "stacking up" the surface reflectivity where desired. This approach works particularly well with narrow emission band phosphors. Coatings can be optimized to reflect the primary emission while antireflection coating the surface for all other visible wavelengths.

2.1 Basic Photometry and Coating Design

It is easy to see how the amount of visible light available influences an observer's vision. This paper employs photometric quantities to describe light. To calculate the amount of visible light available, L_{Vis}, from a source of spectral radiance $L(\lambda)$, one must apply the following equation [Boyd 1985]:

$$L_{Vis} = k\int_0^\infty V(\lambda)L(\lambda)d\lambda \qquad (7)$$

This equation describes the summation of all light from the source over all wavelengths, weighted by the spectral response of the human eye, $V(\lambda)$ (Figure 6). To complete the calculation, the integral is multiplied by k, the luminous efficacy, a constant used to convert radiometric units to photometric units. For example, this integral can be interpreted graphically to calculate the amount of visible light emitted from the P43 phosphor (Figure 7). To do this, one would multiply Figure 6 by Figure 7, sum the individual components over all visible wavelengths and then multiply by k, yielding the amount of visible light (luminance) emitted from the P43 phosphor in photometric units. The above equation can be modified and used to calculate the impact of filters and reflectors on the amount of visible light available by including the spectral nature of the reflector inside the integral. For a reflector, $R(\lambda)$, the equation becomes:

$$L_{Vis} = k\int_0^\infty V(\lambda)R(\lambda)L(\lambda)d\lambda \qquad (8)$$

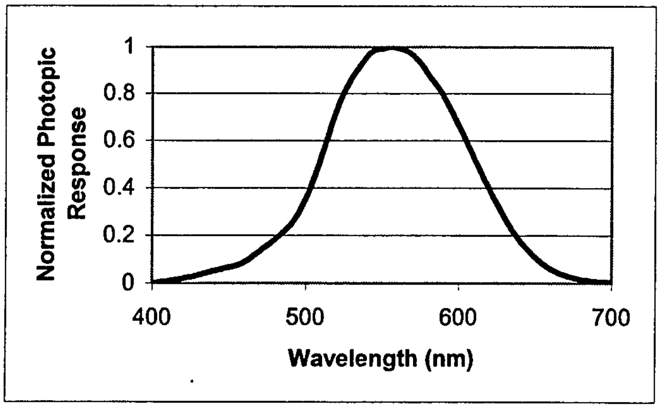

Figure 6. Photopic response of the human eye [Wyszecki and Stiles 1982].

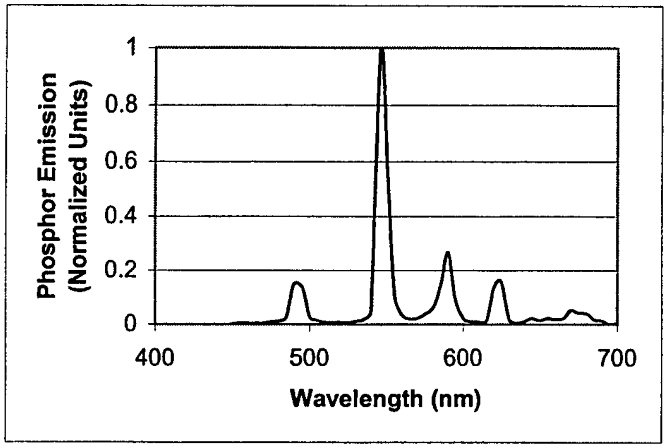

Figure 7. Normalized P43 phosphor emission.

This integral can also be expressed graphically as the multiplication of Figure 6 by Figure 4 and Figure 7, the summation of the individual components over visible wavelengths, and then multiplication by k. The result is the amount of visible light emitted from the P43 phosphor that is reflected from a polycarbonate visor inclined at 45 degrees. Using this approach, the amount of light reflected can be expressed as a percentage by dividing the reflected light by the incident light. In terms of the integrals used earlier, this ratio can be described as:

$$R_{source} = \frac{k\int_0^\infty V(\lambda)R(\lambda)L(\lambda)d\lambda}{k\int_0^\infty V(\lambda)L(\lambda)d\lambda} \times 100\% \tag{9}$$

If this is applied to the P43 example, one will find that 6.3% of the visible light from a P43 phosphor will be reflected from an uncoated polycarbonate visor, inclined at 45 degrees. Using a similar development and by applying the fact that T = 1 – R, the photopic transmission of a surface can be expressed:

$$L_{Vis} = k\int_0^\infty V(\lambda)T(\lambda)L(\lambda)d\lambda = k\int_0^\infty V(\lambda)(1 - R(\lambda))L(\lambda)d\lambda \tag{10}$$

or as a percentage of the total incident light using:

$$T_{Photopic} = \frac{k\int_0^\infty V(\lambda)T(\lambda)L(\lambda)d\lambda}{k\int_0^\infty V(\lambda)L(\lambda)d\lambda} \times 100\% = \frac{k\int_0^\infty V(\lambda)(1-R(\lambda))L(\lambda)d\lambda}{k\int_0^\infty V(\lambda)L(\lambda)d\lambda} \times 100\% \qquad (11)$$

2.2 Coating Design

This treatment will restrict analysis to the transmission and reflection of the inner surface of the visor. One should keep in mind that the overall transmission of the visor is a function of two surfaces and the bulk material. However, since the coating on the visor's inner surface cannot influence the transmission or reflection of the other two contributors, they will be ignored when comparing coatings.

The goal of this effort is to design a coating such that the reflectance of the source is as high as it needs to be while maximizing photopic transmission through the visor. To improve the pilot's visual performance, the visor's photopic transmission must be approximately equal to the photopic transmission of an uncoated visor surface. One must therefore calculate visible light transmitted through the final visor surface. The photopic transmission of the target's background, as seen through a visor, can be expressed using Equation 10 by replacing $T(\lambda)$ with the spectral properties of the visor's rear surface, denoted as $T_V(\lambda)$ if the surface is uncoated, and inserting the spectral properties of the target's background ($L(\lambda)$). If the visor is coated, replace $T(\lambda)$ with the spectral properties of the visor's rear surface coating, denoted $T_{VC}(\lambda)$, and perform the appropriate integration.

This approach is consistent with the assumption made earlier that the target background is brighter than the target itself. If this is not the case, one should calculate the photopic transmission of the target seen through a visor. This can be expressed using Equation 10 and inserting the spectral properties of the target itself ($L(\lambda)$) and the appropriate visor transmission.

The second parameter to examine is the reflection of the HMD image source from the visor. This is important to ensure the observer receives sufficient light from the HMD to make the symbology visible. The photopic reflectance of the image source by the visor can be calculated using Equation 8 by replacing $R(\lambda)$ with the spectral properties of the visor's rear surface, denoted either $R_{VC}(\lambda)$ or $R_V(\lambda)$, depending on whether the visor is coated or not, and inserting the spectral emission of the HMD source ($L(\lambda)$).

2.3 Optimization

The number of degrees of freedom afforded the engineer by the design can limit optimization of a coating. The simplest coating that might yield the performance required is an antireflection coating with a partially reflecting notch (Figure 8). Designing and optimizing a coating of this nature affords the engineer three primary parameters to manipulate: the reflectivity of the coating within the HMD image source emission band, the width of the reflection band for the HMD source, and the quality of the antireflection coating outside the notch. One could argue that the location of the reflective notch is a fourth parameter. Unfortunately, the selection of the HMD image source will place this parameter beyond the control of the engineer. To minimize the impact of the coating on pilot visual performance, it is recommended that the coating be optimized to transmit visible light equal to the transmission of the uncoated visor surface. The three primary parameters can be combined to yield coatings that transmit as much light as the uncoated visor surface, minimizing the impact of the visor coating, while reflecting significantly more light from the HMD. Some of these parameters will have a stronger impact on the coating performance than others. For example, the width and reflectivity of the notch will strongly influence the amount of HMD image source light available to the pilot. Reducing the reflectivity of the antireflection coating outside the reflective notch may have little impact on the total transmitted light.

3. EXAMPLE COATING DESIGN

3.1 Performance Benchmarks

Two visors historically used on head and helmet mounted displays set performance benchmarks for the technology: the standard polycarbonate visor without a reflective coating and the polycarbonate visor with a 13% reflective metal partial mirror. The standard neutral gray visor without a reflective coating is considered acceptable for target detection ("Tally Ho") but does not reflect much HMD light, requiring a bright HMD image source. Visors with a metallic coating reflect plenty of HMD light but are not acceptable for target detection. Metallic coatings are considered to have a detrimental impact on "Tally Ho" distance due to the associated transmission loss. A solution lies somewhere in between.

The first surface examined here is the uncoated polycarbonate. Two figures of merit of interest are the surface's transmission of all visible light, T_{Phot}, and its reflection of the visible light from the P43 phosphor, R_{P43}. To calculate T_{Phot}, one needs to know something about the nature of the light coming from the target background. Since there are virtually an infinite number of possible target backgrounds to consider, this paper will limit its analysis to one. The target background will be assumed to be spectrally uniform, or white, with all wavelengths considered to have equal radiance. This assumption will simplify the resulting calculation. Using the information displayed in Figure 4, Figure 6, and Equation 11, the photopic transmission of an uncoated polycarbonate surface was calculated to be 93.7%. The calculation of the percent of light from the P43 phosphor can be calculated using a similar approach. Using the information in Figure 4, Figure 7, Figure 6, and Equation 9, the photopic reflectivity of an uncoated polycarbonate surface was calculated to be 6.3%. This result should have been expected because of the nature of the visor reflectivity. It reflects all wavelengths of approximately equal radiance.

The results from the analysis of the metallic reflective surface were equally predictable. Since metallic coatings exhibit relatively uniform reflectivity in the visible region of the spectrum, the 13% reflective surface was modeled as a perfectly uniform, 13% reflector at all visible wavelengths. Using this model, the information in Figure 6, and Equation 11, the photopic transmission of the metal surface was calculated to be 87%. In addition, the reflectance of the light emitted from the P43 phosphor was calculated using a similar approach and Equation 9 to be 13%. One should note that the metal reflects twice as much photopic energy from P43 as the uncoated visor. In addition, one should note that the difference between the photopic transmissions of the two surfaces is only 6.7%. It is surprising that such a small difference in visor transmission can have a significant impact on visual performance. This emphasizes the need to design a visor reflective coating that maximizes photopic transmission.

3.2 Example Design

From the previous analysis, one can conclude that some HMD systems require a reflectivity about twice that of the uncoated visor to provide adequate light from the HMD image source to the observer. It is also easy to see the need for high photopic transmission. Fortunately for the coating design, HMDs tend have image sources that use phosphors with fairly strong, spectrally narrow primary emissions. This tendency can be exploited to design a visor reflector that begins to look like an antireflection coating with a slight reflective spike (Figure 8).

This example design assumes the HMD image source will use a P43 phosphor. As a result, the spectral width and location of the visor coating reflection were chosen to correspond with the primary green emission of the P43 phosphor (Figure 7). The example coating's notch falls between 530 and 565 nm. The next step was to choose the quality of the antireflection coating outside of the reflection notch. To improve the photopic transmission, an average reflection of 0.5% was chosen. This parameter may be limited by manufacturing issues not addressed in this paper. However, once the quality of the antireflection coating and the width of the reflective notch are chosen, only the average reflection inside the reflective notch remains undetermined. Using the parameters established for the coating and Equation 11, the average notch reflectivity was calculated such that the coating's photopic transmission was equal to the transmission of the uncoated polycarbonate surface. The resulting reflectivity was calculated to be 17.1%. Using the approach outlined earlier and Equations 9 and 11, the example coating's photopic transmission and P43 reflection were then calculated. This coating yielded a photopic transmission of 93.7% and a P43 reflectivity of 12%.

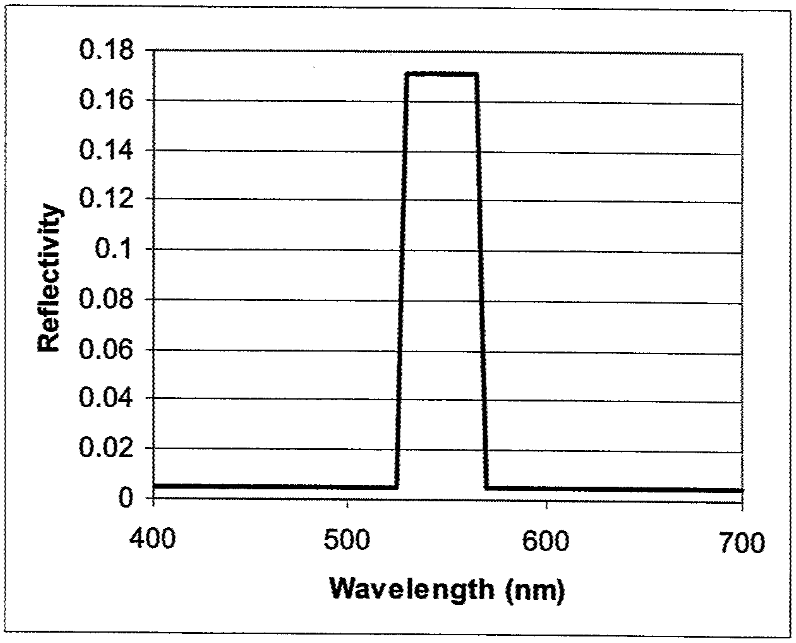

Figure 8. Spectral reflectivity for a potential visor coating.

Table 1. Transmissivity of visible light and reflectivity of P43 phosphor emission for three visor coatings

Coating	T_{Phot}	R_{P43}
Uncoated Polycarbonate	93.7 %	6.3 %
Metallic Reflector (13 %)	87.0 %	13.0 %
Example Design	93.7 %	12.0 %

4. DISCUSSION

4.1 The Impact of Luminance Transmission

In adding a reflecting coating to a visor, the additional luminance transmission loss should be insignificant for spectrally narrow reflectors of peak reflectivity of 50% or less. One should keep in mind that the current visor can transmit as little as 10% of the available light. The addition of such a coating could drop the transmission of a particular narrow spectral band to, at most, 5% while leaving the visor's transmission over the rest of the visible spectrum unchanged. However, if this proves to be a problem, one conceivable solution would be to alter the absorption of the visor to make it more transmissive in the same place, spectrally, as the coating is more reflective (Figure 9). The combination of the two would then yield an overall transmission similar to the standard, uncoated visor.

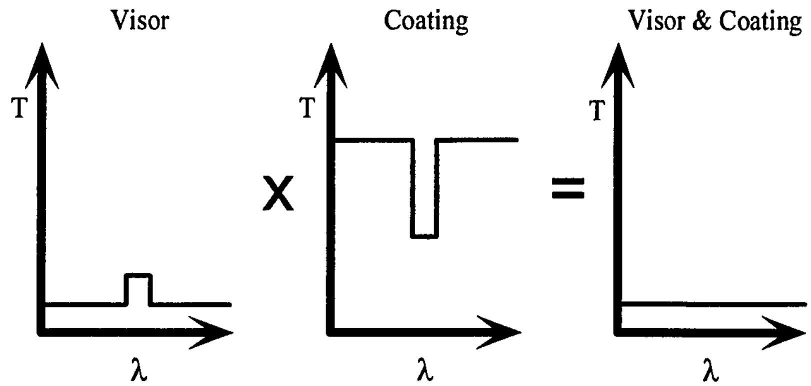

Figure 9. Graphical representation of the combination of visor and coating transmission.

4.2 The Impact of Color Perception

The potential exists for spectrally non-neutral coatings to influence an observer's perception of color. Such color shifts should be investigated for each coating and visor combination using conventional techniques for calculating the color coordinates of cockpit displays, as seen through both uncoated and coated visors, and determining the magnitude of the coordinate shift induced by the coating, such as those outlined by Wyszecki and Stiles [Wyszecki and Stiles 1982]. One then must consult the body of literature on color naming and color recognition to determine if the induced color shift will inhibit an observer's ability to correctly identify the colors presented by the display. The tolerances on color coordinate shift are expected to be fairly large [Post and Calhoun 1988]. However, should color perception become problematic, the approach described in the previous section of altering the absorption of the visor, making it more transmissive where the coating is more reflective (Figure 9), could be applied. Therefore, the impact on color perception is expected to be minimal.

5. CONCLUSIONS

Visor coatings can be engineered to increase the amount of photopic energy available to the observer while minimizing unwanted visual phenomena and minimizing the impact on "Tally Ho" distance. To increase visor transmission, a modified antireflection coating can be applied to the rear surface. This coating effectively "stacks up" reflectivity in a spectral region where the HMD source is strong, such as in the green for the P43 phosphor, while minimizing it everywhere else in the visible spectrum. The end result is a visor surface that transmits more light than an uncoated surface but reflects more HMD light also. Increasing visor photopic transmission increases perceived target contrast and, therefore, increases "Tally Ho" distance. This strategy also enables one to gain the added benefit of minimizing unwanted reflections from the pilot's own face and eyes.

The impact of the visor coating should be minimal. Its effect on overall luminance transmission should be small because of the absorbing dye that tints the daytime visor. The amount of energy from the outside world affected by the coating is small when compared to the visor tint. This tint can absorb more than 50 to 80% of the incident light, depending on how dark the visor is. Color shifts are expected to also be insignificant. The spectral reflections exploited could be 10 to 50% depending on the luminance and spectral characteristics of the HMD source. In addition, the human tolerance for color naming is fairly large and should be adequate to overcome color coordinate shifts induced by the visor coating. Finally, should either luminance transmission or color perception be significantly impacted, compensation can be made for both in the absorption of the visor tint.

ACKNOWLEDGEMENTS

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Night Vision Goggle Cockpit Integration

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ABSTRACT

Retroactively introducing night vision goggles to aircraft whose initial design did not account for them often poses safety and operational concerns. The addition of extra devices, such as Night vision goggles (NVG), are of particular concern in the fighter community. Fighter pilots must continue to contend with where to stow the NVG's during landing and take-off phases of flight until an ejection-safe NVG is fielded. This issue was highlighted recently when an NVG storage case became entangled in the flight controls of an A-10 attack aircraft. In the cargo and bomber communities, non-NVG compatible lighting often poses problems impacting the performance of the goggles. The prohibitive cost of major aircraft lighting modifications often force aircrews to improvise, adapt and overcome the limitations of the cockpit design to perform their missions. Occasionally aircraft System Program Office's (SPO) attempt to solve some of these problems with partially effective low-cost-alternative solutions. Retroactive solutions to effectively introduce and integrate NVGs must be well thought out with the safety of the aircrew as the primary concern. Methods of retrofitting the B-1 Bomber with a light-weight light-blocking curtain will be addressed. Additionally, results of a comparative study on various types of batteries will be presented, with possible solutions for eliminating NVG storage cases from the fighter cockpits concluding this paper.

INTRODUCTION

B-1 Curtain

As night vision goggle performance factors improve with such advances in optical lens coatings and reduced halo intensifier tubes, cockpit integration of these and other devises must constantly be considered in their development and implementation. Fabrics' qualities within the cockpits should be considered prior to introducing NVG's to new weapon systems. Fabrics with high-sheen characteristics reflect excess light causing glare, bloom, and system gain reduction in the NVG's. Many of these aspects although superficial in comparison to other flight issues, could negate the intended weapon system improvements.

An effort to improve the lighting in the B-1 was initiated at the B-1 SPO, Wright-Patterson AFB. Incompatible lighting in the front cockpit was corrected with the addition of a "Christmas Tree" lighting modification. This relatively inexpensive modification involves the installation of a string of NVG-compatible lights around the flight instruments, similar to those used to decorate a tree. These lights enable the crew to look under the NVG's to observe their instruments with their naked eyes without the light effecting the NVG's performance. However, since the Offensive and Defensive System Officers ("Back-seaters) don't require NVG's, lighting modifications were not made to their stations, leaving full spectrum lighting in the aft compartments.

This created problems with incompatible lighting flooding into the forward flight station degrading the NVG's performance. When exposed to excessive light, the NVG's auto-gain feature activates reducing the level of light intensification as a means of protecting the system from over light saturation. The gain reduction results in a general reduction of goggle performance and thus visual acquity to the user.

A means to stop the transition of light from the back to the forward area was needed. A prototype curtain was locally fabricated using a heavy black nylon fabric as a first attempt to stop the "bad" light. They selected a black fabric, as it was perceived to have lower reflectivity. The curtain was installed in the hallway between the fore and aft flight-stations, and then evaluated on the ground for form and function. When viewed through NVGs, the curtain appeared to "glow" from the transmission of non-compatible lighting through the weave of the fabric. A non-porous material was needed to stop the light's transmission. The evaluators improvised and modified the curtain by attaching material from a 35mm projector screen onto the back of the nylon curtain. Although this modification successfully blocked the transmission of light when viewed through NVGs, the resulting curtain was very bulky and concerns of reflectivity and general safety surfaced. The prototype curtain was sent to the Air Force Research Laboratory for spectral evaluation. The materials were immediately recognized as unsuitable for the typical military flight environment. The flammability of the nylon was the first concern and although the characteristics of the projector screen material were unknown, the safety and availability of the material would likely be questionable for general application in fielding the design.

Sample Selection

Efforts to find replacement materials began immediately. Materials had to have low reflectivity and low or zero light transmission. The materials also needed to be fire resistant for use in the cockpit environments.

The samples identified in Table-1 were selected for evaluation. Several of the samples, such as the flight clothing and B-52 material, were materials already approved for use in flight environments. The other samples were selected based on the known flame resistant qualities of both Nomex™ and fiberglass.

Flight clothing was selected for evaluation since their use in flight environments had already been established. Evaluating the flight clothing would also provide a baseline of reflectance levels already tolerated in the cockpits.

SAMPLE #	Description
1	Teflon-Coated Fiberglass (55-5)
2	Teflon-Coated Fiberglass (55-10)
3	Mylar Sandwich
4	Rubber-coated Cotton (two-sides)
5	Flat-Black Rubberized
6	Proto-type (Nylon/screen)
7	NOMEX-Black
8	NOMEX-Sage green
9	TCTO Curtain (Urinal)
10	B-52 Curtain-Cotton (un-coated)
11	B-52 Curtain-Cotton (rubber coated)
12	Green Flight Jacket (CWU-36/P)
13	Teflon-Coated Nomex (63-10)

Table 1. Subject Samples

Set-up & Testing-Transmission

The samples were measured for both light transmission and spectral reflective qualities using the following methods. During transmission evaluation, a Hoffman ANV-120 integrating sphere provided a calibrated light source for transmitting light through the subject materials. Any light transmitted was captured and intensified using an NVG (model AN/AVS-9) on the other side of the subject material. A luminance probe measured the goggles output luminance before and after the subject material was inserted in the light path between the light sphere and the NVG. Light transmitted through the fabric would be a percentage of the light originally measured in the sphere.

The NVG'S were focused to infinity and eyepiece lenses set at zero-diopter using the Hoffman ANV-126 and then centered on the sphere's output. After a brief NVG warm-up, the luminance in the sphere was adjusted to (1.980×10^{-3} Foot-Lamberts). A reference reading was recorded before measuring the samples by placing the luminance probe in the center of the sphere's output. The sample-reading would later be divided by this reference-readings to determine the percentage of light transmitted. Zero light transmission was the desired readings with eight samples meeting this goal. (see Table 2)

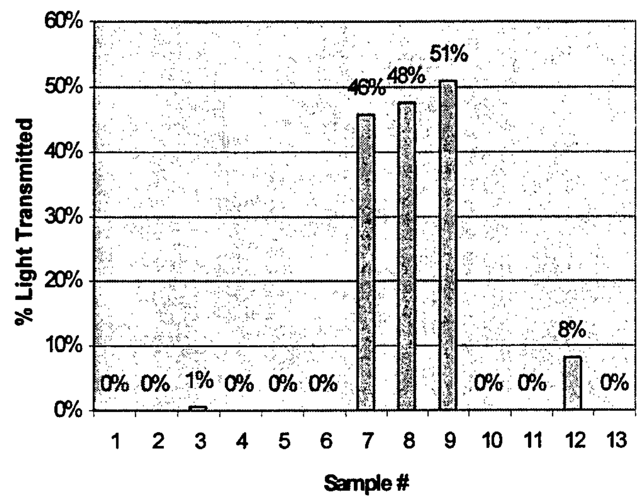
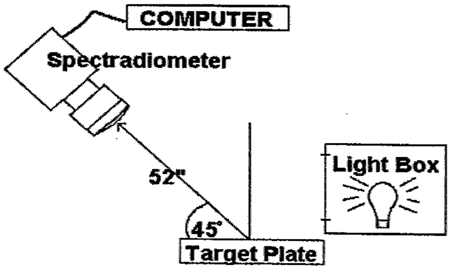


Table 2.Transmission

Set-up & Testing-Spectral Reflectance

Assessing the spectral reflectance qualities of the fabrics involved bouncing a 2856K light source off the subject materials and measuring the reflected light using a spectradiometer. A reference reading of the light source was directly measured to calculate the percentage of light reflected. This would provide the "spectral" reflectance of the material samples.

Figure 1. Measuring Spectral Reflectance

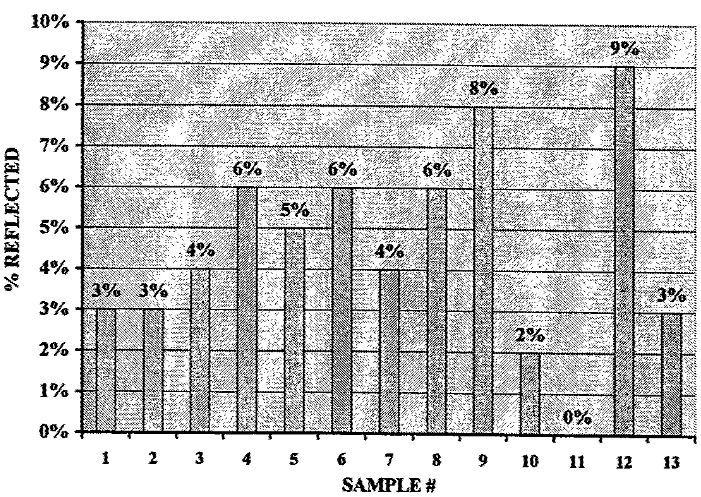


We placed the 2856K light source at a 90° angle to the sample surface and parallel to the original reference measurement axis. The spectradiometer was positioned 45° off the original measurement axis with the lens positioned 52" and centered from the target area to adjust for the focal length of the spectradiometer.

After a 15-minute warm up for the light source, the samples were positioned flat against the target plate and individually scanned and recorded on a laptop computer. The 2856k source was then placed in the sample location and centered in the field of measure for the spectradiometer. A scan of the light source was taken from the same 45° off axis target plate location. This reading would serve as the base line for division of the sample scans giving us the spectral reflectance qualities of the materials. See Table 3 for results.

Table 3. Spectral Reflection Results

The Teflon™-coated fiberglass and Nomex™ materials (samples 1, 2 & 13) performed well exhibiting relatively low reflectance and zero transmission. Just as important,



both qualities were achieved with a single fabric-layer design as opposed to Sample 11, which was the two-layer bulky B-52 curtain. Sample 5 performed well with zero-reflectance, but lacked the necessary flame protection qualities. The original curtain (sample #6), performed well in the transmission tests, but faired relatively poorly when assessed for reflection. It's bulkiness and flammability did not help it's case either. Sample #4 did well in the tests, but was not selected due to flammability concerns.

The relative high reflectivity of standard flight clothing was validated in both this study and in the 1994 B-1 Night Vision Enhancement Project Report, with the need to consider newer, lower reflective fabrics cited.[1]

The manufacture of the Teflon-coated materials, CS Hyde Company, boasts flame resistant qualities in the fiberglass samples, but these fabrics tended to be less pliable with a tendency to crease when folded. This would likely effect the long-term durability of the curtains. We selected the Nomex™ fabric because of it's pliability, flame resistant qualities and from it's prior approval for use in flight environments.

CS Hyde fabricated a proto-type curtain using the Teflon-coated Nomex™. The curtain was evaluated for form and function on the B-1 bombers at Ellsworth AFB, ND with highly positive results. If approved for use, the entire B-1 bomber fleet will likely receive copies of these new light-blocking curtains.

This study was successful in discovering a new lightweight material solution for inexpensively retrofitting the B-1 bombers for NVG operations. Additionally, the B-52 bomber fleet and other airframes could benefit by adopting this new curtain in exchange for their two-layer cumbersome cotton curtains.

Powering NVG's

Field units have loudly expressed their disdain for products powered by lithium or "exotic" batteries. They're justifiably concerned about with the availability of custom designed/special purpose batteries either prior to short notice deployment or when deployed to remote locations. There's a strong preference for a battery that's available at any "grocery store" worldwide.

Lithium batteries pose many logistical problems for supervisors in the field. Storage, disposal and transportation of these hazardous items increases the supervisors workload and budget requirements. With reduced manpower levels across the DOD, supervisors are adamant about minimizing procedures for common tasks. Having to dispose of environmentally hazardous lithium batteries is an arduous task they would prefer to eliminate. Additionally, shipping these items during deployments dramatically increases the paperwork and stress prior to a deployment. But is the use of lithium batteries justified with improved performance?

A two-fold study was conducted to both compare lithium and alkaline batteries and to base line the battery consumption rates of the four-tube (image intensifier) Panoramic Night Vision Goggle (PNVG) system. We anticipate the requirement of this data during final critical design and logistical decisions for the new Integrated PNVG (IPNVG) system.

During the test, we compared the 3.6V AA-size lithium and AAA-size alkaline batteries for endurance under maximum current draw conditions for the four-tube PNVG systems. The 3.6 volt lithium battery is the same battery currently used to power the goggles in the field. The "Banana" mount must have extender caps installed prior to using this AA full-sized battery. We also ran a test with a two-tube, AN/AVS-9 (F4949) NVG for comparison.

EQUIPMENT:

- 7101B Hewlett-Packard strip chart recorder
- 1980A Pritchard™ photometer S/N C-512
- VARIAC Voltage Control
- 4-Watt light bulb w/ holder
- Lab jack
- Foam core lined box 21" h x 20" w x 19" d
- SAFT™ Battery, Lithium 3.6V (AA-size)
- Kodak™ Battery, 1.5 (AAA-size)
- Energizer™ Battery, 1.5 (AAA-size)
- PNVG II, Configuration 4, S/N 0001
- PNVG I, Configuration 2, S/N 0002
- F4949D, S/N 3873

We lined a box with white foam core to provide a relatively even luminance into the goggles objective lenses. The box was placed on its side on an optical table and a lab jack placed six inches into the box. The jack would be used to elevate the goggles into the center of the box opening. A foam core baffle was then placed in front of the lab jack to reflect light back into the box cavity. We then centered a 4-watt light within in the box, in front of the baffle and plugged the light into a variable power controller. The lab jack was raised to approximately center the goggles to be measured in the box. (See Figure 2)

Once initial set-up was accomplished, we calibrated the photometer and placed the detector head perpendicular to the opening of the box approximately one meter from the box opening. This would allow sufficient distance to focus the detector onto the output of the subject NVG.

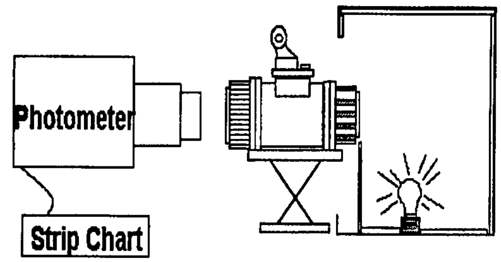


Figure 2. Battery Consumption Test

We selected the 20-minute measuring aperture and a (10:1) scale for low magnification and a strip-chart recorder was attached to the photometer to record the luminance levels. We checked the scale on the recorder and zeroed it to the output of the photometer and set the strip chart recorder to 10V and 1 in/hour scale as a compromise between sensitivity and readability.

The goggles were positioned onto the lab jack and the photometer was focused onto the output of the left channel of the F4949 goggles, and the left-central channel of the PNVG's. We adjusted the 20-minute aperture of the photometer's detector to be overfilled by 2/3 to maximize luminance input. With the basic test set-up accomplished, we turned out the lights and started the strip chart recorder. The photometer measurement aperture was opened and the goggle battery pack switched "ON".

The variable power controller for the 4-watt light bulb was "zeroed" then switched "ON". While watching the luminance level on the photometer, we slowly increased the light bulb's intensity. The intensity was carefully adjusted until the goggles out-put leveled off, indicating activation of the goggles' protective gated power supply system. We then reduced the goggle output by 10% by reducing power to the 4-watt bulb.

Once initiated, we monitored the test hourly. The batteries all supplied consistent power as indicated by the level luminance readings on the strip charts. We concluded the tests when the readings on the strip chart "nosed over" indicating a drop in goggle output luminance caused from a lack of sufficient current to the image intensifiers. At the conclusion of the tests, the photometer's aperture was closed and all associated equipment was shut down.

Two unusual observations were noted during the tests. The first was an asymmetric luminance degradation of the optical channels towards the end of the battery life when testing the four-tube PNVG systems. The output of the left out-board channel was noticeably brighter than the adjacent optical channels. The luminance levels degraded from right to left with the right most channel being the most dim.

Another interesting characteristic we noted was a high rate of flashing in all optical channels when the PNVG I's with AAA batteries reached approximately 1.97 vdc. The image intensifiers began an on/off oscillation at a rate similar to the flash rate of the low battery indicator.

The four-tube PNVG's with the AA Lithium batteries averaged 7.45 hours while the other four-tube PNVG version averaged 11.18 hours using the AAA alkaline batteries. Both battery types would provide sufficient energy to power either a two-tube or four-tube NVG system on a typical 4-5 hour mission. (see Table 4.)

Using the aircraft's power to energize helmet accessories would be ideal for both the user and the maintainers. For the maintainers, a ship-side power supply would reduce the logistical footprint during deployments. However, maximum commonality in aircraft and man-side components must be stressed.

NVG In-flight Storage

Storing NVG' in a fighter cockpit poses serious concerns. Currently, NVGs are removed during critical phases of flight to include landings and take-offs. When removed, today's goggles are placed in their storage case, which typically is the size of a lunch box. When the carry strap of one of these cases became entangled in the flight controls of an A-10 attack jet, the immediate removal of the straps was orderd Air Force wide. However, the issue of storing the case in the jet remains. With the tight confines of today's modern fighter aircraft, there's hardly room for any additional items. The ideal solution would be to simply eliminate the need to remove and store the NVG's. The helmet-mounted Integrated Panoramic Night Vision Goggle (I-PNVG) will solve this as it will remain attached to the pilot's helmet during all phases of flight. They will have the capability to be removed from the pilots' field of view by simply rotating them to an up and stowed position, but will drop down during ejection to provide wind blast protection. (see Figure 3)

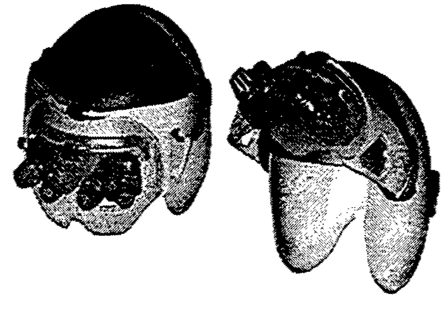


Figure 3. Integrated PNVG

However, until these goggles are fielded, an interim solution to safely stow the today's goggles needs to be devised. An early attempt to solve this problem was initiated by designing an NVG storage bracket for attachment to the inside of the cockpit wall. The goal was to find a design solution that would not require aircraft modifications, would be inexpensive to produce, and could integrate in a maximum number of airframes.

The first bracket design utilized an ANVIS-style NVG helmet mount that allowed the NVG's to easily click in and out of the bracket. The intent of this design approach was to use the unoccupied oxygen regulator storage bracket as a mounting point. Since the actual oxygen regulator would be attached to the pilot's torso harness in-flight, the regulator *storage* bracket would be available for use during flight to mount an NVG storage bracket. (see Figure 4)

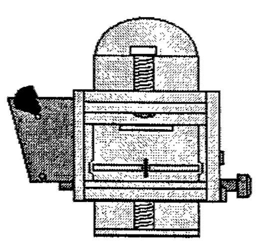


Figure 4. Initial NVG Cockpit Mount-Version I

However, during field evaluation we discovered a couple of problems with this design. The pilots we interviewed explained that the wall-mounted regulator brackets were seldom in serviceable condition due to their flimsy mounting points. In the F-16, the bracket is attached to a thin sheet of a plastic-like material. This caused the NVG storage bracket to wobble during use. The bracket moved during installation and removal making it unstable to use.

Additionally, the position of the wall bracket posed some possible spatial disorientation issues. Since the bracket was positioned on the lower right wall behind the ejection seat, the pilots would have to turn their heads down and to the right during storage and removal of the NVGs. Placing the head at these axis, particularly at night could cause the pilots to experience some levels of spatial disorientation.

The pilots recommended we alter our design to mount the bracket on the canopy's hand rail, or what they referred to as the "towel rack." The hand rails are used to manually lift the canopy open during an emergency ground egress. The right-side hand rail is used to stow a portable floodlight. When not flying, the floodlight is attached to the right lower panel, but during night flights, is brought forward and attached to the rail via a small, adjustable clamp. We redesigned our NVG storage bracket to mount to the same style clamp as is used with the floodlight. (See Figure 5)

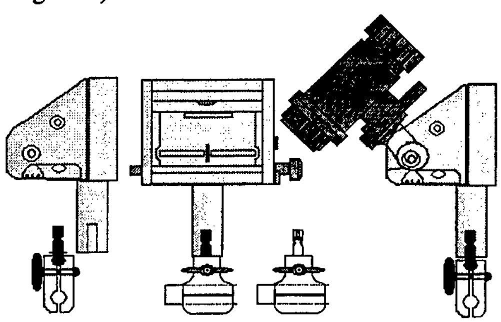


Figure 5. NVG Cockpit Mount-Version II

The design is simple and inexpensive to produce. We sent the newly designed mount to the 113th F-16 Fighter Squadron in Terra Haute Indiana for further assessment and are awaiting feedback to finalize the design. If the design proves worthy of implementation, flight safety in the fighters could be improved with the removal of the NVG storage case. Pilots will be able to safely store their NVG's without having to fumble for storage cases, and the storage cases will no longer pose threats as loose objects within the cockpit. This improved design should also minimize spatial disorientation events by allowing the pilots to store their NVG's without having to turn their heads.

In conclusion, we must ensure integrating future cockpit technologies are well considered to minimize or eliminate retrofitting with band-aid solutions. When selecting power sources for these technologies, logistical support issues must be considered on how they'll impact the manning at the gaining support units, regardless of the edge these additions contribute. If they can't be sustained logistically, they're of no use to the war-fighter. Recommend inviting troops from "the trenches" during early design considerations to add insight to potential designs and identify unanticipated limitations.

ACKNOWLEDGEMENTS

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BIOGRAPHY

MSgt Mike Sedillo is the Superintendent, Visual Display System's Branch at the Air Force Research Laboratory. He maintained NVG systems for ten years and helped write two NVG technical orders and several Life Support-related manuals. He spent 5 years teaching NVG maintenance as the senior military instructor at the Aircrew Life Support technical school. He has a BS in Education and recently received an associates degree in Aircrew Life Support Technologies. MSgt Sedillo is currently engaged with the joint Integrated Panoramic Night Vision Goggles program.

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COCKPIT/NVG VISUAL INTEGRATION ISSUES

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SUMMARY

This paper is divided into two main sections: Visual significance of NVG characteristics and Cockpit/NVG integration issues. The first section deals with the relationship between the NVG characteristics discussed in the previous paper and visual capability. The second section explores several issues associated with successfully integrating the NVG with the aircraft cockpit for optimum system performance.

VISUAL SIGNIFICANCE OF NVG CHARACTERISTICS

Table 1 is a listing of the NVG parameters discussed in the previous paper paired with the visual parameter that it is most closely related to. Each of these is discussed in the following sections.

Table 1. NVG and Vision Parameters.

NVG PARAMETERS	VISION PARAMETERS
Field-of-view	Visual field
Image quality	Visual acuity
Exit pupil size	Eye pupil diameter
Eye relief	Eyeglasses
Image location (focus)	Accommodation
Luminance level	Brightness
Luminance gain	Visual acuity
Luminance uniformity	Image perception
Beamsplitter ratio	Image perception
Distortion	Image perception
Magnification	Binocular effects
Input/output align.	Binocular effects
Image rotation	Binocular effects
Fixed pattern noise	Masking/distraction
Signal-to-noise ratio	Visual acuity

Field-of-View

The visual parameter that corresponds to the NVG FOV is the human eye's visual field which is approximately 200 degrees horizontally and 120 degrees vertically (Wells et al, 1989). However, this is somewhat misleading since the visual acuity over this range is quite varied. Only the central 3-5 degrees provides high-acuity vision; the visual acuity drops off quite rapidly outside of this area. This means that for a 40 degree FOV NVG some of the resolution on the display is not being used by the visual system; but the "extra" FOV is important for providing peripheral vision information.

The total FOV may be increased by partially overlapping the two NVG oculars as noted in the previous paper. At least one study suggests that there is little performance difference between 100% overlap and 80% overlap for visual recognition performance (Landau, 1990) implying that an 80% overlap binocular NVG may be a good compromise between the need for larger FOV without impacting visual performance. However, in real NVG oculars there are other factors that may produce undesirable binocular effects in the overlap region. If the oculars have a signficant center to edge luminance non-uniformity then this could result in a binocular luminance imbalance for parts of the overlap image region. Barrel or pincushion distortion may not be noticeable for fully overlapped oculars but if they are only partially overlapped then the distortion may result in a mismatch between corresponding points in the two oculars (Self, 1986) producing binocular rivalry.

Image Quality

The visual parameter corresponding to image quality (resolution & contrast) is visual acuity. Normal visual acuity for the human eye is approximately one minute of arc for high contrast, brightly lit targets. However, this acuity is reduced for lower light levels such as those found in the NVG display (maximum of about 1 to 2 foot-Lamberts with typical operational luminances much lower). If one were to match the display image quality to the human eye, a first order design might result in a pixel on the display subtending an angle of one minute of arc. For an image source consisting of 500 by 500 pixels, this would mean an angular subtense of the entire display of 500 minutes of arc, or 500/60 = 8.3 degrees. While this NVG might result in good image quality to the human eye, it would be an extremely small display. Most NVGs provide a FOV that results in an angular resolution larger than one minute of arc suggested by human visual acuity.

Exit Pupil

When the eye pupil is fully within the exit pupil of the NVG then the entire FOV is observed; if the eye pupil is only partially in the exit pupil (and the exit pupil is unvignetted) then the observer will still see the entire FOV but it will be reduced in brightness. This can be particularly disconcerting for NVGs used in high performance aircraft because the pilot may not know whether he is starting to lose the exit pupil or if he is starting to lose consciousness from high acceleration maneuvers. Once the eye pupil is outside the exit pupil then none of the NVG FOV can be seen. It should also be noted that the NVG FOV may become vignetted (lose part of the image) if the eye pupil is too close to or too far away from the exit pupil.

From a visual capability standpoint it is important for the exit pupil to be as large as possible to ensure the eye pupil will remain within it to permit viewing of the NVG. However, large exit pupils typically come only at the expense of greater size of optics and weight on the head. In addition, if the FOV is very large then the eye must rotate to view the edge of the display. Since the eye rotates about a point within the eye, the eye pupil moves within the NVG exit pupil. If the NVG exit pupil is not large enough then it is possible for the entire display to disappear every time the observer tries to move his eyes to view the edge of the display. Exit-pupil-forming optical systems also increase the difficulty of making accurate adjustments for binocular or biocular NVGs in that each eye pupil should be centered in each exit pupil of the NVG.

Eye Relief

As with so many other NVG parameters, larger eye relief usually means larger and heavier optics. The reason for having a large eye relief is to allow the use of eyeglasses with the NVG (Self, 1973; Task et al, 1980). The eyeglasses may be for visual correction, eye protection or both.

Image Location

In order to obtain good image quality the eye lens must focus at the same optical distance as the virtual image produced by the eyepiece. For young eyes which have a fairly large accommodative range there is a tendency to set the focus (for NVGs that have eye-lens diopter adjustment) so that the image is too near. The image may look clear but long term wear of the NVGs with the image at a close distance may lead to visual fatigue. For night operations it makes sense to have the NVG image focussed at the same distance as the aircraft panel instruments to minimize the time required to visually switch between looking at the NVG and looking at flight instruments.

Luminance Level

Brightness is the visual sensation or perception that corresponds to luminance. The luminance level has a significant effect on the pupil diameter of the eye; a higher light level means a smaller pupil diameter and vice versa. The visual acuity of the human eye also varies with eye pupil diameter (Farrell & Booth, 1984). However, for NVG applications the luminance must be kept reasonably low to match cockpit lighting levels for night operations. Thus the resolution observed on the NVG may well be a result of a combination of the inherent resolution of the NVG and the limits of visual acuity of the eye at low light levels.

Luminance gain

There isn't a direct visual analog to luminance gain. However, the higher the gain of an NVG for a given ambient lighting level then the higher the output luminance, which should result in higher visual acuity. A study by Levine and Rash (1989) stated that an 80% reduction in output luminance (equivalent to an 80% reduction in gain) by using a filter did not result in a statistically significant reduction in visual acuity. However, for starlight conditions their data showed a 37 percent reduction in visual acuity (not statistically significant) which is a rather substantial loss.

Luminance uniformity

Luminance uniformity is probably not a critical factor for visual performance or acceptance providing the luminance variation is gradual and not excessive. A ratio of 3:1 center to edge luminance variation in NVGs is not unusual. However, if the two NVG oculars are used in a partial overlap mode to increase the horizontal FOV then the luminance uniformity might be of more concern since this would produce a binocular luminance mismatch between the two eyes.

Distortion, image rotation, magnification, and input/ output optical axes alignment

These four geometric mapping parameters are grouped together since, with the exception perhaps of distortion, they are all primarily a problem only for binocular systems. If a monocular image is slightly rotated, or slightly different from unity magnification or slightly shifted in position (optical axes alignment) it really doesn't affect the visual system. However, if the image in one eye is rotated relative to the image in the other eye at some point the amount of rotation is sufficient to cause the visual system to be unable to fuse the two images. This could result in double images or in suppression of one of the images. Similar effects occur if there is a mismatch between the two eyes due to distortion, magnification, or image position differences between the two oculars.

There may also be a less obvious effect due to geometric image mismatch. If the differences are not sufficient to cause image suppression or double imaging they still may be sufficient to cause eye fatigue, nausea, and or headaches when these slightly disparate images are viewed for a long period of time.

In addition, the distortion effects may produce undesirable illusions or image motion for dynamic viewing situations (such as landing).

These four parameters need to be specified based on their effects on binocular vision and not on their individual monocular effects.

Signal-to-noise ratio (SNR)

SNR primarily affects visual acuity. Riegler et. al. (1991) published a study showing the effect of SNR level on visual acuity for different luminance levels and contrasts using NVGs. Four PVS-7 image intensifier tubes were used that ranged in value from a SNR of 11.37 to 17.92. As might be expected the largest visual acuity differences were due to changes in contrast of the targets and light level. However, there was a significant effect due to the SNR of the tubes. The increase in visual acuity going from a SNR of 11.37 to 17.92 depended on the contrast and lighting conditions. For the low contrast (20%), low luminance (1% moon) the improvement in visual acuity was about 27% for the higher SNR tube. But for the high contrast (95%) high luminance (25% moon) the improvement was only about 10%.

Beamsplitter (combiner) ratio

The NVG beamsplitter (if one is used) is not designed to superimpose the NVG image on the real world scene but rather is intended to permit direct viewing of the aircraft HUD undegraded by the image intensifier system. This is accomplished by turning the NVGs off when viewing the HUD and turning them back on when viewing through the windscreen (the on/off switching is done automatically). But, as its name implies, the beamsplitter splits the light so that there is a reduction in luminance coming from the HUD (due to the transmission coefficient of the beamsplitter) and a reduction in luminance coming from the image intensifier (due to the reflection coefficient of the beamsplitter). In general the reflection and transmission coefficients must add up to a number less than one (assuming the beamsplitter coating is neutral with respect to wavelength). This results in a direct trade-off: higher transmission means the HUD will be easier to see but also means lower reflection coefficient which results in a lower NVG scene luminance. For best results the beamsplitter probably cannot vary too much from a 50-50 split (same transmission and reflection coefficient).

Fixed pattern noise

This parameter primarily refers to the visible structure of the fiber optics twister or faceplate (if fiber optics is used in the image intensifier tube). The fiber optics production method results in a hexagonal pattern (also called "chicken wire" for this reason) that may become visible under higher lighting conditions. This acts as a distraction or masking pattern when trying to observe the NVG image. At present there is not a good means of quantifying this parameter and little data on the significance of this parameter with respect to visual performance. Typical specifications state that the "chicken wire" shall not be objectionable.

COCKPIT/NVG INTEGRATION ISSUES

Since NVGs do not attach to any part of the aircraft it is usually assumed (incorrectly) that there really are no integration issues. In fact there are several potential integration problems a few of which are described herein.

Cockpit lighting

One of the earliest and most obvious NVG cockpit integration problems was the incompatibility of the NVGs with standard cockpit lighting. Most cockpit lighting is produced by incandescent bulbs filtered to produce red, white or blue-white lighting (depending on aircraft) for unaided nic flying. The filtered incandescent lights, how ᵣ, emit tremendous amounts of near infra-red energy to which the NVGs are very sensitive (700nm to 900nm). This produces considerable light pollution in the cockpit for the NVGs. The result is much like sitting in a well-lit room trying to look outside at night; the reflected light from the window is far greater than the meager light from outside coming through the window so one only sees the room reflections in the window instead of outside.

Several techniques have been developed to reduce or eliminate this problem (Holly, 1980; Task & Griffin, 1982; Mil Specification Mil-L-85762). These techniques include using filters to remove the near infra-red, using baffles to redirect the light away from the windscreen, and using alternate lighting sources such as electro-luminescent lighting (which has a very low infra-red component). It should be noted that just filtering the incandescent light and making it blue-green does NOT mean that the filter has removed the offending infra-red light. Many plastic filters that make the incandescent lighting appear blue-green are almost totally transparent in the 700-900 nm range so one must be careful in selecting filters for this purpose.

The phrase "NVG compatible" when referring to aircraft interior and exterior lighting has taken on at least two meanings. There is no question that the Mil-L-85762 lighting specification intent is to insure that the cockpit is illuminated with light that is visible to the unaided eye but is as invisible as possible to the NVGs. In the case of exterior lighting it is desirable to have lighting that is visible through the NVGs and to the unaided eye but insure that it does not "overpower" the NVGs.

Yet a third meaning of "NVG compatible" is for the light source to be visible ONLY to the NVGs and not to the unaided eye such as in aircraft landing lights for covert operations. Given these different interpretations of the phrase "NVG compatible" it is recommended that one be explicit in defining exactly what level of NVG visibility is desired.

Aircraft head-up display

Here again is another area in which "NVG compatible" is ill-defined. For some applications it may be desirable to be able to see the HUD image through the NVG image intensifier system (for non-beamsplitter NVGs) in which case one would like the NVGs to be able to "see" the light from the HUD. For other applications where the NVG has a combiner for viewing the HUD directly it is desirable to have the NVG be totally insensitive to the HUD image to prevent double imaging (direct view and NVG view). A further concern with some recent NVG designs is that the objective lens of the NVG may not be located in a position where it can see the HUD.

If the NVGs are to be used to view the HUD symbology then the symbol sizes need to be sufficiently large so that the resolution of the NVGs can still permit the pilot to easily read the symbols. This means the HUD symbol sizes should be absolutely no smaller that 20/60 (15 minutes of arc) and preferably larger.

Another issue of NVG and HUD compatibility is the transmission coefficient of the HUD combiner. The HUD image is produced by reflection from a combiner located directly in front of the pilot. This combiner therefore reduces the amount of light that is available for NVG viewing when looking through the combiner (even with the HUD off) due to the transmission coefficient of the combiner. The transmission coefficient may be 50% or less which means the scene viewed through the combiner will appear significantly darker that looking around the combiner. If the HUD is "on" it is even more difficult to view through the HUD due to the radiance of the HUD symbology.

Aircraft windscreen

There are several separate integration issues associated with the aircraft windscreen. The most obvious is the spectral transmission of the windscreen. Most windscreens are designed with the visible wavelengths (400-700nm) in mind. Some windscreens do absorb light in the very near infra-red where the NVGs are most sensitive (700-900nm). This can significantly reduce the effective gain of the NVGs. Transmission coefficients for windscreens measured at their installed angle can range from 70% down to 20% or less depending on the aircraft and viewing angle through the windscreen. As the viewing angle is steeper (toward the lower, forward part of the windscreen) the percent transmission is lower. This is unfortunate since for many applications this is the part of the windscreen that is most critical for air-ground target acquisition and landing.

Another area of integration concern has to do with the aperture of the NVG objective lens. When a pilot views through a windscreen with unaided vision his eye pupil is on the order of 2 to 4 mm in diameter (daylight through early evening lighting). Thick, curved, plastic windscreens don't affect the pilot's visual acuity because his eye pupil is relatively small (ray bundle sizes are limited by the pupil). However, if a larger size aperture is used for imaging (such as an NVG objective lens) then the size of the windscreen over which the wavefront aberrations are averaged is larger and the potential for reduced clarity is greater. This is typically not a problem for flat glass or thin glass windscreens but for the more recent bird-strike resistant windscreens made of curved plastic it is a very real concern. The effect of the interaction on the larger NVG aperture with the windscreen is lower effective system resolution.

A third area of concern has to do with simple geometry. The NVGs protrude from the face by a considerable distance (as much as 8 inches). For small cockpits this can become a problem as pilots try to look out to the side where there is not much clearance with the windscreen. The NVGs can hit the windscreen causing scratches and not making the pilot very happy either.

Some NVG designs position the objective lens higher or further off to the side than the natural eye position. Windscreens are designed around a "design eye" and all optical quality measurements are made from this nominal viewing box. Since the NVG objective lens may be located at a significantly different position there may be a considerable decrease in optical quality due to the windscreen. In particular, if the objective lens is higher and therefore closer to the slanted windscreen, it will be looking through the windscreen at a steeper angle which tends to reduce transmission and to enhance distortion effects.

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Pinkus, A. R., & Task, H. L. (2000). Night vision goggles objective lens focusing methodology. *Proceedings of the 38th SAFE Association*, http://www.safeassociation.com

Night Vision Goggles Objective Lens Focusing Methodology

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ABSTRACT
Before performing an airborne mission that uses night vision goggles (NVGs) , aircrew must properly set the NVG's various adjustments: interpupillary distance, tilt, eye relief, height, eyepiece and objective lens focus. Currently, aircrew use a Hoffman 20/20 test unit to pre-focus their NVG objective lenses at optical infinity before boarding their aircraft. They may also refocus their objective lenses while in the cockpit and during the course of the mission. This paper examines observers' abilities to resolve targets of different sizes, viewed through NVGs, as a function of different pre-focused distances corresponding to "focusing errors".

INTRODUCTION

Objective: The ultimate objective of this effort was to determine if there was any difference in NVG visual acuity depending on whether NVGs were focused using a Hoffman 20/20 test system or distant ambient objects. However, due to the unavailability of a Hoffman 20/20 test unit during the time available to conduct this study, the secondary objective was to determine the sensitivity of NVG visual acuity to the distance of objects used to focus the NVGs.

Background: The Hoffman 20/20 test system was designed to provide a distant (infinity) optical image of a test pattern to determine the level of resolution/visual acuity available in an NVG and determine that the NVG could focus at infinity (objective lens optical adjustment). It is currently being used to pre-adjust objective lens focus prior to flight to insure the NVGs are properly focused. However, the Hoffman 20/20 uses a relatively narrow-band light emitting diode (LED) illuminator which may result in a different objective lens focus than what would be obtained under typical broad-band night illumination. In addition, pressure changes due to altitude or misadjustment due to accidental impact of NVGs on the canopy may destroy the objective lens focus obtained during the preflight adjustment using the Hoffman 20/20. The question is "can aircrew readjust the NVG objective lenses in-flight and obtain focus (i.e., visual acuity) at least as good as they obtained using the Hoffman 20/20?" Two studies were conducted to provide some indirect information to aid in answering this question. The first study was conducted to determine the relative sensitivity of observers' visual acuity to intentionally defocused objective lenses and the second was conducted using a single trained observer to assess focusing sensitivity using a different methodology. The second study was prompted by the inconclusiveness of the first study.

METHOD - STUDY ONE

Observers

The trained observers were one female and two males, highly experienced with the operation of NVGs. They ranged in age from 38 to 49 years, each having normal (20/20) or corrected-to-normal binocular visual acuity.

Stimuli

Landolt C's - The test stimuli were closely-sized computer-generated, high contrast (70% Michelson; Farrell & Booth, 1984) Landolt C's (National Academy of Sciences, 1980) printed using a high resolution, photo-grade laser printer. The print out of each target was mounted on 18 cm x 18 cm (7" x 7") squares of foam board. Each target varied in gap size and represented, when converted, a specific Snellen visual acuity value (20/xx). The back of each target was labeled with four different bar code patterns. Each bar code contained identification information for that particular target such as target number, target type, the corresponding visual acuity (20/xx), the target contrast, and the gap's orientation. For each experimental trial, a Landolt C was placed in the center of a larger foam board surround 56 cm x 56 cm (22" H x 22" L). This surround was secured to the front of a black light-tight wooden box. The box measured 66 cm H x 56 cm W x 36 cm L (26" H x 22" W x 14" L) and sat on top of a stand. The surround had the same reflectance as the background of the Landolt C's. This box housed a bar code scanner/reader used to automate the recording of Landolt C target information. The light-tight box prevented the incompatible red laser beam from the bar code scanner from affecting the NVGs. The bar code reader connected directly to a computer at the experimenter's station. The entire set up was positioned at 54.9 meters (180'; near NVG optical infinity) from the observer. A four button response box was used to record the observer's response (gap up, down, left or right). The computer recorded the button press response and Landolt C bar code information as well as other pertinent information.

Apparatus

NVGs - Participants viewed the target stimuli using a pair of ITT model F4949D (SN 3873) NVGs. The goggles had a gain of approximately 5600 as measured using the Hoffman ANV-120 NVG Test Set. Before the start of each test session, the optical alignment of the NVGs was verified using the Hoffman ANV-126 Night Vision Tester.

Each test session was conducted in a light-tight laboratory. The observer was seated with the NVGs secured in a stationary mount directly in front of them. The observer was able to adjust the NVGs to the proper height for viewing. An external regulated power supply was used to energize the goggles.

The NVG eyepieces were preset to -0.5 diopters using a Keuffel & Esser dioptometer. At the beginning of each test session the observer would set up and pre-focus the NVGs. After dark-adapting for 10 minutes, the NVGs were powered on. The observer focused the objective lenses by viewing a large, high-contrast square-wave resolution chart.

Illumination sources and Illumination levels - The stimuli were illuminated using a moon lamp outfitted with an adjustable 2856K color temperature incandescent bulb (MIL-L-8576A, 1986). Metal apertures were used to achieve the desired illumination level. Using apertures to adjust illumination intensity did not affect the 2856K color temperature. The illumination on the Landolt C's was 4.0 x 10^{-3} lux (3.72 x 10^{-4} fc). The output from the NVGs was approximately 5.14 nits (1.5 fL). Since the observer was so far away from the stimulus area, the surrounding area was for the most part dark. To illuminate a larger portion of the NVG's field-of-view, the observer looked through a large, white 122 cm x 153 cm (4' x 5') illuminated mask having a 15 cm x 20 cm (6" x 8") aperture located about 366 cm (12') in front of their viewing position. This illuminated area also produced about 1.5 fL goggle output. The near and far fields were a good brightness match when viewed through the goggles.

Procedure

Each of the three observers completed 240 trials (24 trials x 10 Snellen acuity levels) on each of three days. For a particular day, the observer focused his/her goggles at one of three focus distances. The order of the focus distances were counterbalanced across observers. During each trial, the observer, at 54.9 meters (180'), attempted to identify the orientation of the Landolt C gap with choices being left, right, up, and down.

Eight repetitions, with randomly presented orientations, were performed at a particular acuity level followed by eight more repetitions at another acuity level. This was repeated 10 times, in a random fashion, with each acuity level used once to complete a session. Three sessions were conducted per day to achieve the total of 240 trials.

For each trial, the experimenter, using pre-determined randomized stimuli ordering, placed a Landolt C onto a small ledge centered on the surround while keeping it blocked from the observer's view. The ledge centered the 'C' and was not visible when viewed through the NVGs. The experimenter pressed a switch to scan the bar code on the back of the target. The experimenter would then move away from the Landolt C and the observer had about four seconds to view the stimulus. At the end of the four-second interval, the computer would beep an alarm and the experimenter would immediately block the stimulus from the observer's view. The observer would announce their response and it was recorded. The observer was not provided with any feedback on their performance.

RESULTS - STUDY ONE

Due to recording problems, there were 10 groups of 24 trials (i.e., combination of observer, focus distance, and acuity) where responses from less than 24 trials were obtained. Table 1 contains the percent of trials in which the orientation was correctly identified. Chance alone would result in 25% correctly identified trials. It is assumed that percents in Table 1 that are less than 25% would approach 25% with a sufficient number of trials. The percents from Table 1 were transformed to adjusted for chance values and are shown in Table 2.

Table 1. Percent correct trials (N = 24) for each observer, focus distance, and acuity.

Snellen Acuity (20/xx)	Observer #1 Focus Distance (ft)			Observer #2 Focus Distance (ft)			Observer #3 Focus Distance (ft)		
	80	100	180	80	100	180	80	100	180
13.50	29	42	29	21	29	21	29	29	29
15.17	21	17	42	42	46	33	33	33	46
17.04	13	25	25	25	42	42	35	33	38
19.15	33	33	30	38	38	25	54	46	50
21.52	48	50	54	46	43	38	42	21	42
24.18	58	58	64	54	46	67	75	58	63
27.16	83	79	58	67	58	83	96	83	96
30.52	79	88	88	63	83	100	96	92	96
34.29	96	100	96	96	92	92	100	100	96
36.35	94	100	96	100	83	100	100	100	100

Table 2. Percent correct (N = 24) adjusted for chance. Percents in italics were not used for modeling.

Snellen Acuity (20/xx)	Observer #1 Focus Distance (ft)			Observer #2 Focus Distance (ft)			Observer #3 Focus Distance (ft)		
	80	100	180	80	100	180	80	100	180
13.50	*6*	22	*6*	*0*	6	*0*	6	6	6
15.17	*0*	*0*	22	22	28	*11*	11	11	28
17.04	0	0	0	0	22	*22*	13	11	17
19.15	11	11	7	17	17	0	39	28	33
21.52	30	33	39	28	24	17	22	0	22
24.18	44	44	52	39	28	56	67	44	50
27.16	78	72	44	56	44	78	94	78	94
30.52	72	83	83	50	78	100	94	89	94
34.29	94	100	94	94	89	*89*	100	100	94
36.35	92	*100*	94	100	78	*100*	*100*	*100*	100

The non-italicized values in Table 2 were converted to normal equivalent deviates (NED). An NED is the value of a standard normal variable whose cumulative probability (expressed as a percent) would equal the percent correct adjusted for chance. Since an NED cannot be computed for 0% or 100%, 0% was set to 1% and 100% was set to 99%. The NED values were used as the dependent variable in a linear regression with acuity as the independent variable (a linear relationship is assumed). This procedure is referred to as Probit Analysis (Finney, 1980, Pinkus & Task, 1989). The estimated NED = b_0+b_1*acuity was transformed back to percents. For each observer and focus distance, the acuity level that corresponded to 50% and 75% correct, adjusted for chance, was determined and shown in Table 3.

Table 3. Snellen acuity levels corresponding to 50% and 75% correct, adjusted for chance.

	$50\ P_A$			$75\ P_A$		
	Focus Distance					
Observer	80	100	180	80	100	180
#1	26.2	25.0	26.3	29.9	27.8	29.8
#2	26.3	26.4	24.5	29.8	32.9	26.3
#3	22.0	24.2	22.2	25.4	27.8	26.3
Mean	24.8	25.2	24.3	28.4	29.5	27.5
Std	2.5	1.1	2.1	2.6	2.9	2.0

Table 4. Analysis of variance results.

P_A	Source	SS	DF	SSE	DFE	F	p
50	Focus Distance	1.09	2	5.19	4	0.42	0.6834
75	Focus Distance	6.13	2	21.75	4	0.56	0.6085

The acuity levels corresponding to 50% and 75% correct were used as dependent variables in a one factor (focus distance) repeated measures analysis of variance. Results are shown in Table 4.

METHOD - STUDY TWO

Study Two was substantially simpler and faster than Study One and the technique can be more directly applied to answer the original question regarding the Hoffman 20/20. Since it was apparent from the first study that there was no difference in visual acuity performance for the range of defocus distances selected, a different approach to the focusing issue was devised. Focusing the objective lenses of NVGs is done by physically moving the objective lens of the NVG closer to or further from the image intensifier tube. At infinity focus the objective lens is at its closest distance to the tube; as objects closer than infinity are brought into focus the objective lens must move away from the image intensifier tube. This movement is very small and difficult to measure but provides a means of determining change in focus position. A single trained observer focused the NVGs at six different distances (3, 6, 12, 18, 30 and 46 meters or 10', 20', 40', 60', 100' and 150', respectively) 10 times each for each of two focusing stimuli. The first stimuli was a grating somewhat similar to the grating target used in the Hoffman 20/20. The second stimuli was a point source of infrared light. A digital caliper was used to measure the overall length of the NVGs for each of the 120 focus settings (6 distances, 10 repetitions, 2 focus stimuli). Using first-order lens imaging theory (Hecht and Zajac, 1975, p.-168) it is possible to derive a theoretical equation to relate the NVG objective lens movement to the distance of the stimulus to be focused. This theoretical movement relationship can then be compared to the obtained results. It was hypothesized that there would be no difference in focusing ability between the grating and point source stimuli.

RESULTS - STUDY TWO

The results for Study Two are shown in tabular form in Table 5. The data in Table 5 are the average (over 10 repetitions) lengths of one NVG ocular for each of the distance and stimuli conditions. The theoretical equation only relates the relative movement of the objective lens with respect to focus distance so it was necessary to "anchor" the equation. The objective lens should have been closest to the image intensifier tube for "infinity" focus. Based on the results of Study One, there was no difference in visual acuity (focus) between 80', 100', and 180' indicating that these distances were essentially "infinity" as far as the NVGs were concerned. Therefore the 150' distance was taken as the "anchor" point. The theoretical data was produced by setting the 150' data point to be equal to the average of the 20 focus settings (10 for point source and 10 for grating) obtained at 150' (as can be seen in Table 5). Results are in Figure 1 and Table 5.

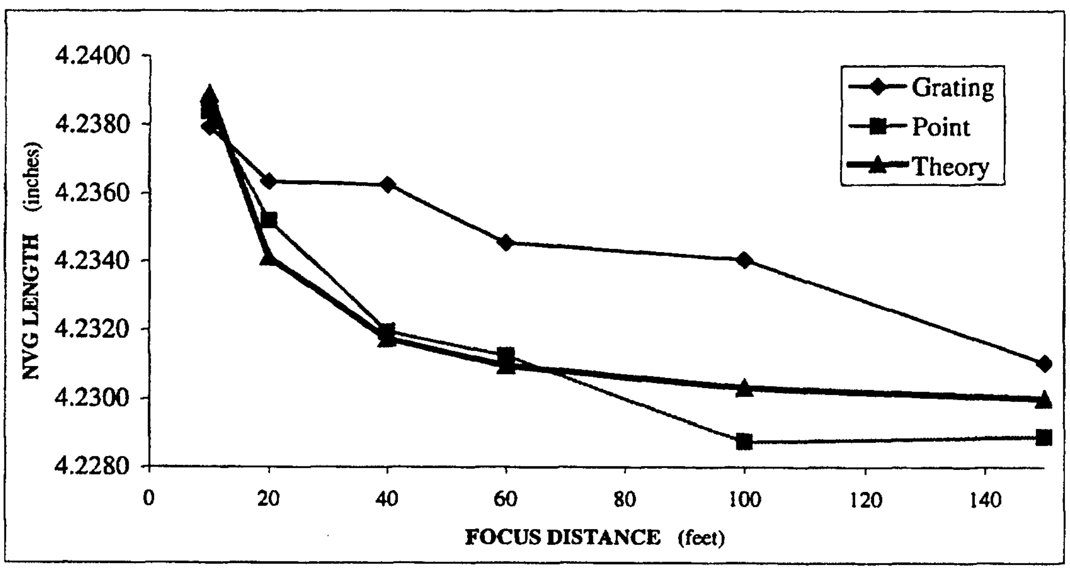

Figure 1. Graphical results of NVG ocular length as a function of focus distance for two focusing stimuli.

Table 5. NVG length as a function of focus distance and focus stimuli (all data in inches)

Distance	Grating	Point	Theory
10'	4.2380	4.2384	4.2389
20'	4.2364	4.2352	4.2341
40'	4.2363	4.2320	4.2317
60'	4.2346	4.2313	4.2309
100'	4.2341	4.2288	4.2303
150'	4.2311	4.2289	4.2300

DISCUSSION and CONCLUSIONS

The first study described in this paper attempted to assess focusing sensitivity of the NVGs by assessing visual acuity for different levels of defocused objective lens settings. Previous theoretical calculations indicated the depth of field of the NVGs is such that a focus error should be noticeable around the 100' or so, distance. However, it is clear from the results of the first study that there was no statistically significant difference in visual acuity for the three focus distances investigated. The repeatability and reproducibility of NVG visual acuity measurements has not been determined but it is apparent that there is a certain amount of variance associated with measuring NVG visual acuity. This makes it difficult to detect small differences in parameters that may affect visual acuity. If a broader range of defocus distances were investigated (which needs to be done) it is expected that there would be a significant effect on NVG visual acuity. The Probit technique, used to obtain visual acuity, is extremely fatiguing and time consuming for observers which is what led to the technique developed in the second study.

Since the primary issue is whether or not the stimulus used to focus the NVGs makes a difference in the quality of the focus obtained, we believe the technique developed in the second study provides a better and more convenient means to address the issue. Surprisingly, the second study resulted in a statistically significant difference in focus settings (all six distances; analysis of variance) between focusing on a distant (150') point source versus a square-wave grating. Both methods produced similar results at 10' and at the distant 150' but the grating stimulus lagged behind the point source for the intermediate distances. We have no explanation for this effect but it deserves a bit more attention in the future. For the "optical infinity" (150') distance, there was no statistically significant difference between the grating stimulus and the point source stimulus. This would imply that the quality of focus should be the same, independent of the focus stimulus (providing it is a reasonable stimulus). Since this second study involved only one highly trained observer it would be well worth while to repeat this technique with a larger number of trained observers and with a broader range of focusing stimuli and lighting levels. We believe that this technique, after some refining, is probably the best method of determining the focusing differences, if any, between using the Hoffman 20/20 and using ambient objects for focus adjustment. Future plans are to refine the technique in the laboratory and then try it out in the field.

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BIOGRAPHIES

Alan Pinkus has been a US Air Force research psychologist since 1982. As a human factors engineer, he has worked on major systems including the Royal Saudi Air Force KE-3 tanker, Gunship 2, LANTIRN, Air Force One and Joint-Stars. As a researcher, he has worked in the areas of image display metrics, night vision goggles, apparent motion, aircraft lighting, transparency analysis, vision from space, workload assessment and has lectured for NATO AGARD in Europe. Alan has a BS Degree (Wright State University, 1974), an MA (University of Dayton, 1980) and a PhD (Miami University, 1992), all in Experimental Psychology. He holds eight patents in the area of night vision goggle ancillary devices and has over 25 publications. He is a member of SAFE, Association of Aviation Psychologists, the Human Factors and Ergonomics Society (Southern Ohio Chapter) and is active in the American Society for Testing and Materials Subcommittee (ASTM) F7.08 on Transparent Enclosures and Materials.

H. Lee Task (please see the associated session paper entitled, "Integrated Panoramic Night Vision Goggles Fixed-Focus Eyepieces: Selecting A Diopter Setting")

II. NIGHT VISION RELATED PATENTS

This section contains reprints of the following AFRL/HEC patent abstracts that describe NVG-related test and ancillary devices.

Task, H. L., Courtright, J. F., & Genco, L. V. (1983). *U.S. Patent No. 4,398,685,* ***Aerial Day/Night Refueling Stations.*** Washington, DC: U.S. Patent and Trademark Office.

Wyatt, I. S., & Task, H. L. (1985). *U.S. Patent No. 4,554,543,* ***Glide Slope Indicator System.*** Washington, DC: U.S. Patent and Trademark Office.

Task, H. L. (1985). *U.S. Patent No. 4,554,544,* ***Diffuse Incandescent Runway Marker Light Apparatus For Overt/Covert Operations.*** Washington, DC: U.S. Patent and Trademark Office.

Task, H. L. (1986). *U.S. Patent No. 4,580,196,* ***Night Vision Compatible Illumination For Vehicle Crewmember Workspace.*** Washington, DC: U.S. Patent and Trademark Office.

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Pinkus, A. R., Task, H. L., & Marasco, P. L. (2002). *U.S. Patent No. 6,401,589 B1, **Limiting Airborne Target Designating Laser Canopy Returns.*** Washington, DC: U.S. Patent and Trademark Office.

United States Patent [19]

Task et al.

[11] **4,398,685**

[45] **Aug. 16, 1983**

[54] **AERIAL DAY/NIGHT REFUELING STATIONS**

[75] Inventors: **Harry L. Task**, Dayton, Ohio; **John F. Courtright**, San Antonio, Tex.; **Louis V. Genco**, Enon, Ohio

[73] Assignee: **The United States of America as represented by the Secretary of the Air Force**, Washington, D.C.

[21] Appl. No.: **242,817**

[22] Filed: **Mar. 11, 1981**

[51] **Int. Cl.**³ **B64D 39/00**

[52] **U.S. Cl.** .... **244/135 A**; 244/3.16; 244/161

[58] **Field of Search** .... 244/135 A, 3.16, 161; 250/341, 342; 353/28, 84, 13

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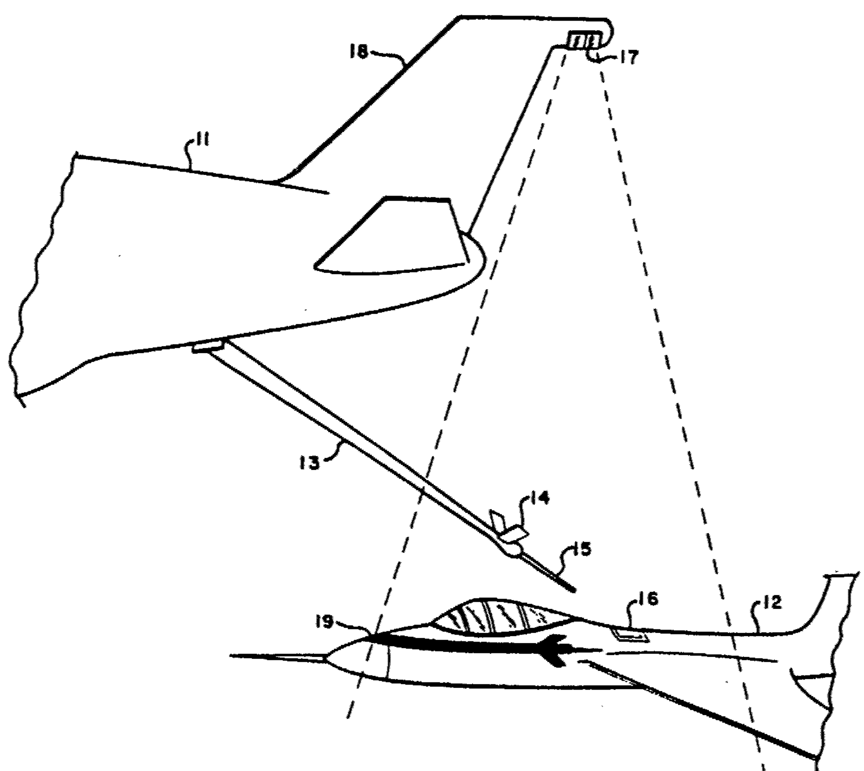
Primary Examiner—Trygve M. Blix
Assistant Examiner—Ivy M. Shum
Attorney, Agent, or Firm—Donald J. Singer; Bobby D. Scearce

[57] **ABSTRACT**

An improved aerial refueling system, suitable for operation under nighttime or other limited visibility conditions, is described, and comprises a tanker aircraft with refueling boom depending rearwardly thereof, a receiver aircraft having a fuel receptacle for interconnection with the boom, means disposed on the tanker for illuminating the receiver aircraft with infrared light during hookup and refueling, infrared sensitive viewing means and an optical imaging device on the tanker through which the boom operator may view the boom and receiver aircraft to guide the boom into position for connection with the receiver aircraft.

2 Claims, 2 Drawing Figures



United States Patent [19]

Wyatt et al.

[11] **Patent Number: 4,554,543**

[45] **Date of Patent: Nov. 19, 1985**

[54] **GLIDE SLOPE INDICATOR SYSTEM**

[75] Inventors: **Ivan S. Wyatt**, Gilbert, Ariz.; **Harry L. Task**, Dayton, Ohio

[73] Assignee: **The United States of America as represented by the Secretary of the Air Force**, Washington, D.C.

[21] Appl. No.: **473,392**

[22] Filed: **Mar. 8, 1983**

[51] **Int. Cl.**[4] **G08C 5/00**

[52] **U.S. Cl.** .... **340/948**; 73/178 T; 244/183; 340/951; 340/953; 340/972

[58] **Field of Search** .... 340/945, 947, 948, 951, 340/952, 953, 954, 956, 972, 981; 73/178 T; 244/175, 183; 350/433; 250/350; 455/611, 617

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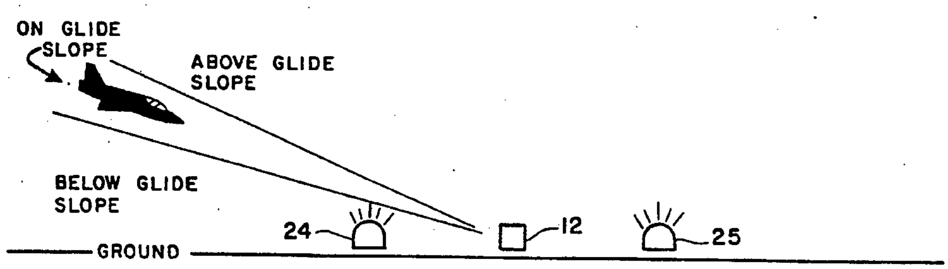
Primary Examiner—John W. Caldwell, Sr.
Assistant Examiner—Michael F. Heim
Attorney, Agent, or Firm—Donald J. Singer; Bernard E. Franz

[57] **ABSTRACT**

A glide slope indicator system in which light from an incoming aircraft's landing light is shaped by spherical/cylindrical lens combination into a line image which strikes a linear photodiode array. By determining which photodiode in the array the center of the line image strikes, the glide slope angle can be determined. An appropriate signal is communicated to the pilot via a pair of indicator lights mounted on the runway depending upon whether the aircraft is above, below or on the desired glide slope angle.

6 Claims, 6 Drawing Figures



United States Patent [19]

Task

[11] **Patent Number: 4,554,544**

[45] **Date of Patent: Nov. 19, 1985**

[54] **DIFFUSE INCANDESCENT RUNWAY MARKER LIGHT APPARATUS FOR OVERT/COVERT OPERATION**

[75] Inventor: **Harry L. Task**, Dayton, Ohio

[73] Assignee: **The United States of America as represented by the Secretary of the Air Force**, Washington, D.C.

[21] Appl. No.: **536,142**

[22] Filed: **Sep. 26, 1983**

[51] **Int. Cl.**[4] **G08G 5/00; B64F 1/18**

[52] **U.S. Cl.** **340/953**; 313/116; 340/84; 340/947; 340/955; 362/62

[58] **Field of Search** 340/947, 981, 950, 953, 340/952, 954, 955, 815.18, 84, 321; 362/227, 234, 252; 313/112, 116; 219/354

[56] **References Cited**

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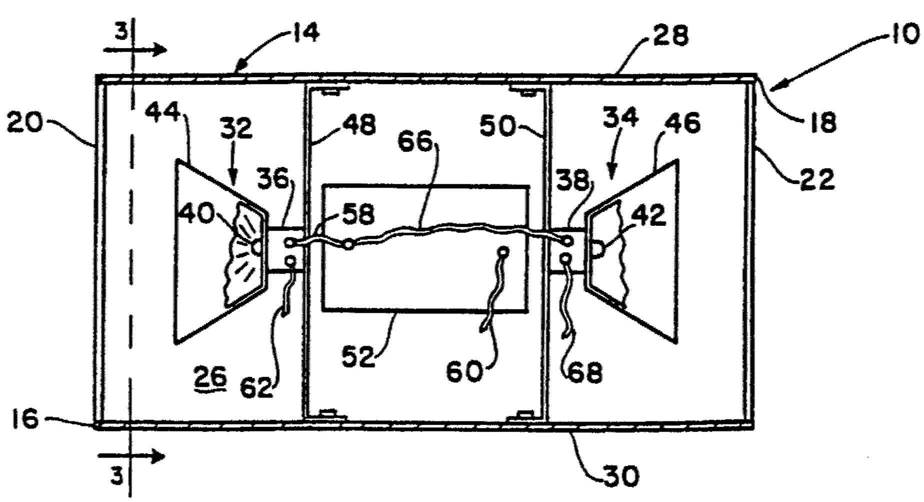
Primary Examiner—James J. Groody
Assistant Examiner—Brent A. Swarthout
Attorney, Agent, or Firm—Donald J. Singer; John R. Flanagan

[57] **ABSTRACT**

A diffuse incandescent runway marker light apparatus has a housing with a visible light diffusing plate mounted in one end and an infrared light diffusing plate mounted in the other end, and a pair of incandescent light sources mounted in the housing and aimed toward the respective housing end plates. A switch, when flipped to a first position, turns on one light source for producing visible illumination and turns off the other light source. The switch, when flipped to a second position, turns off the one light source and turns on the other light source for producing infrared illumination. In such manner, the appropriate type of illumination for marking the runway for overt or covert landing operation may be selected. When the switch is flipped to a third position, both light sources are turned off.

4 Claims, 4 Drawing Figures



United States Patent [19]

Task

[11] **Patent Number: 4,580,196**

[45] **Date of Patent: Apr. 1, 1986**

[54] **NIGHT VISION COMPATIBLE ILLUMINATION FOR VEHICLE CREWMEMBER WORKSPACE**

[75] Inventor: **Harry L. Task**, Dayton, Ohio

[73] Assignee: **The United States of America as represented by the Secretary of the Air Force**, Washington, D.C.

[21] Appl. No.: **688,944**

[22] Filed: **Jan. 4, 1985**

[51] **Int. Cl.**[4] **B64D 47/02**

[52] **U.S. Cl.** **362/62**; 362/800; 362/226

[58] **Field of Search** 362/62, 63, 800, 803, 362/226, 254; 244/118.5

[56] **References Cited**

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2098714	11/1982	United Kingdom	362/800

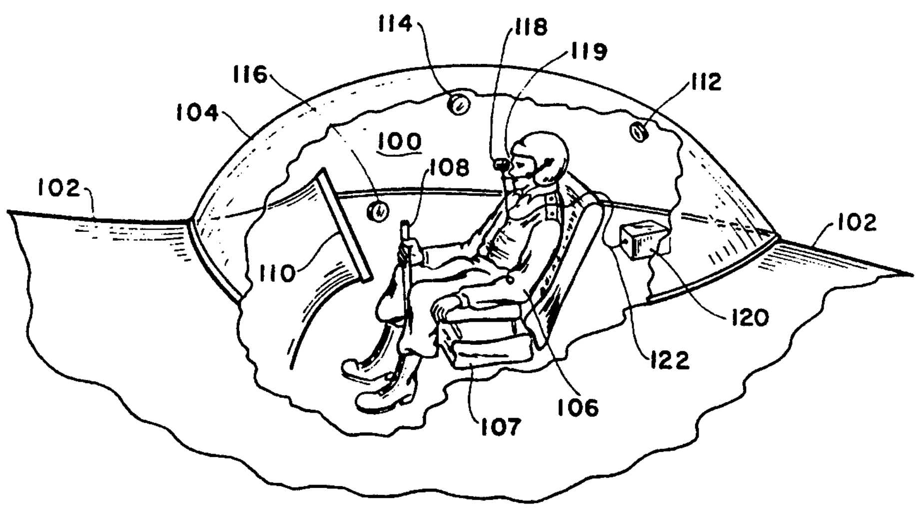
Primary Examiner—Ira S. Lazarus

Attorney, Agent, or Firm—Donald J. Singer; Gerald B. Hollins

[57] **ABSTRACT**

An arrangement for conveniently changing the illumination in an aircraft cockpit or other enclosure to a spectrum compatible with night vision infrared equipment including provision for easy return to the original illumination source. Selected LED elements are employed in multiple element arrays using a tether connected package that can be excited directly from existing wiring in fixtures.

17 Claims, 3 Drawing Figures



United States Patent [19]

Task et al.

[11] Patent Number: 4,607,923

[45] Date of Patent: Aug. 26, 1986

[54] CONTRAST SENSITIVITY FUNCTION MEASUREMENT CHART AND METHOD

[76] Inventors: Harry L. Task, 275 Main St. Apt. 411 Whitney Towers, Watertown, Mass. 02172; Louis V. Genco, 2010 Shadow Cliff, San Antonio, Tex. 78232

[21] Appl. No.: 690,214

[22] Filed: Jan. 10, 1985

[51] Int. Cl.[4] A61B 3/02

[52] U.S. Cl. 351/239; 351/243; 351/246

[58] Field of Search 351/239, 243, 246

[56] References Cited

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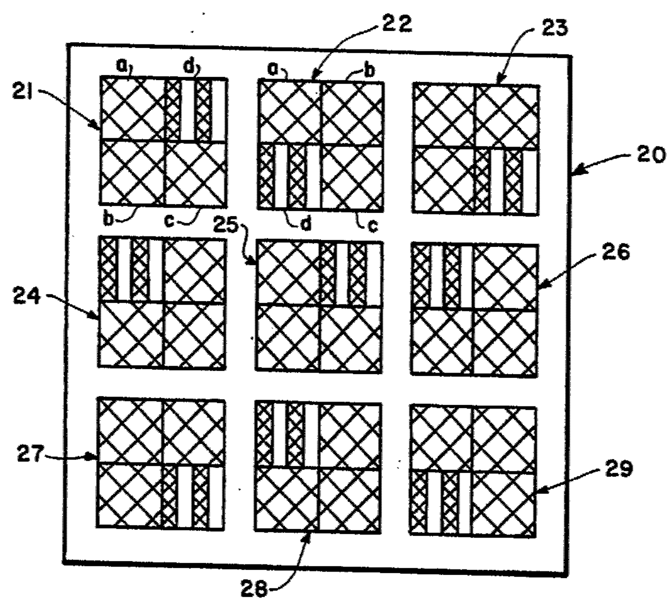
Primary Examiner—Rodney B. Bovernick

Attorney, Agent, or Firm—Donald J. Singer; Bobby D. Scearce

[57] ABSTRACT

A novel device and method for determining the contrast sensitivity of a subject is provided and comprises a test chart including a plurality of patches systematically organized in a predetermined array, each patch having a plurality of adjacent patterned areas, at least one of which is a pattern of alternate light and dark regions of predetermined contrast, and the remaining patterned areas are solid gray patterns of predetermined reflectance, each contrast pattern being characterized by a space average reflectance equal to the predetermined reflectance value of the adjacent gray patterned areas. The spatial frequency and contrast of the alternate dark and light regions may be varied in the array of patches. In the method for determining the visual contrast sensitivity of the vision system of a subject, a chart of the invention is displayed to the subject at successively shorter distances, and the greatest distance at which the subject can resolve each contrast pattern is determined and recorded.

12 Claims, 3 Drawing Figures



United States Patent [19]

Task et al.

[11] **Patent Number: 4,707,696**

[45] **Date of Patent: Nov. 17, 1987**

[54] **PORTABLE GLIDE SLOPE INDICATOR**

[75] Inventors: **Harry L. Task**, Dayton, Ohio; **Ivan S. Wyatt**, Gilbert, Ariz.

[73] Assignee: **The United States of America as represented by the Secretary of the Air Force**, Washington, D.C.

[21] Appl. No.: **823,872**

[22] Filed: **Jan. 29, 1986**

[51] **Int. Cl.**⁴ **G08G 5/00**

[52] **U.S. Cl.** .... **340/954**; 73/178 T; 244/114 R; 340/947; 340/955

[58] **Field of Search** .... 340/947, 948, 952-956, 340/976, 950; 73/178 R, 178 T; 343/5 LS, 5 GC; 364/428, 434; 362/62; 244/114 R; 342/33, 34

[56] **References Cited**

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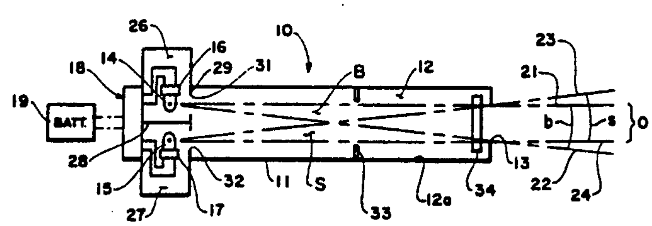
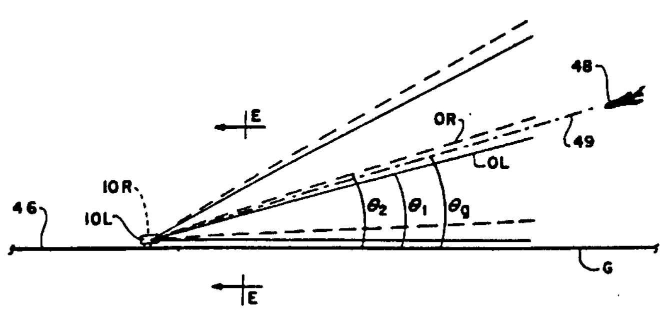
Primary Examiner—James L. Rowland
Assistant Examiner—Brent A. Swarthout
Attorney, Agent, or Firm—Bobby D. Scearce; Donald J. Singer

[57] **ABSTRACT**

An improved glide slope indicator system for facilitating aircraft landings under adverse lighting conditions on remote or austere landing sites is provided which comprises a pair of indicators deployable near ground level on each side of a runway, each indicator including a housing having an optical window and a pair of light sources mounted in predetermined spaced relationship to each other and to the optical window and connected to a power source and related circuitry to project a well defined first blinking and second steady light beam of predetermined angular divergence and overlap, one indicator disposed to project beams with an overlap elevated at a first angle relative to horizontal and the other indicator disposed to project beams with an overlap elevated at a second angle relative to horizontal different from the first, with a preselected glide path lying between the two overlaps. An infrared filter may be included in each indicator to project beams observable only with infrared sensitive viewing aids. The system may be battery powered for portability.

7 Claims, 5 Drawing Figures





United States Patent [19]
Pinkus

[11] **Patent Number:** **5,070,239**
[45] **Date of Patent:** **Dec. 3, 1991**

[54] **NIGHT VISION GOGGLE AMBIENT ILLUMINATION TESTING**

[75] Inventor: **Alan R. Pinkus**, Oxford, Ohio

[73] Assignee: **The United States of America as represented by the Secretary of the Air Force**, Washington, D.C.

[21] Appl. No.: **608,932**

[22] Filed: **Nov. 5, 1990**

[51] **Int. Cl.**[5] **G01J 1/42;** G01D 18/00
[52] **U.S. Cl.** .... **250/252.1;** 250/504 R
[58] **Field of Search** .... 250/252.1 A, 330, 332, 250/331, 493.1, 504 R, 504 H; 358/113

[56] **References Cited**

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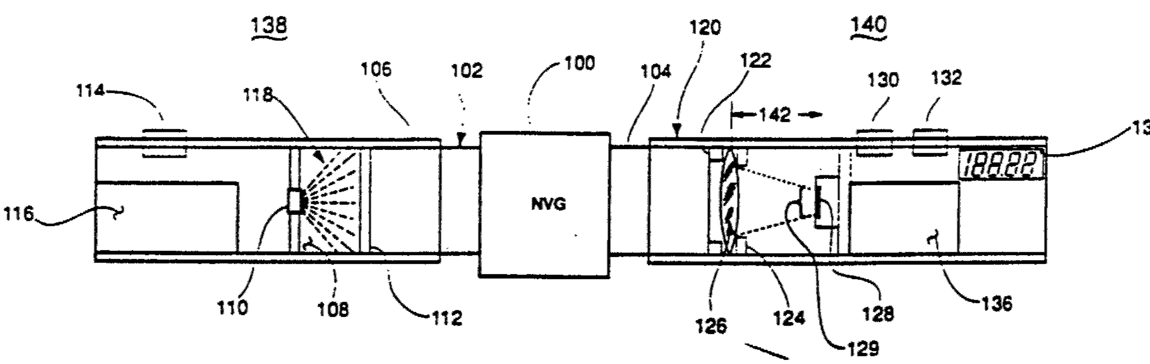
Primary Examiner—Constantine Hannaher
Assistant Examiner—Edward J. Glick
Attorney, Agent, or Firm—Gerald B. Hollings; Donald J. Singer

[57] **ABSTRACT**

A night vision goggle capability evaluation apparatus useful in assessing the degree of illumination present in a proposed NVG operating environment is disclosed. The evaluation apparatus includes portable illuminator and detector devices that are battery operated and optionally coupled to the input and output ports of the goggle during both their own calibration and during measurement of the proposed operating environment. The disclosed apparatus operates by calibrating the NVG output measuring detector from the saturated and dark output extremes of the NVG system and then using this calibrated detector to measure the output of the NVG system and determine whether is it receiving adequate light for satisfactory performance.

8 Claims, 1 Drawing Sheet



United States Patent [19]

Craig et al.

[11] Patent Number: 5,396,069

[45] Date of Patent: Mar. 7, 1995

[54] PORTABLE MONOCULAR NIGHT VISION APPARATUS

[75] Inventors: Jeffrey L. Craig, Beavercreek; Charles Bates, Jr.; Harry L. Task, both of Dayton; Sheldon E. Unger, Englewood, all of Ohio

[73] Assignee: The United States of America as represented by the Secretary of the Air Force, Washington, D.C.

[21] Appl. No.: 85,388

[22] Filed: Jul. 1, 1993

[51] Int. Cl.^{6} H01J 31/50

[52] U.S. Cl. .... 250/330; 250/214 VT; 372/38

[58] Field of Search .... 250/504 H, 330, 214 VT; 372/38

[56] References Cited

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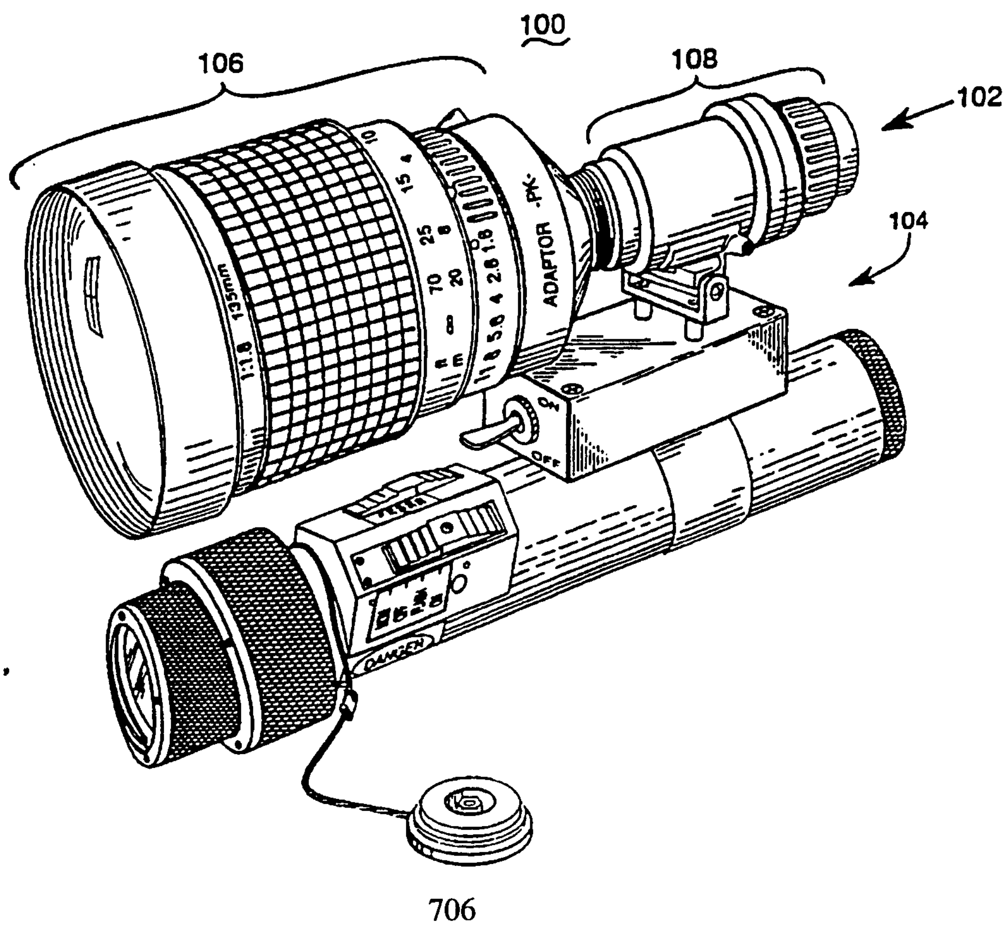
Primary Examiner—Carolyn E. Fields

Attorney, Agent, or Firm—Gerald B. Hollins; Thomas L. Kundert

[57] ABSTRACT

A monocular night vision apparatus employing an infrared energy spectrum source of illumination and a camera lens and night vision image intensifier combined receiver apparatus into a small hand-held portable package that is both low in cost and reliable in nature is described. The night vision transmitter apparatus includes a laser diode energy source that is coupled to an aperture controlled and focus controlled optical system and driven by an electronic closed-loop feedback energization circuit which employs self-contained battery sources of energy. Multiple operating modes and operating intensities of the light source are provided through a plurality of signal inputs to the closed feedback loop of the laser diode energy source. Disturbance of the closed feedback loop by reflected energy within the optical transmitter apparatus is precluded by the use of feedback prevention optical alignment in the transmitter's optical system.

1 Claim, 4 Drawing Sheets



United States Statutory Invention Registration [19]

Task et al.

[11] **Reg. Number:** **H1599**

[45] **Published:** **Oct. 1, 1996**

[54] **SYNTHETIC-COLOR NIGHT VISION**

[75] Inventors: **Harry L. Task**, Dayton; **Alan R. Pinkus**, Fairborn, both of Ohio

[73] Assignee: **The United States of America as represented by the Secretary of the Air Force**, Washington, D.C.

[21] Appl. No.: **498,449**

[22] Filed: **Jul. 5, 1995**

[51] **Int. Cl.**^{6} **H04N 9/04**

[52] **U.S. Cl.** **348/33**; 348/32; 348/34; 348/42

[58] **Field of Search** 348/32, 33, 34, 348/42

[56] **References Cited**

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5,440,352	8/1995	Deter et al.	348/33

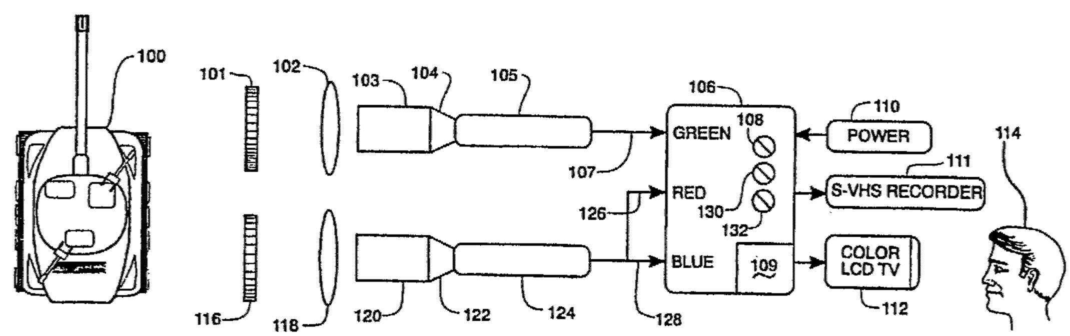
Primary Examiner—Bernarr E. Gregory

Attorney, Agent, or Firm—Gerald B. Hollins; Thomas L. Kundert

[57] **ABSTRACT**

A synthetic color arrangement for a night vision inclusive surveillance system and its display is disclosed. The system partitions an input scene video signal into spectrally segregated scene components which are provided with separate processing as video signals and then recombined into a composite but now multiple color inclusive output representation of the input scene. The system in effect shifts input spectral components to a different part of the electromagnetic spectrum, the visible range of the spectrum, where operator controllable new spectral wavelength values are assigned to each different input scene spectral wavelength. Use of charge coupled device video camera elements, a video signal mixer apparatus, input wavelengths within both the visible and infrared spectral regions and signal processing according to the NTSC standards are also included. Military and non military uses of the apparatus are contemplated.

18 Claims, 2 Drawing Sheets



United States Patent [19]

Pinkus

[11] **Patent Number: 5,567,937**

[45] **Date of Patent: Oct. 22, 1996**

[54] **NIGHT VISION DEVICE WAVELENGTH TEST PATTERN**

[75] Inventor: **Alan R. Pinkus**, Fairborn, Ohio

[73] Assignee: **The United States of America as represented by the Secretary of the Air Force**, Washington, D.C.

[21] Appl. No.: **500,302**

[22] Filed: **Jul. 10, 1995**

[51] **Int. Cl.**[6] **G01J 1/42**

[52] **U.S. Cl.** **250/252.1**; 250/332; 345/83

[58] **Field of Search** .... 250/252.1 A, 332, 250/339.02, 339.05, 495.1; 345/82, 83

[56] **References Cited**

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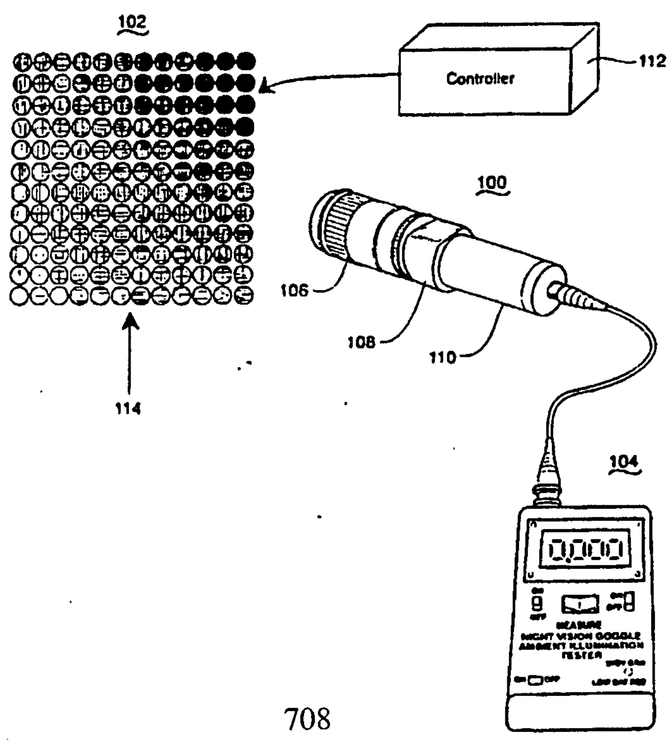
Grinberg et al. "Visible to Infrared Image Converter for Dynamic Infrared Target Simulation Applications" SPIE vol. 226 IIST (1980)/pp. 129-132.

Primary Examiner—Davis L. Willis
Assistant Examiner—Kiet T. Nguyen
Attorney, Agent, or Firm—Gerald B. Hollins; Thomas L. Kundert

[57] **ABSTRACT**

A night vision device test arrangement for determination of spectral sensitivity field of view and other operating characteristics of night vision devices. The test arrangement includes a controllable array of radiant energy emitters such as narrow-band light emitting diode elements used to display a night vision device test pattern. The displayed test pattern may be located in the infrared or infrared and visible spectrum regions and may be altered by user command to have different configurations including different physical size, shape and array location and different spectral content. Control of the test pattern may employ a computer or a manual selection apparatus. The disclosed apparatus is especially suited to in-the-field GO/NO GO rapid performance verification of night vision device equipment. Military and non-military uses are contemplated.

18 Claims, 4 Drawing Sheets



United States Patent [19]

Pinkus et al.

[11] **Patent Number: 5,608,213**

[45] **Date of Patent: Mar. 4, 1997**

[54] **SPECTRAL DISTRIBUTION EMULATION**

[75] Inventors: **Alan R. Pinkus**, Fairborn; **Harry L. Task**, Dayton, both of Ohio

[73] Assignee: **The United States of America as represented by the Secretary of the Air Force**, Washington, D.C.

[21] Appl. No.: **552,402**

[22] Filed: **Nov. 3, 1995**

[51] **Int. Cl.**[6] **H04N 17/00**

[52] **U.S. Cl.** **250/252.1**; 250/330; 250/495.1

[58] **Field of Search** .... 250/494.1, 495.1, 250/252.1 A, 330

[56] **References Cited**

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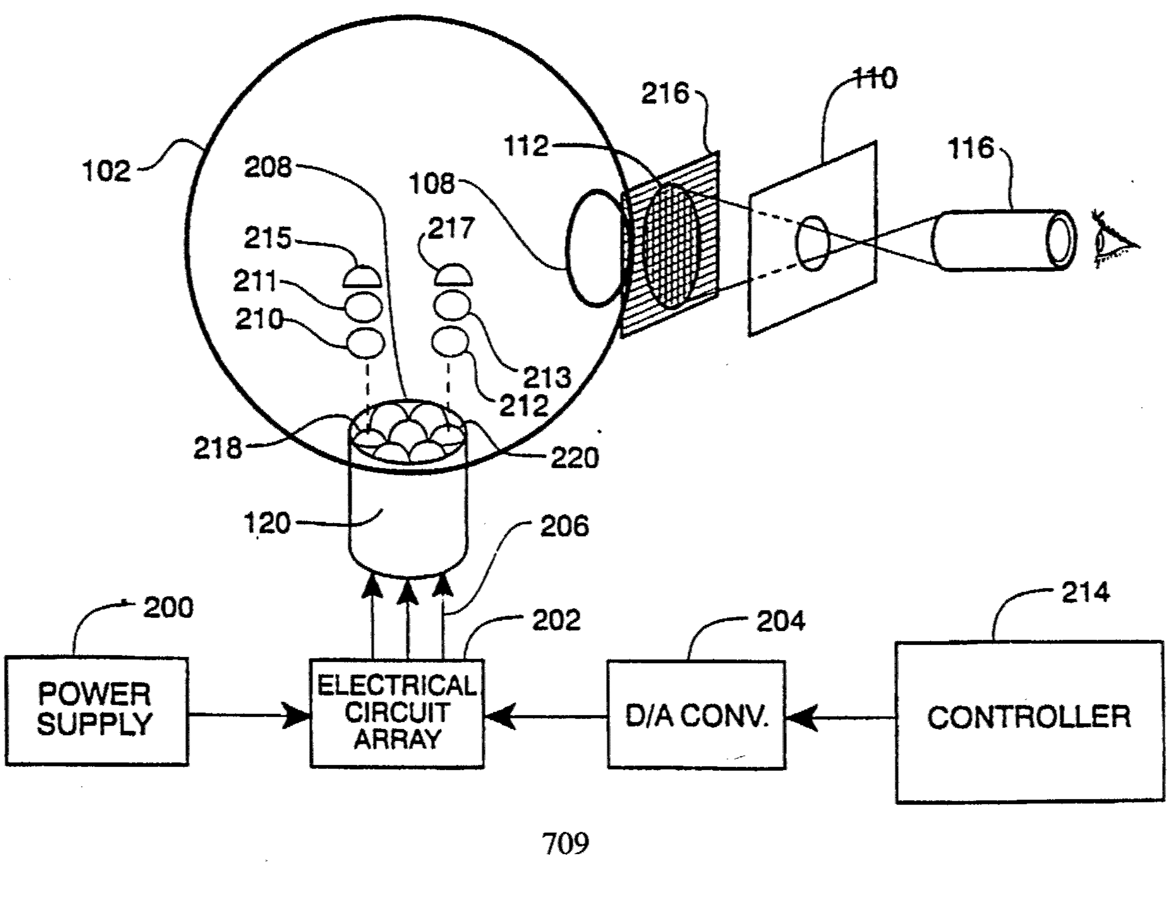
Primary Examiner—Carolyn E. Fields

Attorney, Agent, or Firm—Gerald B. Hollins; Thomas L. Kundert

[57] **ABSTRACT**

A test arrangement for assessing the spectral energy distribution-determined response of a night vision device or other electro-optical apparatus. The test arrangement provides a library of spectral energy-distributed test signals or input scenes which may be selected to represent for example typical or extreme conditions expected during field use of the tested night vision device. The test signals originate in an array of energy transducer devices such as light emitting diode elements with each such light emitting diode element proving a limited wavelength component of the wide band composite optical signal received at the input port of the night vision device. Each component signal is arranged to be controlled electrically in presence or absence and also controlled electrically in radiance or intensity according to the needs of the scene being presented; such control is provided by a manual controller or by a programmed digital computer or by other controlling apparatus such as a programmed logic array. The composite test signal may include both infrared and visible components. In addition to control of the composite test signal, other aspects of the performed test such as test scene data storage may also be accomplished in the controller or computer. The disclosed apparatus is especially suited to performance verification of night vision systems in a laboratory environment prior to field use of similar systems. Military and non-military uses are contemplated.

20 Claims, 4 Drawing Sheets



United States Patent [19]

Task et al.

[11] **Patent Number: 5,679,949**

[45] **Date of Patent: Oct. 21, 1997**

[54] **NIGHT VISION DEVICE AUTOMATED SPECTRAL RESPONSE DETERMINATION**

[75] Inventors: **Harry L. Task**, Dayton; **Alan R. Pinkus**, Fairborn, both of Ohio

[73] Assignee: **The United States of America as represented by the Secretary of the Air Force**, Washington, D.C.

[21] Appl. No.: **491,390**

[22] Filed: **Jun. 16, 1995**

[51] **Int. Cl.**^{6} **G01J 5/52**

[52] **U.S. Cl.** .... **250/252.1**; 250/504 R

[58] **Field of Search** .... 250/504 R, 252.1 A

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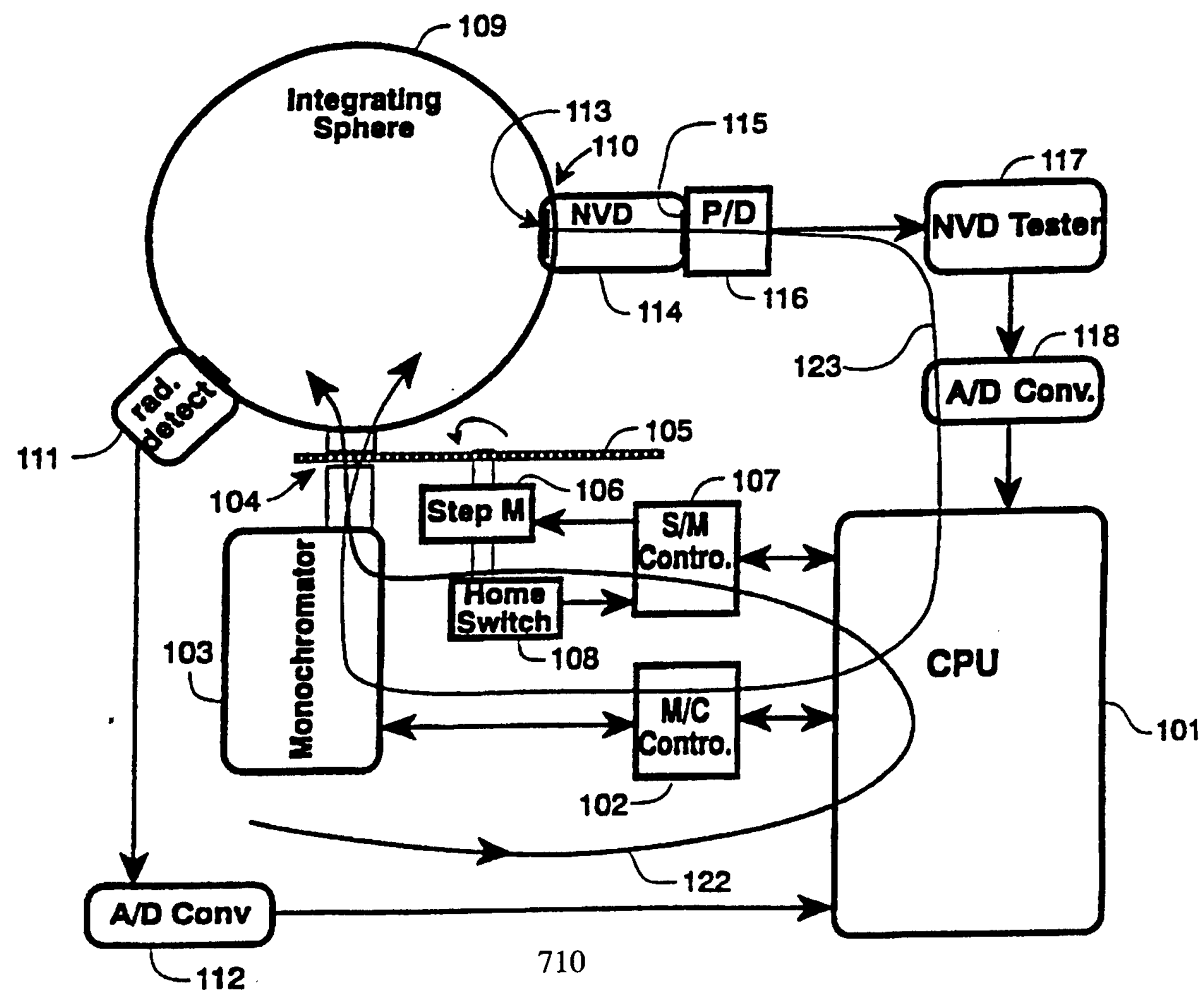
Ukhanov et al., "Spectroradiometric Apparatus for Testing IR Receivers", Sov. J. Opt. Technol., 47(1), Jan. 1980, pp. 13–15.

Primary Examiner—Carolyn E. Fields
Attorney, Agent, or Firm—Gerald B. Hollins; Thomas L. Kundert

[57] **ABSTRACT**

An automated and preferably computer-controlled night vision device test arrangement for determination of spectral sensitivity in the infrared or other input spectrum regions. The test arrangement includes feedback control of night vision device input port signal levels, incremented selection of input signal wavelength, loop-residing spectrum increments and automated collection and presentation of test results.

18 Claims, 3 Drawing Sheets



United States Patent [19]

Pinkus et al.

[11] **Patent Number: 5,729,010**

[45] **Date of Patent: Mar. 17, 1998**

[54] **NIGHT VISION DEVICE LOCALIZED IRRADIANCE ATTENUATION**

[75] Inventors: **Alan R. Pinkus**, Bellbrook; **Harry L. Task**, Dayton; **Peter L. Marasco**, Kettering, all of Ohio

[73] Assignee: **The United States of America as represented by the Secretary of the Air Force**, Washington, D.C.

[21] Appl. No.: **712,506**

[22] Filed: **Sep. 11, 1996**

[51] **Int. Cl.**[6] **H01J 31/50**

[52] **U.S. Cl.** .... **250/214 VT**; 313/524

[58] **Field of Search** .... 250/207, 214 VT; 313/524, 528, 534; 315/149

[56] **References Cited**

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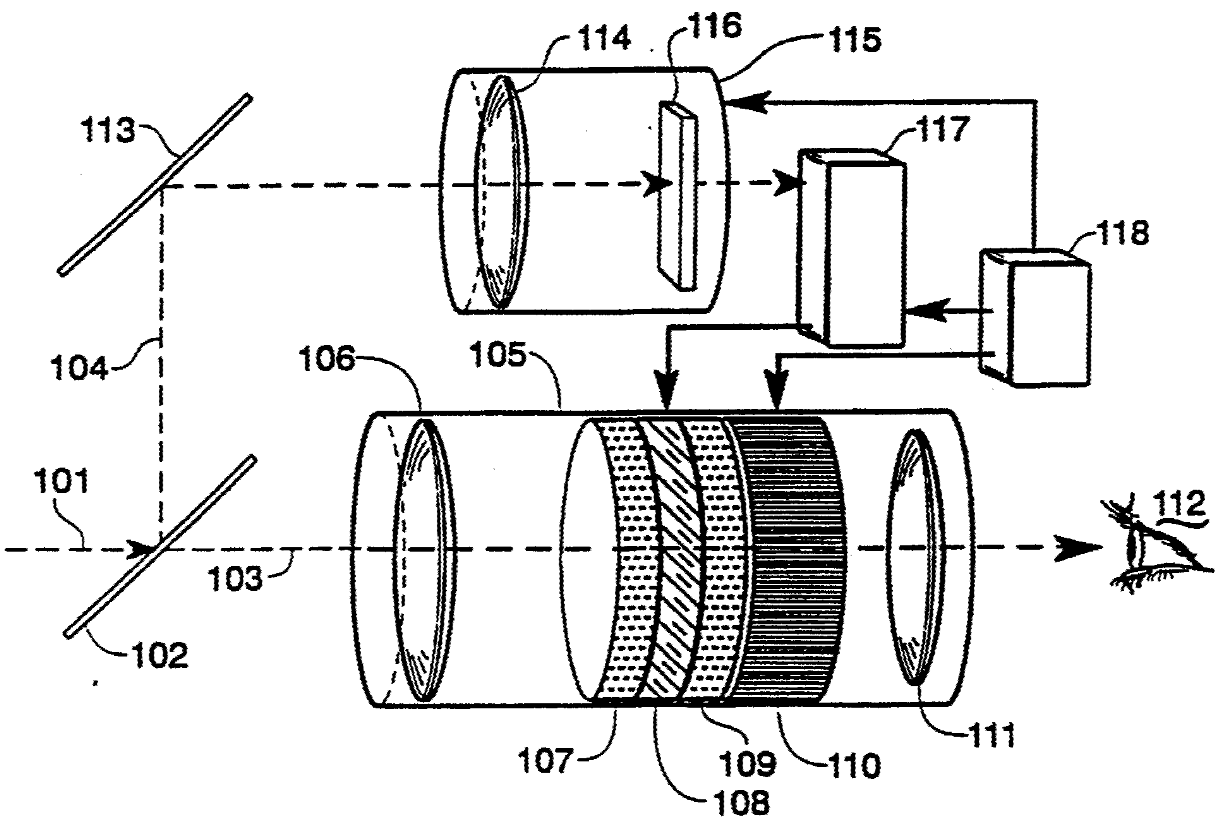
Primary Examiner—Stephone B. Allen

Attorney, Agent, or Firm—Gerald B. Hollins; Thomas L. Kundert

[57] **ABSTRACT**

A night vision device enhancement wherein occurrence of a bright object in an input scene of the night vision device is precluded from adversely affecting reproduction of adjacent low radiance level portions of the input scene. By optically limiting or excluding bright object input scene portions from the night vision device input field the disclosed system precludes both image intensifier-related effects, effects such as blooming and current saturation, and also precludes automatic gain control-related effects such as full-field sensitivity decrease based on the bright object. Plural embodiments of the system are disclosed, embodiments based on bright object attenuation by both yet to be developed photo active materials such as photochromics and embodiments which use present state of the art liquid crystal materials and accompanying electronics. Military and non-military uses of the improved night vision device are contemplated.

18 Claims, 3 Drawing Sheets



United States Patent [19]

Task et al.

[11] **Patent Number: 5,760,953**

[45] **Date of Patent: Jun. 2, 1998**

[54] **ADAPTOR FOR NIGHT VISION GOGGLES**

[75] Inventors: **Harry L. Task**, Dayton; **Peter L. Marasco**, Kettering, both of Ohio

[73] Assignee: **United States of America as represented by the Secretary of the Air Force**, Washington, D.C.

[21] Appl. No.: **667,185**

[22] Filed: **Jun. 21, 1996**

[51] **Int. Cl.**^{6} **G02B 23/00**; G02B 7/02

[52] **U.S. Cl.** **359/409**; 359/827

[58] **Field of Search** 359/353, 400, 359/408, 409, 410, 421, 827; 2/10, 209.13

[56] **References Cited**

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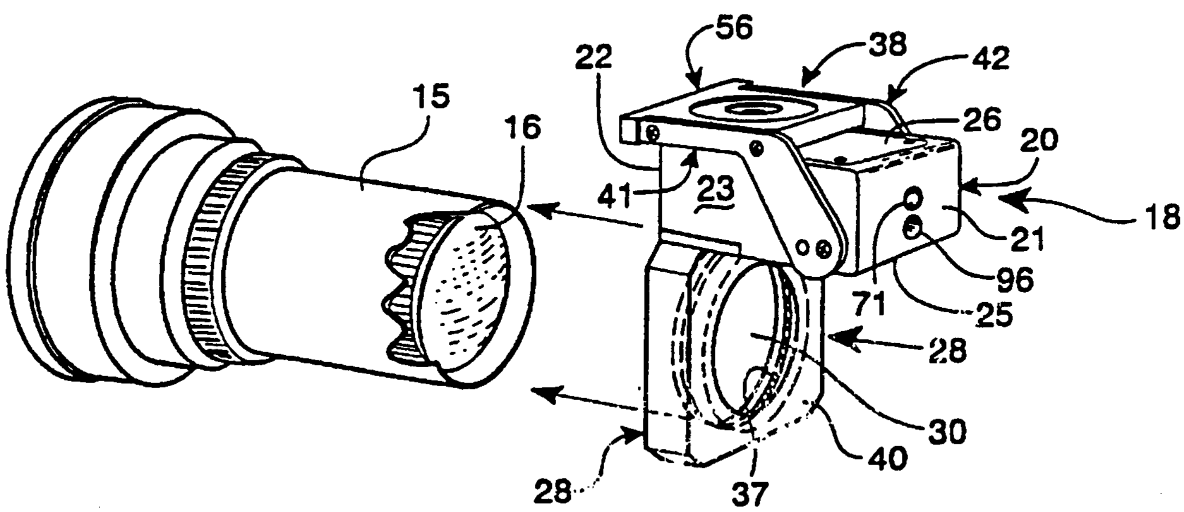
Primary Examiner—Paul M. Dzierzynski
Assistant Examiner—Mark A. Robinson
Attorney, Agent, or Firm—Edward W. Nypaver; Thomas L. Kundert

[57] **ABSTRACT**

An adaptor detachably mounted on an ocular of night vision goggles for quickly adjusting the objective lens focus to clearly view far and near objects. The adaptor includes a positive optical power or close-up lens mounted in a holder pivotally mounted between a stowed, inoperative position and an operative position locating the close-up lens in axial alignment with the objective lens of the ocular. The close-up lens has an effective diameter substantially smaller than the diameter of the objective lens to raise the F/number of the objective lens/close-up lens combination for increasing the depth of focus for enhanced near viewing. Auxiliary illumination is provided by a battery powered infra-red Light Emitting Diode (LED) mounted in the adaptor and energized by a switch as the lens holder moves toward its operative position.

10 Claims, 5 Drawing Sheets



United States Patent [19]

Task et al.

[11] **Patent Number: 5,926,265**

[45] **Date of Patent: Jul. 20, 1999**

[54] **LOW-LEVEL LIGHTING COMPARATOR**

[75] Inventors: **Harry L. Task**, Dayton; **Alan R. Pinkus**, Bellbrook, both of Ohio

[73] Assignee: **The United States of America as represented by the Secretary of the Air Force**, Washington, D.C.

[21] Appl. No.: **08/837,135**

[22] Filed: **Apr. 14, 1997**

[51] **Int. Cl.**[6] **G01J 1/10**; G08B 25/00

[52] **U.S. Cl.** **356/229**; 340/815.75; 340/525

[58] **Field of Search** 356/229, 230, 356/231, 232, 49, 50; 340/461, 462, 525, 815.47, 815.75, 979

[56] **References Cited**

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Primary Examiner—Frank G. Font

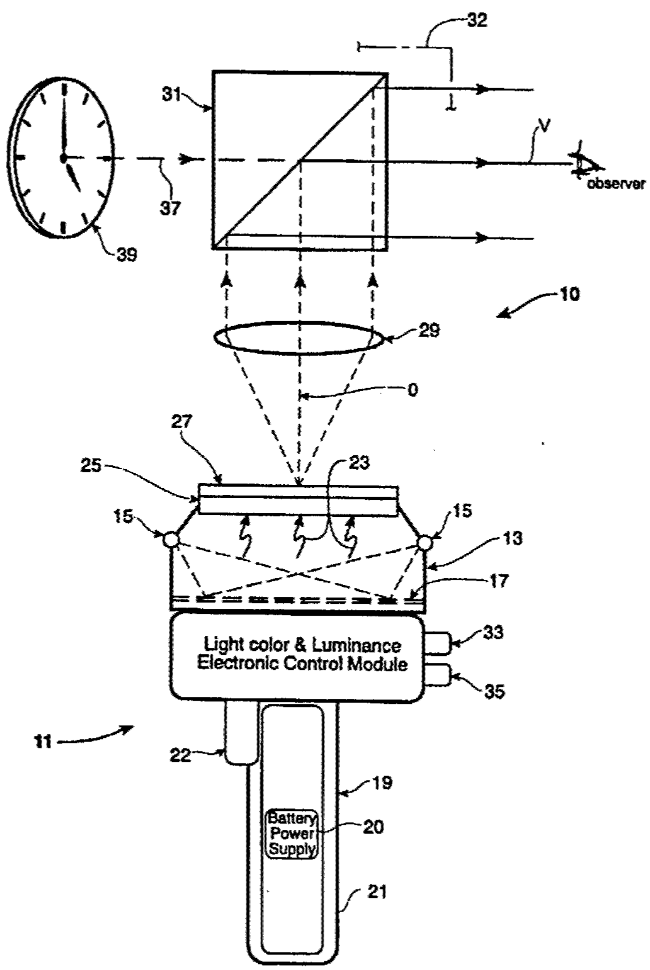
Assistant Examiner—Zandra V. Smith

Attorney, Agent, or Firm—Bobby D. Scearce; Thomas L. Kundert

[57] **ABSTRACT**

An instrument and method for optically calibrating and balancing low level luminances of lighted instrument panel displays within the operator station of a vehicle is described which comprises a self-contained, calibrated luminance source and a beamsplitter for combining and juxtaposing an image of the calibrated luminance source with an image of the luminance from a lighted instrument panel display to be calibrated or balanced, whereby the images may be compared in luminance, the lighted instrument panel display being adjustable in intensity using the vehicle instrument panel light trim capability.

4 Claims, 2 Drawing Sheets



(12) **United States Patent**
Task et al.

(10) **Patent No.: US 6,194,701 B1**
(45) **Date of Patent: Feb. 27, 2001**

(54) **PORTABLE NIGHT VISION GOGGLE HAZE AND TRANSMISSIVITY MEASUREMENT DEVICE**

(75) Inventors: **Harry L. Task**, Dayton; **Alan R. Pinkus**, Bellbrook; **Sheldon E. Unger**, Englewood, all of OH (US)

(73) Assignee: **The United States of Americas as represented by the Secretary of the Air Force**, Washington, DC (US)

(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 0 days.

(21) Appl. No.: **09/287,078**

(22) Filed: **Apr. 6, 1999**

(51) **Int. Cl.**^{7} **G01N 21/59**; G01N 21/958

(52) **U.S. Cl.** .... **250/214 VT**; 356/432; 356/333

(58) **Field of Search** .... 250/214 VT, 216, 250/559.16, 559.17, 330, 333, 339.11, 341.8; 356/432, 433, 434, 435, 443, 445, 446, 447, 448, 337, 338

(56) **References Cited**

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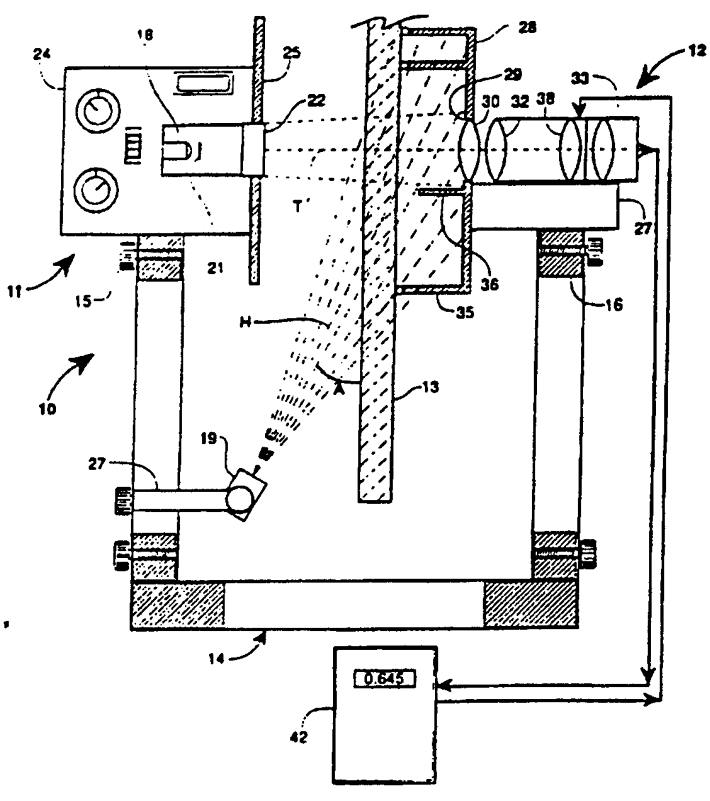
Primary Examiner—John R. Lee
(74) *Attorney, Agent, or Firm*—Bobby D. Scearce; Thomas L. Kundert

(57) **ABSTRACT**

Device and method are described for measuring transmissivity and haze in transparencies as detected through night vision goggles, including an emitter portion and a sensor portion, the emitter portion including a first light source for presenting an image to the sensor portion through the transparency and a second light source for projecting a haze producing light onto the transparency, the sensor portion including a light intensifier tube and a photometer for measuring the luminance output of the light intensifier tube and quantifying attenuation (transmissivity) and haze (light scatter) characteristics of the transparency as viewed through night vision goggles.

6 Claims, 3 Drawing Sheets



(12) **United States Patent**
Pinkus et al.

(10) **Patent No.:** **US 6,401,589 B1**
(45) **Date of Patent:** ***Jun. 11, 2002**

(54) LIMITING AIRBORNE TARGET DESIGNATING LASER CANOPY RETURNS

(75) Inventors: **Alan R. Pinkus**, Bellbrook; **Harry L. Task**, Dayton; **Peter L. Marasco**, Kettering, all of OH (US)

(73) Assignee: **The United States of America as represented by the Secretary of the Air Force**, Washington, DC (US)

(*) Notice: This patent issued on a continued prosecution application filed under 37 CFR 1.53(d), and is subject to the twenty year patent term provisions of 35 U.S.C. 154(a)(2).

Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 0 days.

(21) Appl. No.: **09/501,290**

(22) Filed: **Feb. 9, 2000**

(51) **Int. Cl.**[7] **F41F 5/00**
(52) **U.S. Cl.** **89/1.1**
(58) **Field of Search** 244/129.3; 89/1.11

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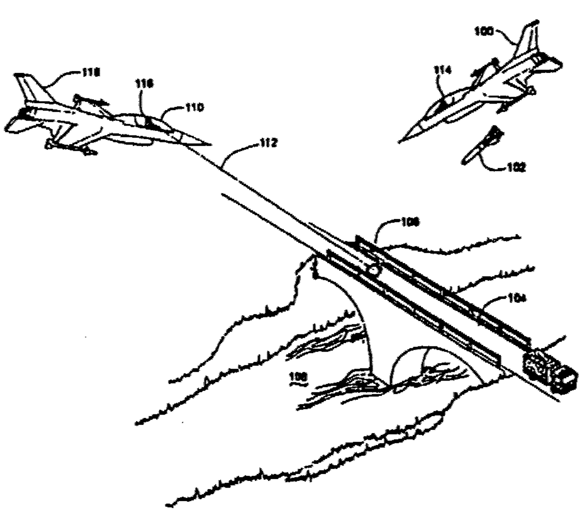
Primary Examiner—Charles T. Jordan
Assistant Examiner—Jordan M. Lofdahl
(74) *Attorney, Agent, or Firm*—Gerald B. Hollins; Thomas L. Kundert

(57) **ABSTRACT**

A laser energy window arrangement especially usable in a tactical aircraft having night vision equipment-aided cockpit visual information input requirements. The laser energy window arrangement enables use of laser apparatus directed external to the aircraft for target designation or other purposes while minimizing the amount of energy from such laser returning spuriously inside the cockpit where it inherently acts a noise signal for night vision equipment. The laser energy window limits the portion of the aircraft windshield or canopy exposed to laser radiation and its effects to a relatively small area, an obscurable area generating significantly reduced amounts of spurious return energy in comparison with use of the laser directly through an unlimited windshield, canopy, or other type of transparency. Transmission of spurious return energy from the laser energy window to remaining portions of the windshield or canopy is precluded by interruption of transmission paths within the windshield or canopy material and transducing the interrupted path energy into heat dissipated within or outside of the aircraft and not affecting the remainder of the canopy. Potentially increased aircraft to target standoff range, reduce need for aircrew use of laser eye protection gear, reduced laser induced windshield or canopy degradation and other benefits are identified for aircraft uses of the invention. Use of the window invention in other non aircraft and non military aircraft settings is also contemplated.

15 Claims, 5 Drawing Sheets



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