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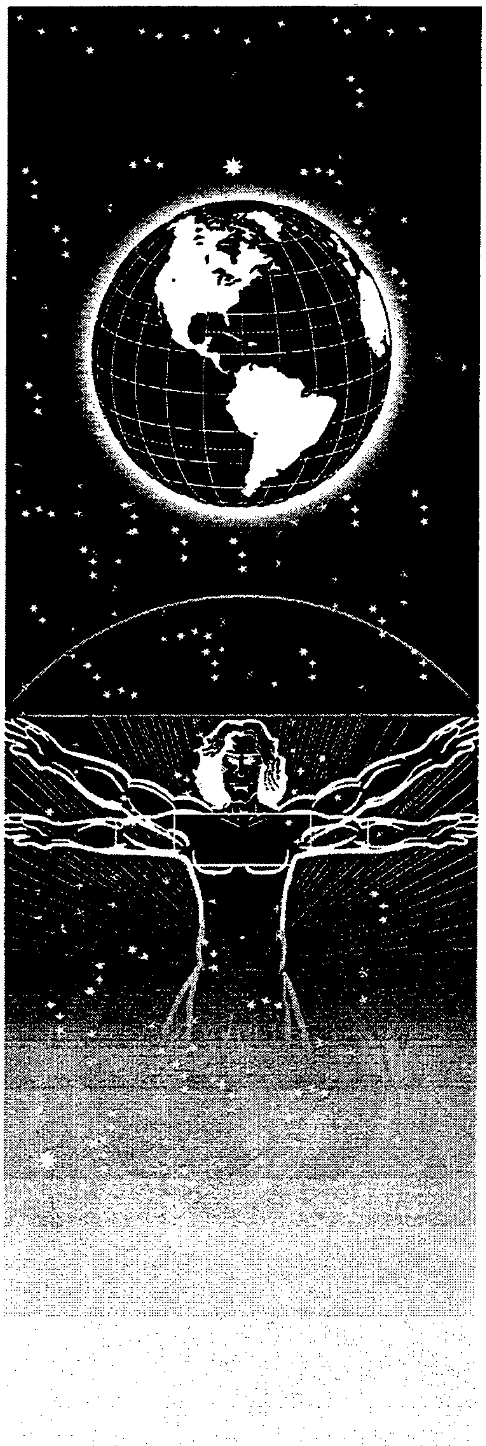

UNITED STATES AIR FORCE ARMSTRONG LABORATORY

WF-360TL Laser System Hazard Evaluation

Kenneth S. Keppler, Major, USAF

December 1997

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Occupational and Environmental Health
Directorate
Optical Radiation Division
8111 18th Street
Brooks AFB, TX 78235-5215

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Kenneth S. Keppler

KENNETH S. KEPPLER, Maj, USAF
Chief, Optical Engineering Branch

Leon N. McLin, Jr.

LEON N. MCLIN, JR., Lt Col, USAF, BSC
Chief, Optical Radiation Division

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Armstrong Laboratory (AFMC)
Occupational and Environmental Health Directorate
Optical Radiation Division
8111 18th St.
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Misuse of a commercial hand-held laser illuminator led to the US Coast Guard's first documented laser eye injury. As a result of this incident and planned use of several new laser systems, the Coast Guard asked the Optical Radiation Division (AL/OEO, Brooks AFB, TX) to assist with a coordinated health risk assessment of three laser systems for use by Coast Guard aviation. This report documents evaluation of a WF-360TL aircraft mounted, near infrared (810 nm wavelength) laser illuminator. The main purposes of our evaluation were to: measure laser output parameters, determine eye and skin hazard potential, and provide advice for safe operation and maintenance of this system. Our output parameter measurements agreed well with the system manufacturer's (Westinghouse Electro-Optical Systems, FL) measurements. AL/OEO measurement results were as follows: 4.5 W average output power, 1.5 mm (horizontal) by 9.0 mm (vertical) exit beam spot size, and 85 mrad (horizontal) by 66 mrad (vertical) far field beam divergence at the 1/e intensity points. Hazard parameters based on worst case output parameters were as follows: 6.9 m (23 ft) Nominal Ocular Hazard Distance, 4.5 Optical Density at 810 nm requirement for laser eye protection, and a skin hazard distance of 0.5 m (1.6 ft).

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LIST OF ACRONYMS

AL/OEO	Armstrong Laboratory/Optical Radiation Division
ANSI	American National Standards Institute
CCD	Charge Coupled Device
CW	Continuous Wave
IR	Infrared
LEP	Laser Eye Protection
LHAZ	Laser Hazard Analysis Software Package
LOS	Line-Of-Sight
LSO	Laser Safety Officer
MPE	Maximum Permissible Exposure
NOHD	Nominal Ocular Hazard Distance
OD	Optical Density
SAR	Search and Rescue
SHD	Skin Hazard Distance
TEM	Transverse Electromagnetic
TRT	Turret Assembly
USCG	United States Coast Guard
WF-360TL	W for Westinghouse, F for FLIR, 360 for degrees of azimuth pointing angle, T for TV camera and L for Laser

WF-360TL LASER SYSTEM HAZARD EVALUATION

INTRODUCTION

Misuse of a commercial hand held laser illuminator was the primary cause of the United States Coast Guard's first documented laser eye injury. The injury circumstances were described in a 21 Jan 94 U.S. Dept. or Transportation/United States Coast Guard Memorandum from LCDR Paradise to the Chief, Aviation Division. The following paragraph is a summary of the incident as described in the Memo:

> Following an unsuccessful night vision devices flight test, a laser illuminator was inadvertently left on an individual's desk with the warning label down. The next morning, the desk owner found the device, turned it on and looked into the front (exit aperture) of the laser. The resulting laser exposure produced a permanent burn on the back of one of the mishap individual's eyes. If the burn had been at the worst case location in the back of the eye (i.e., the fovea/center of vision), there would have been permanent and significant loss of vision. Fortunately, this was not the case and the mishap individual escaped with no noticeable degradation of vision.

As a result of the first documented injury and the growing threat of laser eye injuries resulting from increased use of potentially hazardous laser systems, the U. S. Coast Guard (USCG) initiated a laser safety program in 1994. As part of this program, the Optical Radiation Division (AL/OEO) at Brooks AFB was asked to perform a coordinated health hazard risk assessment of three separate laser systems used by Coast Guard aviation. The following three systems were evaluated: an AIM-1 laser, embedded in the turret of a FLIR 2000 infrared system; a diode laser illuminator which is part of the Dark Invader Image Intensified video camera; and, the laser diode array imbedded in the turret of the WF-360TL fusion sensor. The AIM-1 laser and Dark Invader diode laser assessments were conducted from 28 Nov 94 to 2 Dec 94 at Coast Guard Air Station Elizabeth City, NC. The hazard assessment for these two laser systems is documented in Armstrong Laboratory Consultative Letter number AL/OE-CL-1995-0027. This report documents the hazard assessment of the WF-360TL laser system tested from 7 - 9 Nov 94 at USCG Air Station Miami, FL.

The WF-360TL (W for Westinghouse, F for FLIR, 360 for degrees of azimuth pointing angle, T for TV camera and L for Laser) avionics package is housed in a gimbaled turret system (see Figure 1). The USCG plans to use this system on the RG-8A prototype (pusher/puller propelled) aircraft for law enforcement and Search and Rescue (SAR) missions. As of Dec 94, the USCG had purchased four of the WF-360TL systems. The Air Force also uses these systems, however, a laser range finder (the Army's Milios 'eye safe' system) is used in place of the diode illuminator laser. Coast Guard system operators will use the 810 nm wavelength diode to illuminate objects in the Charge Coupled Device (CCD) TV camera for night observation and viewing. A 6.5 mm focal length collimator lens set is used to provide uniform illumination of the TV camera field of view.

The purpose of this investigation was to determine the hazard potential of the USCG WF-360TL laser system. Specifically, AL/OEO personnel planned and conducted field (on-site) test measurements and analysis of collected data to determine the eye hazard distance (Nominal Ocular Hazard Distance or NOHD), skin hazard distance (SHD) and protection requirements (i.e., Optical Density, or OD, for laser

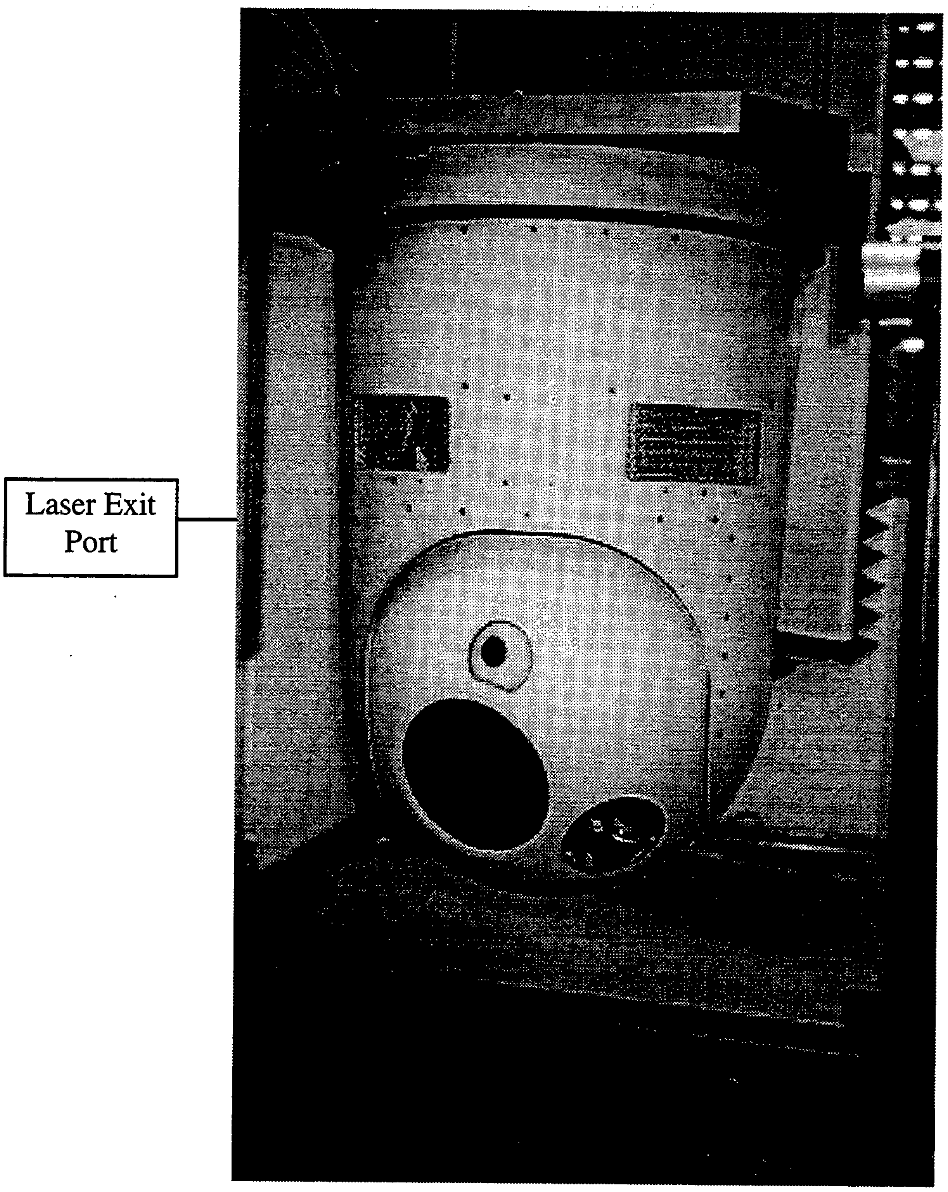

Figure 1. WF-360TL Turret Assembly

eye protection) for this laser. The following AL/OEO personnel participated in this effort: Maj Kenneth S. Keppler (Chief, Optical Engineering Branch), TSgt L. Dwayne Lambert (NCOIC, Optical Engineering Branch), and SrA James W. Lamorte (Instrumentation and Telemetry System Specialist).

A complete system hazard evaluation would include investigations of eye and skin hazard potential for depot maintenance personnel, mission support personnel and flight crews. In addition, there would be protection requirements recommendations for each personnel group. The primary focus of this evaluation was for maintenance personnel operating the system in a shop environment. Since AL/OEO personnel never observed the system mounted on the prototype aircraft, hazards to aircrews were not separately evaluated. In addition, where applicable, laser eye protection (LEP) requirements recommendations for aircrews require a 'safe-to-fly' evaluation. This type of evaluation assesses possible adverse effects of visible light attenuation (i.e., reduced visibility of cockpit displays) and is beyond the scope of this report. AL/OEO recommends a 'safe-to-fly' evaluation be conducted prior to any in-flight use of laser eye protection by aircrew members. The Optical Radiation Division at Brooks AFB, TX can provide assistance in planning and executing such evaluations.

Test methods based on national laser safety standard guidance, assumptions during test planning, and test procedures used to collect laser output parameters will be described in the next section of this report. Then test results and a discussion of how these results were used to determine hazard distances and protection requirements will be presented. The final two report sections summarize our conclusions based on the measurement results and final safety guidance recommendations, respectively.

TEST METHODS, ASSUMPTIONS AND PROCEDURES

Test Methods

The plan for this test was to collect field measurement data of a prototype WF-360TL laser system. The USCG at Coast Guard Air Station Miami, FL was performance testing a prototype system during the AL/OEO effort. AL/OEO measurements were conducted in a trailer (future avionics system test facility) located at Air Station Miami. Following the field test, AL/OEO members analyzed collected data to determine appropriate eye and skin hazard distances and compare these results with laser output specifications (see Table 1 below). These specifications were provided by the WF-360TL avionics system manufacturer (Westinghouse Electro Optical Systems).

Table 1. Manufacturer's Output Parameters for the WF-360TL Laser

Average Output Power	4.5 Watts Continuous Wave
Exit Beam Spot Size	1.0 mm (H) x 8.0 mm (V)
Exit Beam Divergence	66.3 mrad (H) by 54.1 mrad (V)

A brief review of laser safety guidance will facilitate understanding of our method of test. The American National Standard for Safe Use of Lasers (ANSI Z136.1-1993) provides adequate guidance for determining skin and eye damage hazard distances for most commonly used laser systems. Two key laser safety related terms defined in ANSI Z136.1 are the Maximum Permissible Exposure (MPE) and the Nominal Ocular Hazard Distance (NOHD). The MPE is defined as, 'The level of laser radiation to which a person may be exposed without hazardous effect of adverse biological changes in the eye or skin.' ANSI defines the NOHD as, 'The distance along the axis of the unobstructed beam ...beyond which the irradiance ... during operation is not expected to exceed the appropriate MPE.'

ANSI provides the following equation for use in determining the NOHD for a circularly symmetric, Gaussian laser beam:

$$r_{NOHD} = \frac{1}{\phi}\left(\sqrt{\left(\frac{1.27\Phi}{MPE} - a^2\right)}\right) \text{ cm} \qquad (1)$$

Where:

r_{NOHD} is the Nominal Ocular Hazard Distance ***in cm***
ϕ is the beam divergence at the 1/e intensity points
Φ is the total radiant output power (for a cw laser)
MPE is the ANSI Maximum Permissible Exposure Limit
a is the diameter of the emergent beam in cm

A similar equation can be derived for a rectangularly symmetric beam, like the WF-360TL laser. This equation is:

$$r_{NOHD} = \frac{1}{\phi_1 \phi_2} \sqrt{\frac{\sqrt{\left(X^2 - 4\phi_1^2 \phi_2^2 \left(a_1^2 a_2^2 - \left[\frac{\Phi}{MPE} \right]^2 \right) \right)} - X}{2}} \text{ cm} \qquad (2)$$

Where:

r_{NOHD} is the Nominal Ocular Hazard Distance ***in cm***
ϕ_1 is the horizontal beam divergence at the 1/e intensity points
ϕ_2 is the vertical beam divergence at the 1/e intensity points
Φ is the total radiant output power (for a cw laser)
MPE is the Maximum Permissible Exposure Limit
a_1 is the horizontal diameter of the emergent beam in cm
a_2 is the vertical diameter of the emergent beam in cm
and X is $(a_1^2 \phi_2^2 + a_2^2 \phi_1^2)$

Eye and skin hazard distances can be determined by substituting the appropriate eye and skin MPE's provided in ANSI (MPE_5 for eyes and MPE_7 for skin) and the output parameters of a given laser system into equation 2. Per ANSI convention, the emergent beam diameters are at the 1/e intensity profile points for a Gaussian type laser beam.

Based on the above ANSI guidance, the AL/OEO test team planned to measure the following output parameters for use in determining eye and skin hazard distances: average output power, exit beam diameter (horizontal and vertical) and the far-field beam divergence (horizontal and vertical). Per the above equations, small errors in the beam divergence value would result in greater NOHD uncertainty than errors in other measured parameters. Thus, the test team attempted to minimize uncertainties in our beam divergence measurements. In order to accomplish this, two different divergence measurement techniques were planned. In addition, cross sectional beam intensity profile (for reasons explained in the following section on assumptions) measurements were attempted.

Assumptions

For purposes of simplicity, the ANSI NOHD equation is based on the assumption that the cross sectional laser beam intensity profile is Gaussian (see Figure 2). In Gaussian laser theory, the cross sectional intensity profile of a circular zero, zero transverse electromagnetic ($TEM_{0,0}$) mode laser beam is assumed to have a circularly symmetric two dimensional Gaussian shape. If all the energy/power in a Gaussian beam were combined into a cylindrical shaped beam profile with energy density/irradiance equal to the Gaussian beam peak, then the radius of the cylindrical beam would be the same as the distance for a Gaussian beam from the central beam peak to the 1/e points. For this reason, ANSI uses the (conservative) 1/e intensity points for hazard analysis purposes. For system performance measurements, the $1/e^2$ diameter is often used because a cylindrical beam with this diameter would have energy/irradiance equal to the average intensity over a given Gaussian beam profile.

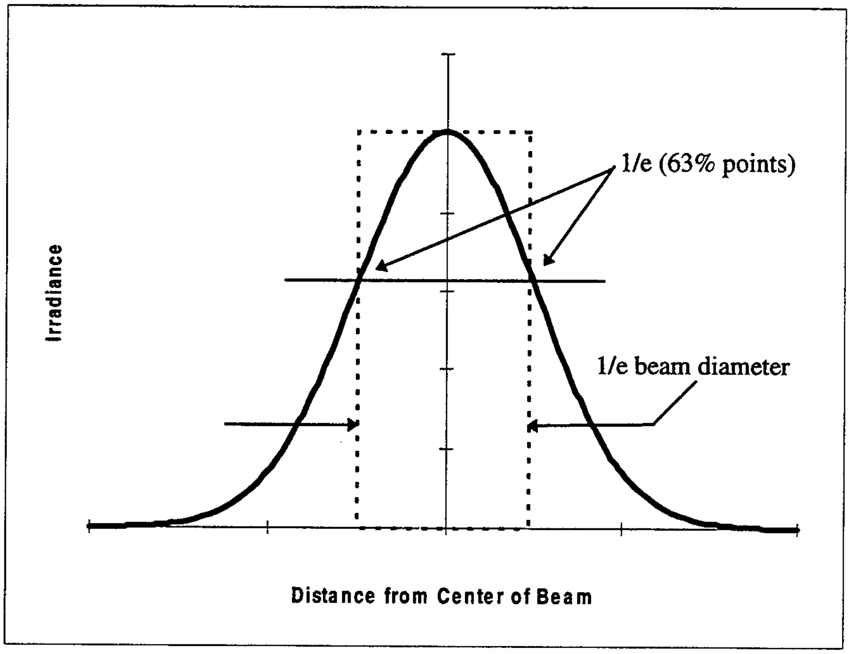

Figure 2. Gaussian Beam Profile

As shown in the text, Laser Electronics by Verdeyen, the beam divergence initially increases exponentially (near field divergence) and then, after a critical distance is reached, increases linearly (far-field). The expression for a Gaussian beam in Verdeyen's text can be used to derive the mathematical relationship between the 1/e and $1/e^2$ far-field beam divergences. Such a derivation, which is beyond the scope of this report, shows that the 1/e divergence can be obtained by simply dividing the $1/e^2$ divergence by 1.414 (the square root of 2). Since the beam divergence differs depending on the location in the intensity profile, it is important to know which diameter of a laser beam is being measured when attempting to determine the divergence of any given beam.

It is important to note that a perfect Gaussian beam only exists in theory. Any real laser beam will be at least somewhat non-Gaussian. In addition, smooth two dimensional intensity profile curves will only exist for circularly symmetric laser cavities that are restricted (usually via cavity construction) to firing in the $TEM_{0,0}$ mode. Since the WF-360TL laser we are testing contains a rectangular diode array laser, it is certainly not circularly symmetric. In addition, we did not know *a priori* what the actual intensity profile of the beam would be. For test planning purposes we assumed the beam would have a 'flat top' intensity profile. We planned to measure the far-field beam cross sectional intensity profile to check the accuracy of this assumption. Assuming a flat top profile would imply that the 1/e and $1/e^2$ intensity profile points would be at the same place. Results of this comparison for the WF-360TL laser system are discussed in the Results and Discussions Section of this report.

Procedures

General

A special procedure was used to stabilize the WF-360TL turret Line-Of-Sight (LOS) during the test. The Westinghouse field representative used the control panel to obtain the desired laser propagation direction (i.e., horizontal or parallel to the floor). When the desired propagation direction was properly set, the Westinghouse representative cut electrical power to the turret servo motors to lock the turret LOS in place for the test duration.

Average Power Measurement

The power measurements were simple and straight forward. Due to the small size of the laser beam at the turret exit window, we were able to fire the beam directly into a power meter detector (focusing lens was not required). Westinghouse specification values were used to predict the irradiance of the output spot so we could chose detectors with damage thresholds below the predicted irradiance levels. We used two different power meters to cross check our results, the PM500D digital readout meter (serial #597) with a PM10 detector head (serial #781) and a PM500A analog meter (serial #578) with a PM30V1 detector head (serial #790).

Exit Diameter Measurement

Since the 810 nm wavelength WF-360TL laser is barely visible to the unaided eye (except during direct exposure of person with dark adapted vision) , we used burn paper positioned 1 mm from the turret exit aperture to determine the laser beam exit diameters. A total of four burns were recorded. Laser firing (exposure) times for each burn were approximately: 3 seconds, 2 seconds, and two short bursts (less than one second).

Beam Divergence Measurement

Two methods, spot size versus range and lens focusing, were used to measure laser beam divergence. In the spot size versus range method we estimated the beam spot size at various ranges from the turret exit window. A hand-held IR viewer was used to observe the spot at each measurement location. We drew an outline of the spot on a large piece of paper taped to a wooden backstop. Our initial plan was to measure the spot size at 50, 100, 125 and 150 cm distances from the turret exit window.

For a Gaussian beam, the divergence should gradually increase in the near field (region where Fresnel diffraction predominates) and become constant in the far field (region where Fraunhofer diffraction occurs). Somewhat detailed calculations in the text, Optics, by Klein show that far-field (Fraunhofer) diffraction occurs at a distance, D, from a given aperture.

$$D \cong \text{area of the aperture/wavelength of the light}$$

For a Gaussian beam, the area of the beam at it's waist (smallest point) is substituted for the area of the aperture in the above equation. The WF-360TL has a beam waist inside the turret (due to an internal collimating lens set). Thus, it was difficult to determine the size and location of the beam waist. Using the Westinghouse output spot size data of 1.0 mm by 8.0 mm and the 810 nm wavelength, D would be 9.9 m (or 32 ft). Most likely the internal beam waist is smaller than the spot size at the turret exit window, thus, we would expect the far-field of the beam to begin less than 10 m (1000 cm) from the turret exit window.

When measuring beam spot sizes in the far-field, one would expect spot size increases calculated between any two successive equal distant data points to be the same. If this did not hold true, we planned to measure spot sizes at further distances until the divergence measurements remained consistent.

For the lens focusing method, we measured the spot size of the focused beam in the back focal plane of a 12 inch focal length lens. As in the spot size method, we drew an outline of the spot on a piece of paper (located at the back focal plane) while viewing the spot through a hand-held IR viewer. As stated in the book Introduction to Optics by Frank and Leno Pedrotti, the diameter, d, of the spot in the back focal plane of a lens with focal length, f, is

$$d \cong f\phi \qquad (3)$$

Where:

ϕ is the beam divergence.

NOTE: Per the Pedrotti text, this relationship is true for a circularly symmetry Gaussian $TEM_{0,0}$ beam (with diameter several times smaller than the diameter of the focusing lens). Since the WF-360TL beam is rectangular and it's output mode was unknown we were unsure if this method would provide accurate results (resource limitations prevented adequate pre-test analysis of this technique). Nonetheless, we decided to try this method to see how the results compared with the spot size versus range beam divergence measurement method.

Beam Profile Measurement

Beam divergence calculations by the system manufacturer were based on a spot size measurement at 580 cm (19 ft) from the laser turret exit window. In order to check manufacturer's values, we measured the beam power at 2 cm intervals across the horizontal and vertical axes of the beam 580 cm from the exit window. A secondary reason for performing this test was to measure the beam intensity profile to see if it was Gaussian along each axis. A Molectron Power Max 500D (PM500D), serial #597 and PM3 Detector head, serial #769 were used for our measurements. A 1.1 cm diameter tube was placed on the detector head to block off-axis background light. Figure 3 shows our test set up.

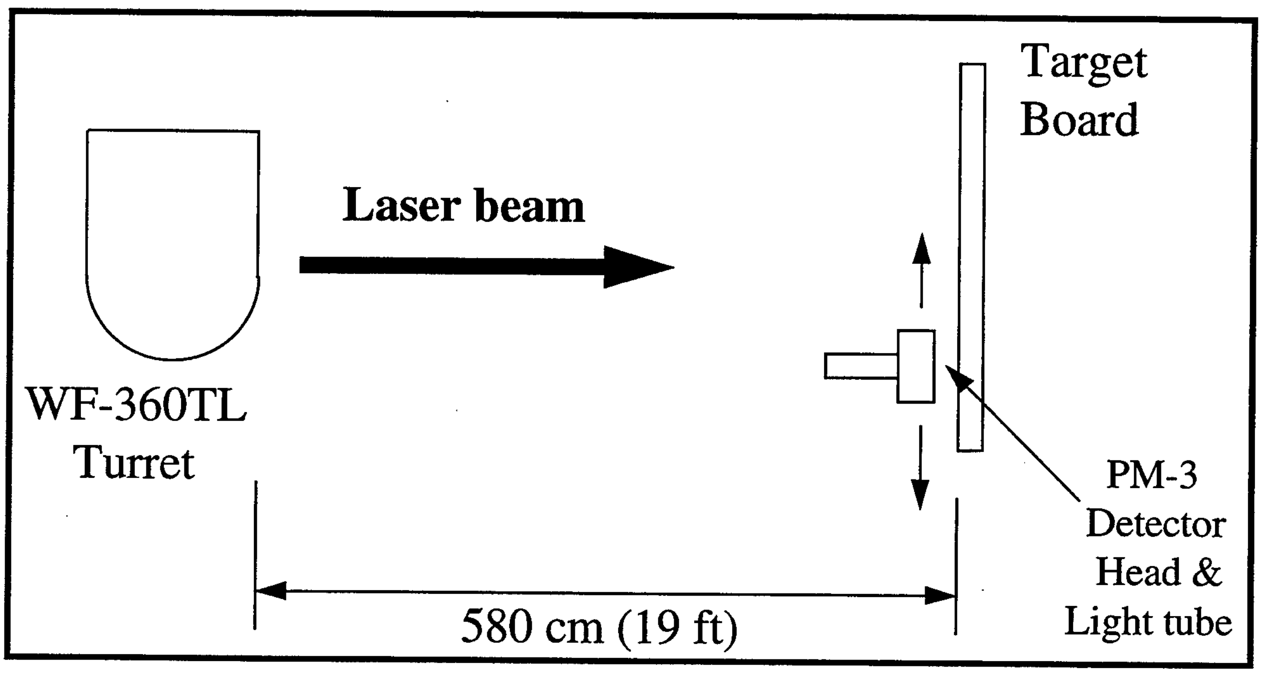

Figure 3. Beam Profile Test Set-Up

RESULTS AND DISCUSSIONS

Based on analysis of data collected using the test procedures described in the previous section, we determined the Nominal Ocular Hazard Distance (NOHD), the worst case required optical density (OD) for laser eye protection, and the skin hazard distances for the WF-360TL. The values were 6.9 m (23 ft), 4.5, and 0.5 m (1.6 ft) for the NOHD, OD, and skin hazard distances, respectively. Test data used to determine these hazard values was collected from 7 - 9 Nov 94. The part numbers for all the WF-360TL Diode Illuminator systems used are listed in Table 2 below. The TRT number is for the turret housing for the laser unit. The following paragraphs contain test results and discussion concerning analysis of the laser output data.

Table 2. WF-360TL Diode Illuminator Part Numbers

IIU	797R159G01	2001
TDE	798R119G01	2002
CP	797R245G02	2010
AAE	797R165G01	2005
TRT	797R204G04	2002

Test Results

Average Power Measurement Results

The average laser output power measured with the PM500D was 4.5 W. The ANSI Z136.1 Hazard Category for a laser with this output power at 810 nm is Class IV - most hazardous. Momentary (less than one second) peak readings of up to 4.7 W were observed over a measurement time period of 15 seconds. With the PM30V1 we measured an average output power of 4.4 W with momentary peak readings up to 4.6 W. Since the ANSI MPE values are based on 10 second exposure times for near IR wavelengths, the highest average power reading, 4.5 W was used for safety calculations. NOTE: This value is in complete agreement with the manufacturer's average output power specification of 4.5 W.

Laser Beam Exit Diameter Measurement Results

Our best estimate of the WF-360TL laser exit spot size is 1.5 mm horizontal by 9 mm vertical. Using the burn paper technique described in the Test Procedures section, the 3 and 2 second exposure times were clearly overexposures (visible burn marks completely through the paper). The last two exposures, less than 1 second in duration, both resulted in burn spot sizes of 1.5 mm by 9 mm. Since these values were relatively close to the Westinghouse specification value of 1.0 mm by 8 mm and since the NOHD is minimally effected by the exit size for this laser, the test team decided there was no need for further investigation.

Beam Divergence Measurements Results

Based on AL/OEO beam divergence data analysis, the calculated WF-360TL beam divergences were 85 mrad at the 1/e points (horizontal) and 66 mrad at the 1/e points (vertical). Analysis of initial spot size measurements, at ranges from 50 to 150 cm from the turret exit window, yielded inconsistent results. If the beam were Gaussian with no external beam waist we would have expected a gradual increase in beam divergence as distance from the turret window increased, then a steady increase as we reached the far-field. If an external waist, we would have expected to see the beam divergence initially decrease, until the waist was reached, then gradually increase and finally reach a constant value in the far-field. Instead, AL/OEO calculated beam divergences from data at the initial ranges appeared to fluctuate randomly as distance increased. As a result, spot size measurements were taken at 340, 360, 380 and 400 cm distances. In addition, three to four separate spot size observations were made at each distance to reduce data uncertainties (see Appendix A for data table). Usually the repeated observations at a given range agreed except for one inconsistent data point. In these cases, the assumed 'errant' data point was thrown out.

The linear increase in spot size with increasing range, as shown in AL/OEO data analysis, implies measurement of far-field beam divergence (i.e., beam divergence was increasing linearly). These results are consistent with our far-field distance prediction of less than 1,000 cm from the turret window (based on Westinghouse's exit spot size data as discussed earlier in the beam divergence test procedures section). Preceding with the assumption we were in the far-field, the calculated horizontal and vertical beam divergences based on our data were 129 and 99.5 mrad, respectively. The intensity profile points for these divergences were unspecified because at the time we did not know how far out on the beam intensity profiles the IR viewer would 'see'.

Following our test at Miami Air Station, we tried a simple test in our laboratory to resolve this intensity profile measurement uncertainty issue. In the test, we determined that the IR viewer 'sees' an IR beam out to approximately the 90 % intensity profile points. Since there are no clear guidelines on how to convert from 90% (or $1/e^2$) to $1/e$ for rectangular beams, we used the conversion factor for a circular beam. Thus, if we assume our calculated beam divergences were based on spots measured at the 90 % points, then we divide these divergences by the circular beam conversion factor of 1.515. Using this conversion technique, we obtained our final beam divergence values stated above: 85 mrad horizontal and 66 mrad vertical at the $1/e$ points.

This was the AL/OEO teams first attempt at using the focusing lens technique and the test was unsuccessful. During a Rockwell Laser Industries training course, following this test, a common mistake using this technique was described. The mistake occurs when measuring the minimum beam spot size behind the lens instead of the beam spot size in the back focal plane of the lens. This was the most likely cause of poor agreement with the increase in spot size as a function of range technique. As a result of this probable error, focusing lens measurement data and accompanying analysis are not presented.

<u>Beam Profile Measurement Results</u>

While AL/OEO measurements were crude (and only at one location - 580 cm), the test team observed non-Gaussian cross-sectional beam intensity profiles across both the horizontal and vertical axis. The team had hoped to observe either a flat-topped intensity profile or a nearly Gaussian profile in order to more accurately determine the final beam divergence values. Figures 4 and 5 show the horizontal and vertical beam profiles, respectively. The horizontal profile appears flat top in nature on the edges, but non-uniform across the top. The vertical profile appears to be skewed to one side (possibly due to misalignment of the internal collimating lens). Non-uniformity's in both profiles may have been due to imperfections in the laser diode or the internal collimating lens. The test team observed 'dark spots' of random size and location when looking at the beam profile through the IR viewer. These 'dark spots' could partially explain the non-uniform intensity profiles.

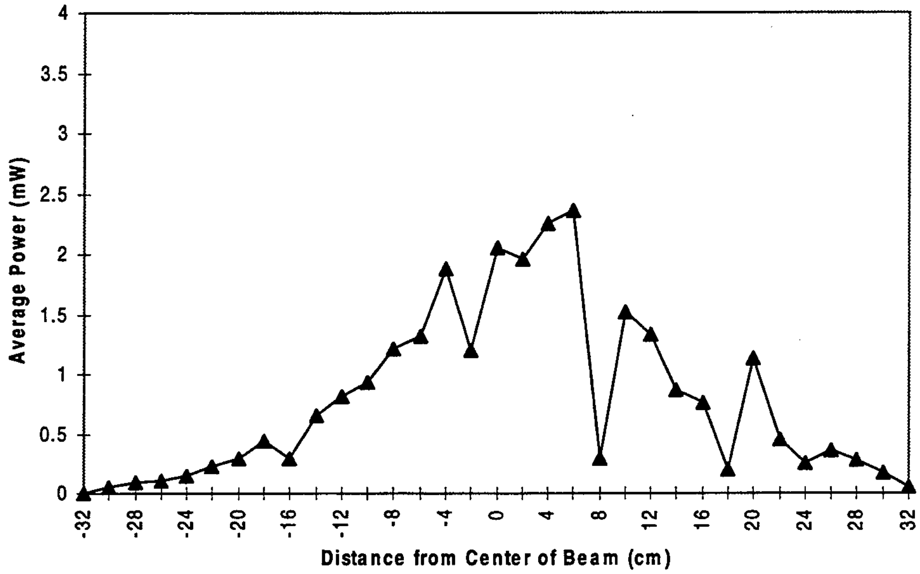

Figure 4. WF-360TL Laser Beam Horizontal Profile at 580 cm (19 ft)

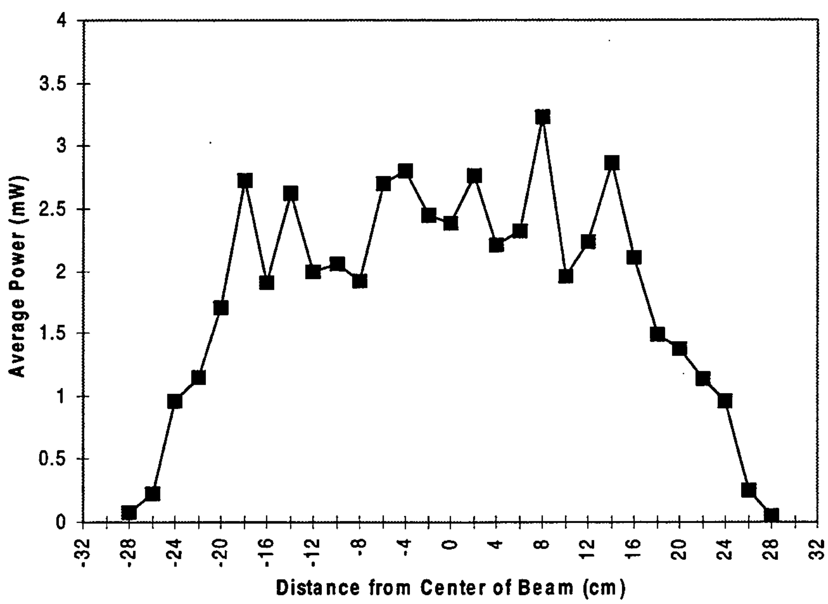

Figure 5. WF-360TL Laser Vertical Beam Profile at 580 cm (19 ft)

Curve fitting programs could be used to try and smooth the profile data but the results would be of questionable value. Thus, the profile data was not used to help determine the final beam divergence values. It is, however, interesting to note that using our originally calculated beam divergence values (i.e., 129 and 99.5 mrad), the predicted horizontal and vertical spot sizes at 580 cm are 68.7 cm and 58.0 cm, respectively. These values are close to the intensity profile plot spot sizes. The values are even closer when one considers that the 1.1 mm diameter light tube on the detector was perpendicular to our data collection plane, so that the off-axis beam energy traveling in the direction of the detector/tube combination was truncated at the outside edges of our measurements. This would result in a measured spot size smaller than the actual spot. Thus, the predicted values above show excellent agreement with the spot sizes of 64 cm and 56 cm from the intensity profile plots.

Hazard Analysis

Nominal Ocular Hazard Distance

The NOHD for the WF-360TL laser system evaluated during the AL/OEO test was 6.9 m (23 ft). This value was determined using the output parameters previously discussed. Specifically, the following values were used: output spot size, 1.0 mm (horizontal) by 8.0 mm (vertical); beam divergence, 85 mrad (horizontal) and 66 mrad (vertical) at 1/e points; and average output power 4.5 W. In addition, ANSI Z136.1 1993 guidance provided an MPE value of 1.68 mW/cm^2 for the 810 nm wavelength and recommended 10 second exposure duration. Atmospheric attenuation is not included in this NOHD because atmospheric effects for this hazard distance are negligible (i.e., no change in even the third significant digit of the NOHD value).

A Microsoft Excel spreadsheet, developed by AL/OEO, was used to determine the NOHD. A printout of this sheet is shown in Figure 6. This sheet included NOHD's for Optically Aided Viewing devices as listed in MIL HDBK 828. The NOHD value was checked using LAZAN (a commercial laser hazard software package produced by Rockwell Laser Industries). The spreadsheet and LAZAN results were identical. Our in-house laser hazard analysis software package, LHAZ, was not used because it does not currently have the capability to do rectangular beam hazard analyses.

In spite of the test team attempts to minimize beam divergence uncertainty, this output parameter accounts for the greatest uncertainty in the NOHD value of 6.9 m. Since the beam profile was non-uniform we were unable to clearly identify the intensity profile location of our spot size measurements (i.e., 1/e, $1/e^2$, or 90 %). Based on the intensity profile data and the AL/OEO lab test, the IR viewer spot sizes were assumed to be at the 90 % intensity profile points. If we had assumed the IR viewer data points represented 1/e spot sizes, the resulting NOHD would have been 4.6 m. As this NOHD value demonstrated, changes in beam divergence values have significant effects on the NOHD. In contrast, doubling the spot size produces no change in the first two significant digits of the NOHD value. Average power measurement errors can also have significant effects on the NOHD, however, of all the parameters we measured, average power was the most repeatable and was verified by two separate power meters. Thus, uncertainty in the measured average power value is relatively low.

One last cross check we performed was an attempt to determine the range from the turret where the largest laser irradiance incident on a detector with a 1.1 mm aperture equaled the MPE irradiance value of 1.68 mW/cm^2. The uncertainty in this measurement was high because the irradiance values fluctuated rapidly as the detector location across the non-uniform beam spot changed. Based on this crude experiment the test team estimated the MPE irradiance level was reached at 8 m from the turret exit window. Considering the uncertainty in this range, this agrees well with the 6.9 m calculated NOHD.

3/28/97

Purpose of this spreadsheet is to determine the NOHD for WF360TL laser
Filename: nohdrct.xls

1. Rectangular NOHD equation (Eqn 2 in this report) has many terms, so start by simplifying:
Define the term X, as $a_1^2\phi_2^2 + a_2^2\phi_1^2$

Where a is exit beam diameter and ϕ is 1/e far field divergence angle

a_1 (cm)	a_2 (cm)	ϕ_1 (mrad)	ϕ_2 (mrad)	X (cm^2rad^2)
0.8	0.1	66.00	85.00	0.004668

2. Define Y as the rectangular beam NOHD term inside first squareroot with MPE and Φ
Per ANSI (Z136.1 - 1993), the MPE_5 for 810 nm is 1.66E-03 W/cm^2

Φ (W)	MPE (W/cm^2)	Y(cm^4rad^4)
4.5	1.68E-03	903.2172

3. Insert X and Y values into equation to determine the rectangular beam NOHD.

a_1 (cm)	a_2 (cm)	ϕ_1 (mrad)	ϕ_2 (mrad)	NOHD(m)	NOHD(ft)
0.8	0.1	66	85	6.91	22.66

4. Use MIL HDBK 828 TABLE A-I to determine optically aided viewing hazards.
MIL HDBK 828 considers, 7x50 binoculars, and 8 cm & 12 cm entrance diam optical systems.
To determine the NOHD with optical aides, multiply output power by system gain factor.
ANSI Z136.1 - 1993, page 84 provides guidance for Optically aided viewing (0.4 to 1.4 μm)
For 7 x 50 binoculars, the optical gain, G, is the magnifying power (7x) squared or 49
For 8 cm entrance aperture, $G = (D_o^2/d_e^2)$
Where D_o is 8.0 cm and d_e is 7 mm pupil diameter (worst case), thus G = 131
For 12 cm entrance aperture, $G = (D_o^2/d_e^2)$
Where D_o is 12.0 cm and d_e is 7 mm pupil diameter, thus G = 294

Using the NOHD equation above and multiplying output power by G yields following NOHDs:

	Unaided	7x50	8 cm	12 cm
NOHD(m)	6.9	48.4	79.1	118.5
NOHD(ft)	23	159	259	389

Figure 6. NOHD Spreadsheet

Predicting how test results from this WF-360TL system will correlate with measurements of other WF-360TL lasers is a challenging task at best. Maximum power and minimum beam divergence specifications would make this a straightforward task. However, in this absence of this data, additional safety factors should be incorporated into the NOHD analysis if it is to be used for all other WF-360TL systems. For example, the beam divergences could be reduced by 10 % and the output power could be increased by 1 %. This would result in horizontal and vertical beam divergence values of 76.5 and 59.4 mrad, respectively and an average output power of 4.95. The NOHD for these output parameters is 8.1 m (or 27 ft).

Optical Density Required for Laser Eye Protection

The worst case LEP optical density requirement for the WF-360TL laser is 4.5. This condition only applies at the turret exit window and is based on an average power output of 4.5 W and a rectangular exit spot size of 1.0 mm by 8.0 mm. This OD requirement assumes all the laser energy enters an observers eye. This is somewhat overly conservative since the Westinghouse reported beam exit size is 1.0 mm by 8.0 mm and the average night adapted eye pupil is 7 mm. In addition, as Figure 7 shows, the LEP OD requirement drops off rapidly as distance from the turret exit window increases. This rapid drop off is due to the relatively large beam divergence values. If maintenance procedures can be developed that will prevent direct ocular beam exposure at ranges closer than 1 m (approximately 3 ft), then the OD requirement drops to 1.6.

Range (m)	Beam Width (cm)	Beam Height (cm)	Beam Area (sq cm)	Laser Irradiance (W/sq cm)	**Required OD for LEP**
0	0.15	0.9	0.14	33.33	**4.3**
0	0.1	0.8	0.08	56.25	**4.5**
1.00	8.62	7.41	63.87	0.07	**1.6**
2.00	17.14	14.02	240.30	0.02	**1.0**
4.00	34.18	27.24	931.07	4.83E-03	**0.5**
6.00	51.22	40.46	2072.37	2.17E-03	**0.1**
8.00	68.26	53.68	3664.21	1.23E-03	**0.0**
10.00	85.31	66.90	5706.58	7.89E-04	**0.0**

Figure 7. OD Versus Range Spreadsheet

Skin Hazard Distance

The skin hazard distance for this WF-360TL laser system is 0.5 m (1.6 ft). This value was determined using the same laser output parameter values and spreadsheet used to determine the NOHD. The skin MPE per ANSI Z136.1 1993 is 3.25 J/cm^2. Per ANSI guidance, a 10 sec exposure duration can be assumed and thus a time averaged MPE of 0.325 W/cm^2 was used for AL/OEO calculations.

CONCLUSIONS

In general, the WF-360TL laser output parameter values from AL/OEO test results agreed well with the manufacturer's values (see Table 3 below). The AL/OEO team used output parameters calculated

Table 3. Summary of WF-360TL Laser Output Parameters

Laser Output Parameter	Manufacturer's Value	Our Measured Value
Average Output Power	4.5 W	4.5 W
Exit Spot Size (Horizontal x Vertical)	1.0 mm x 8.0 mm	1.5 mm by 9.0 mm
Exit Beam Divergence 1/e intensity points (Horizontal x Vertical)	66.3 mrad x 54.1 mrad	85 mrad x 66 mrad

from test measurements and guidance in the 1993 American National Standard for Safe Use of Lasers (ANSI Z136.1 1993) to determine the Nominal Ocular Hazard Distance, required Optical Density for laser eye protection, and the Skin Hazard Distance. Table 4 below summarizes the analysis results.

Table 4. WF-360TL Hazard Parameters

Nominal Ocular Hazard Distance (NOHD)	6.9 m (23 ft)
NOHD for 7 x 50 binoculars	48.4 m (159 ft)
NOHD for 8 cm Optical System	554 m (1820 ft)
NOHD for 12 cm Optical System	9490 m (31200 ft)
Optical Density for LEP at 810 nm	4.5
Skin Hazard Distance (SHD)	0.5 m (1.6 ft)

The results in Table 4 are for the single WF-360TL system measured. If these results will be used as definitive safety guidance for all WF-360TL lasers, then key output parameters should be multiplied by appropriate safety factors and hazard values should be recalculated using the more conservative values. As an example, the beam divergence values could be decreased by 10 % and the output power increased by 1 %. The resulting hazard parameter values would then be: 8.1 m (27 ft) for NOHD, 4.6 for OD and 0.6 m (1.9 ft) for Skin Hazard Distance.

Precise beam divergence measurements were AL/OEO's greatest test challenge. In spite of attempts to minimize the uncertainty in measurements used to determine this parameter, this was still the laser output parameter with the highest uncertainty. Where possible, the most conservative assumptions where made when analyzing data to determine this parameter.

RECOMMENDATIONS

In this section, general safety recommendations for shop use of the WF-360TL laser are provided based on our analysis results and on guidance in the American National Standard for Safe Use of Lasers. In addition, recommendations for future laser tests are provided.

WF-360TL Safety Recommendations

1. The most important safety recommendation concerning use of this system is to appoint a Laser Safety Officer (LSO) at each location where this system will be used and ensure the chosen individual(s) attends a basic laser safety course. We suggest either the Navy Laser Safety Course taught in Norfolk, VA by Dr. Richard Hughes (916-626-6840) or the Basic Laser Safety Officer course taught by Rockwell Laser Industries (513-271-1568) in Cincinnati, OH. The Optical Radiation Division (210-536-3625) at Brooks AFB sponsors an annual course and can recommend other appropriate courses. A trained LSO can act as a focal point for local laser safety training and policy questions concerning hazards from this laser system.

2. When practicable, this laser should be operated within a controlled area (i.e. locked building, room, hangar, etc.). Laser warning signs, per ANSI guidance, should be posted on all area entrances.

3. All personnel who will be inside the controlled area during laser firing must be briefed on laser hazard distances and laser eye protection requirements. In addition, they must wear laser eye protection (LEP) if inside the Nominal Ocular Hazard Distance of 6.9 m (23 ft) during laser firing. The worst case protection requirement is for LEP with an Optical Density of 5 at the 810 nm laser wavelength. Finally, all personnel in the firing area must remain outside the Skin Hazard Distance of 0.5 m (1.6 ft) during laser firing.

4. If possible, design an enclosure that will physically block access to the beam during maintenance activities. This could be a beam block covering the turret exit aperture, a tube facing the direction of laser firing or a box shaped device. The inside of the device should be coated with a black type material that will absorb and/or diffusely reflect the laser light (i.e., black felt).

5. Refer to the American National Standard for Safe Use of Lasers (ANSI Z136.1 1993) for more detailed safety requirements.

Recommendations for Future Measurement Tests

1. Advanced measurement training will greatly facilitate future beam divergence measurements. Since beam divergence is the primary output parameter affecting skin and eye hazard distances, we need reliable methods to measure this parameter with the greatest possible accuracy. In addition, we need to understand how ANSI standard assumptions apply to beams we are measuring. When possible, two independent methods should be used to measure this beam parameter.

2. During an Aug 95 advanced measurements training course, we were taught a 'knife-edge' beam divergence measurement technique. This technique has great promise, especially for non-circular beams. When practical this method should be used for divergence measurements.

Laser System Acquisition Recommendation

During acquisition of future avionics system using lasers, manufacturer's should be required to meet minimum laser beam divergence and maximum laser output power specifications. Traditionally, laser systems have been required to meet 'do not exceed' beam divergence values and minimum output power specifications so that system *performance requirements* will be met. If minimum divergence and maximum power specifications can be added, this will greatly facilitate hazard analysis for bulk purchases (i.e., more than one or two) of systems using lasers.

REFERENCES

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APPENDIX A

The following Tables show collected and calculated data from the 'spot size vs range' beam divergence technique described in the Procedures subsection of the Test Methods, Assumptions and Procedures section of this report. Data points with strikethrough lines were discarded when determining average spot sizes in Table A-2.

Table A-1. Measured WF-360TL Laser Illuminator Spot Size vs Distance from Exit Aperture

Range (cm)	**Spot Height (cm)**	**Spot Width (cm)**	**Range (cm)**	**Spot Height (cm)**	**Spot Width (cm)**
340	38.5	34.0	380	~~41.5~~	~~37.0~~
	37.8	34.1		42.8	37.7
	39.0	34.2		42.5	38.0
				42.8	38.0
360	40.0	35.5	400	45.5	40.0
	40.1	36.0		45.0	~~37.7~~
	~~40.7~~	36.0		44.9	40.0
				45.6	40.1

Table A-2. Averaged WF-360TL Laser Illuminator Spot Size vs Distance from Exit Aperture

Range (cm)	Spot Height (cm)	Spot Width (cm)	Spot Height Change over 20 cm's (cm)	Spot Width Change over 20 cm's (cm)
340	38.5	34.1		
360	40.1	36.0	1.6	1.9
380	42.7	38.0	2.6	2.0
400	45.3	40.0	2.6	2.0