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VISUAL IMPAIRMENT FROM EXPOSURE TO HIGH INTENSITY LIGHT SOURCES

Prepared for

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BIOTECHNOLOGY, INC.

Report No. 63-2

VISUAL IMPAIRMENT FROM EXPOSURE TO HIGH INTENSITY LIGHT SOURCES

BioTechnology, Inc. Report No. 63-2

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FOREWORD AND ACKNOWLEDGEMENTS

Much of the material in this report is taken from an earlier publication entitled "Flash Blindness Protection for Naval Aviators." The earlier study, classified Secret-Formerly Restricted Data, was produced by the Matrix Corporation of Arlington, Virginia, under Contract Nonr-3445(00) with the Office of Naval Research and was published in December 1962. The earlier report contains information concerning the development of flash blindness protective devices and the implications of the use of such devices for low level attack missions.

The present report was prepared since it was felt that the security level of the earlier report might restrict dissemination of information concerning flash blindness per se to only those individuals interested in direct military applications. It was felt that the compilation of available information concerning flash blindness research and the comparisons among such studies might be of interest to a wider audience.

A general discussion of nuclear detonations and of nuclear radiation effects is presented in this report. This discussion is based entirely on information obtained from unclassified documents.

The present manuscript was reviewed by Dr. Gilbert C. Tolhurst, Physiological Psychology Branch, Office of Naval Research, and by Captain Walton L. Jones, MC, USN, Airborne Equipment Branch, Bureau of Naval Weapons. Their many helpful suggestions are most appreciated.

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INTRODUCTION

This report describes research conducted to determine the visual incapacitation which results from exposure to high intensity light sources. Direct viewing of a sufficiently intense source can result in permanent retinal damage. Less intense light may produce "flash blindness," a temporary but reversible loss of vision which does not involve permanent damage.

It is only within about the last ten years that substantial scientific interest has been shown in the effects of high intensity light on vision. At the present time, man is capable of sustained operation within a space environment. Here, without the diffusion of light by the atmosphere, he may transition rapidly from extreme darkness to very bright light. This change could cause serious loss of visual efficiency. A second concern, particularly for the military, is over the effects of the extremely intense visible radiation released during a nuclear detonation. During combat conditions, an aviator operating within a nuclear environment might be exposed to the light from a number of bursts. Since for the most part these bursts would be from weapons other than his own, he would not be prepared for them and would not know in advance to shield his eyes. Consequently, he might suffer a period of impairment lasting for many seconds. On certain missions, a loss of vision for only a few seconds could cause complete failure.

Within the space and the nuclear combat environments, flash blindness, rather than permanent retinal burns, appears to be the primary problem. It is doubtful that an astronaut will look directly at the sun for a long enough period to produce permanent damage. It is also improbable that an aviator will be looking directly at an unexpected nuclear burst. It is only through such direct viewing that he might suffer retinal burns. It is quite likely, however, that in either environment an individual will be exposed to enough light to produce some period of flash blindness. For this reason, the bulk of this report is concerned with the problem of flash blindness rather than with that of permanent retinal damage.

The Army, Navy, and Air Force have supported a number of programs in recent years designed to develop devices and procedures to protect a person from flash blindness. Certain of these efforts have been concerned with passive protective devices such as monocular eye patches and low transmittance goggles. Others have investigated more elaborate active protective systems which operate only when exposed to high intensity light. These include goggles which become opaque either through the activation of explosive components or through a basic change within the chemistry or physical characteristics of the lens itself. At this time, however, no device has been developed which is totally satisfactory for all military situations.

A separate part of programs recently sponsored by the military has been directed towards specifying, with precision, the extent of the flash blindness hazard in nuclear combat situations. While the hazard obviously is there, until this time it has been stated only in terms more qualitative than quantitative. There is no comprehensive model which will indicate the extent of the flash blindness hazard as a function of such parameters as altitude of burst, altitude of observer, distance from burst, viewing angle, and meteorological conditions. The development of appropriate protective devices will be aided by the preparation of such a model.

HIGH INTENSITY VISIBLE RADIATION

It is important to understand the nature of the physical stimuli which are likely to produce visual impairment. As indicated, these consist of nuclear explosions and solar radiation. In the case of nuclear radiation, however, much information concerning the exact spectral distribution during the time history of a burst is still to be obtained. There is a better understanding of solar radiation as it exists both in and out of the atmosphere of the earth.

Nuclear Radiation Effects

Published information concerning the spectral emittance characteristics during the time history of a bomb burst deals mostly with low yield weapons. Byrnes et al (1955) state that a 20 KT weapon produces a fireball approximately 90 feet in diameter, 0.1 milliseconds after detonation. This expands to ten times this size during the first second and retains this size during the first three seconds. During this time the fireball is cooling rapidly. The surface temperature at 0.1 millisecond is 300,000°K. After 10 milliseconds, it has cooled to 2,000°K. There is then a rise in surface temperature which reaches a maximum of 7500°K early in the first second. After three seconds the fireball drops to ambient temperature. During this time the radiant flux per unit area and the quality of radiation change considerably as the surface temperature of the fireball changes.

Figure 1 presents the spectral emission curves of black bodies 300,000°K, 2,000°K, and 6,100°K, approximating the three phases of the atomic fireball described above. These curves provide a fairly accurate picture of the spectral emittance characteristics during the

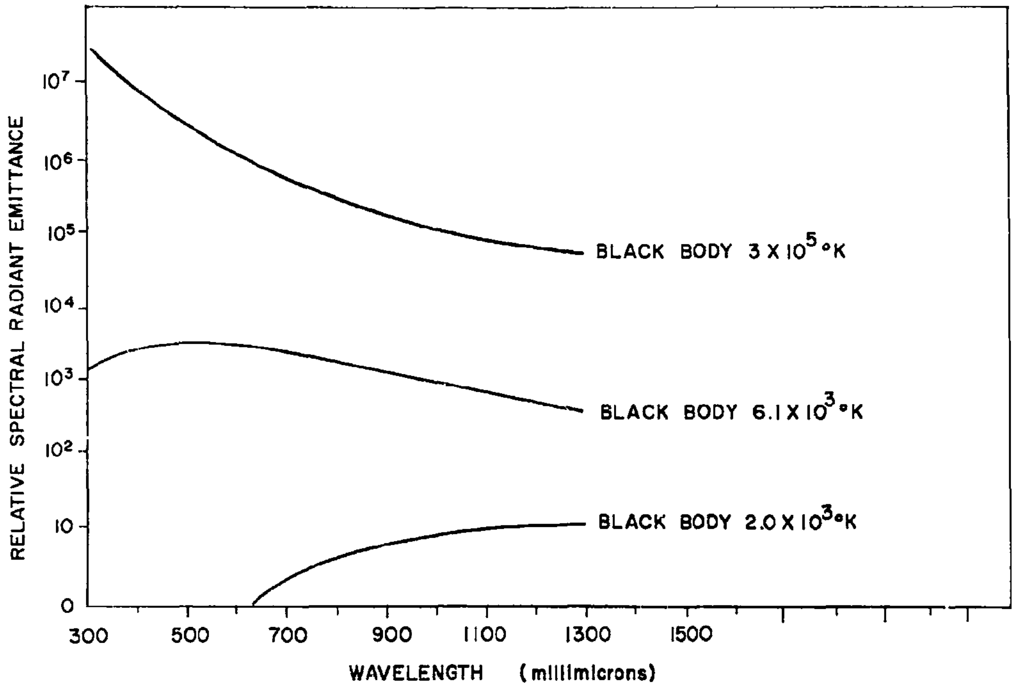

Fig. 1. Spectral emission curves of black bodies 300,000° K, 6100° K, and 2000° K. (Byrnes et al, 1955)

bomb burst. Note that at 0.1 millisecond, while the surface temperature is quite high, maximum radiation occurs in the ultraviolet and visible portion of the spectrum. At 10 milliseconds, primary radiation is in the red and infrared bands. During the latter part of the burst history, radiation is distributed fairly evenly from the ultraviolet band through the entire visible spectrum and into the infrared band.

The above discussion was concerned with a weapon of 20 KT yield. For larger weapons there will be an increase in the relative amount of energy at shorter wave lengths. For either class of weapon, however, most of the radiant energy will fall between 300 and 2400 millimicrons, with the greatest part occurring at less than 1400 millimicrons (Brown, 1961).

Glasstone (1962) describes certain characteristics of the visible radiation from a burst with a yield of one-megaton TNT equivalent. He indicates the maximum attained temperature for this type of weapon will be several tens of million degrees. Because of the great heat produced by the nuclear explosion, all materials are converted into gaseous form. Within less than a millionth of a second of the detonation of the weapon, the extremely hot weapon residues radiate large amounts of energy, mainly as invisible X-rays, which are absorbed within a few feet in the surrounding atmosphere. This leads to the formation of a hot, and highly luminous, spherical mass of air and gaseous weapon residues referred to as the weapon fireball. The surface brightness of this fireball decreases with time, but after about a millisecond the fireball from a one-megaton nuclear weapon would appear to an observer fifty miles away to be many times more brilliant than the sun at noon. The intensity of the light is indicated by the fact that high altitude bursts in the megaton range have been seen directly as far as 700 miles away.

Immediately after its formation the fireball begins to grow in size, engulfing the surrounding air. This growth is accompanied by a decrease in temperature because of the accompanying increase in mass. At the same time, the fireball rises, like a hot air balloon. Within seven-tenths of a millisecond from the detonation, the fireball from a one-megaton weapon is about 440 feet in diameter. This increases to a maximum value of about 7,200 feet in ten seconds. It is then rising at a rate of 250 to 350 feet per second. After a minute, the fireball has cooled to such an extent that it no longer emits visible radiation. It has then risen roughly 4.5 miles from the point of burst.

Glasstone also notes that the surface temperatures of the fireball, upon which the brightness (or luminance) depend, do not vary greatly with the total energy yield of the weapon. Consequently, the observed brightness of the fireball in an air burst is roughly the same, regardless of the amount of the energy released in the explosion. However, the brightness of the fireball will vary during the time history of the burst as a function of surface cooling.

Solar Radiation

The luminance of the sun outside the atmosphere of the earth has been estimated to be 2.13×10^8 lumens per square feet or 6.8×10^8 foot-lamberts (Johnson, 1954). In an extraterrestrial environment, with normal light-scattering particles missing, this represents an intense source of visible radiation. This light would certainly be sufficient to produce flash blindness if viewed directly for a brief period or if viewed as reflected from some metallic surface. It has been estimated (Strughold, H. as reported by Brown, 1961) that direct viewing of the sun, by an observer in space, for a period as short as 15 seconds would be sufficient to produce irreversible damage. Even in the upper levels of the atmosphere solar radiation remains intense. Figure 2, supplied by the Scripps Institution of Oceanography (Boileau, 1963), indicates the decrease in the luminance of the disc of the sun which occurs on a clear day as the altitude of observation decreases.

The important feature of solar radiation in space, however, concerns the absence of a diffusing medium. Areas not illuminated directly by the sun will be completely dark. Thus, heavy demands would be placed upon the visual adaptation mechanisms as an astronaut shifts his gaze from illuminated to non-illuminated areas. Flash blindness within this environment could occur more easily than within the atmosphere of the earth.

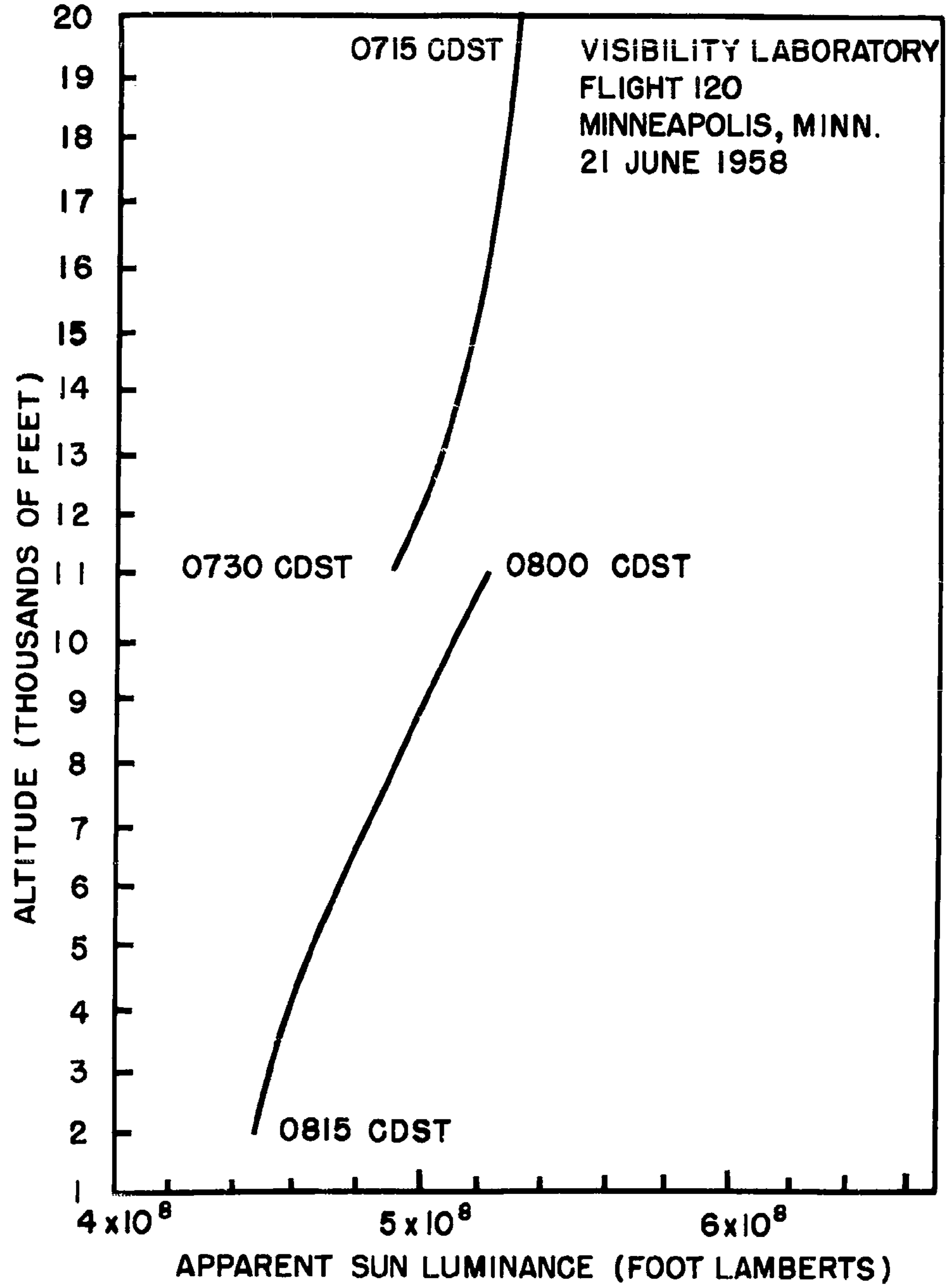

Fig. 2. Decrease in brightness of the sun's disc with decreasing altitude of observation.

RESEARCH CONCERNING EFFECTS OF HIGH INTENSITY RADIATION ON VISION

An understanding of the flash blindness phenomenon requires an understanding of the visual system. Figure 3 represents a cross-section of the human eye and shows the major features of concern for either chorioretinal damage or flash blindness. The most important of these has to do with the mechanism by which the eye adjusts the amount of light which enters. The iris controls this amount of entering light. It is a delicate membrane stretching across the interior of the eye at the base of the corneal bulge, with a circular opening (the pupil) near the center (Wulfeck et al, 1958). The pupil dilates to admit more light and contracts to admit less. The pupil normally varies in diameter from approximately 2 to 8 mm, a ratio of pupillary areas of 1 to 16. However, the ratio of the weakest light the eye can see to the strongest it will tolerate is on the order of 1 to 10 billion. The ratio of pupillary area to eye exposure thus is extremely nonlinear.

A certain time is required for the eye to adjust itself to different input levels of illumination. When the eye is exposed to a sudden increase in illumination which is still within the normal range, there is a brief interval of partial blindness. However, depending upon the extent of the over-stimulation, it usually is possible to see quite effectively again within a short period. The change from a low to high adaptation level customarily occurs in less than a minute. However, the converse is not true. When the illumination is reduced from a high to a very low value, 30 or more minutes may be required for the achievement of maximum sensitivity.

The primary photochemical substances of the eye are located in

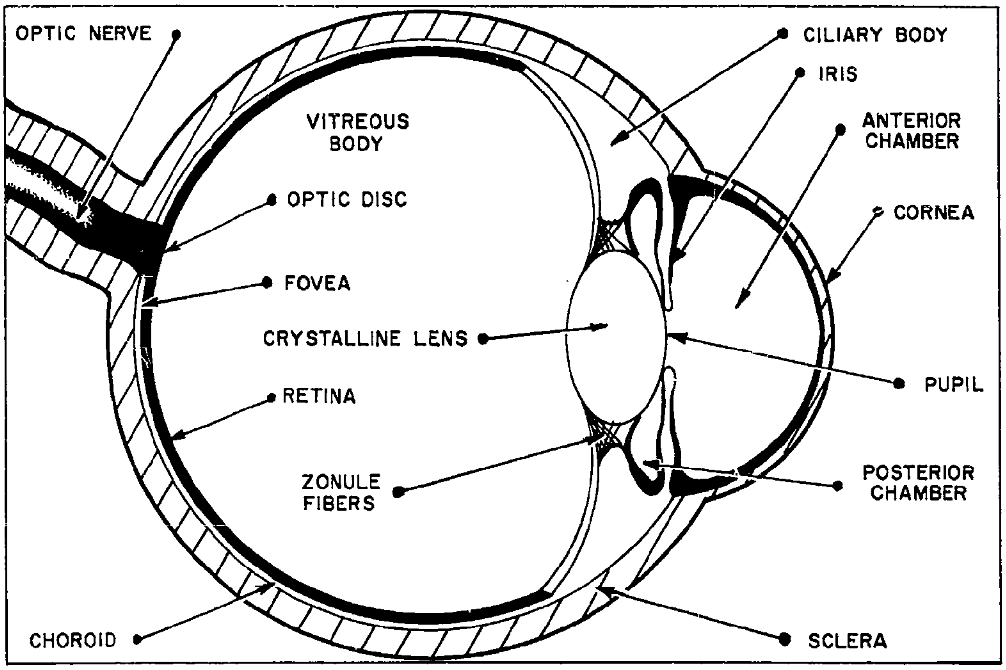

Fig. 3. Cross section of right eye from above. (Wulfeck et al, 1958)

the retina. The retina itself is separated into two regions. The fovea subtends only about 3 degrees of visual angle and is the area of acute daylight (photopic) vision. The surrounding broad area is the peripheral retina which contains elements sensitive to very low light intensities. This is the area which is used in night (scotopic) vision.

Permanent Injuries to the Visual System

Matoush (1960) provides an excellent description of chorioretinal burn, which he describes as a pathological condition of the eye in which there is irreversible tissue damage and some permanent loss of vision. The condition is caused by the absorption of excessive amounts of thermal energy in the retina and in underlying layers, principally the choroid. Susceptibility to this type of damage is traceable directly to one of the fundamental eye processes--that of optical focusing and image formation. As a result of the interrelationship of optics and geometry, the thermal loads on the retina of the eye, and hence the probability of incurring retinal burn, remain quite high at relatively large distances from a nuclear explosion, distances at which most other effects are negligible.

In their long term effect, seriousness of retinal burns depends upon such factors as tissue involvement (size and depth of lesion) and on location in the visual field. Large burns may invite grave after-effects such as retinal detachment; small burns are not likely to cause serious visual impairment unless they occur on the region of the retina associated with acute vision (macula) or perhaps on the blind spot (optic disc). However, of greater concern in tactical planning are the possible immediate effects of retinal burning. Descriptions of post-exposure effects are meager, viz., that immediate vision loss occurs equivalent to severe flash blindness and, on recovery of adaptation, there is possible persistence of discomfort.

Although nuclear explosions release energy in a broad thermal spectrum, covering the ultraviolet, visible, and infrared regions, the thermal radiation that is found to be responsible for retinal burn covers only the visible range and part of the infrared. This selectivity is the result of absorption of the other radiations (ultraviolet and/or infrared) by various elements of the eye--cornea, lens, and intraocular fluids--before they can reach the retina. After the nonattenuated radiation has succeeded in traversing the preretinal media, it is absorbed in the black pigment epithelium of the retina and in the pigment cells of the choroid. In so doing, the light energy is transformed into heat, causing a rise in tissue temperature. This temperature rise may be sufficient to cause irreversible damage (coagulation necrosis) within the absorbing tissues and within neighboring receptor elements, giving rise to a retinal and chorioretinal burn.

The above description of chorioretinal burns, provided by Matoush, deals primarily with radiation levels sufficient only to produce damage to the visual system. Brown (1961) has described the various types of damage to the eyes which may result from exposure to higher radiation levels. Thermal damage may occur to any part of the eye. Exposure to high levels of thermal radiation will result in coagulation in the corneal tissue with resulting opacities. Hemorraghic congestion may occur in the iris. Proteins of the lens tissue may be coagulated with the development of cataracts, and there may be peeling off of superficial layers of the lens (exfoliation).

Brown also discusses the nonthermal injuries which may be inflicted by shorter wavelengths. Ultraviolet radiation wavelengths in the neighborhood of 300 millimicrons are most effective in producing these injuries, but they may result from exposure to light at wave lengths from 365 millimicrons down to below 300 millimicrons. At 300 millimicrons, a flux density of approximately 2 (10^6) ergs per second per cm^2 will produce erythema and edema of cytoplasm with the formation of granular inclusion bodies. This is accompanied by severe itching and burning sensation of the eyes, which may last for several weeks. These effects of exposure to ultraviolet energy are of relatively long latency and require 6 to 8 hours to develop. In addition, the effects of repeated exposures to short wavelength radiation may be cumulative within a 24 hour period. Injuries resulting from exposure to short wavelengths do not occur within the retina itself because virtually all of the energy in this wavelength region is absorbed by the cornea and the lens. Most forms of photophthalamia are induced by shorter wavelengths. They are apparently caused by chemical changes which have a selective effect on nucleic proteins. In spite of the well recognized effects of ultraviolet radiation on the eye, it has proven difficult to induce cataract formation experimentally by exposure to ultraviolet. Subjective symptoms of ultraviolet photophthalamia have been noted following experimental observation of atomic bursts.

Byrnes et al (1955) point out that there is not a direct relationship between distance from the fireball and the chance of experiencing visual damage. The radius of the image of an atomic fireball on the retina varies linearly with the radius of the fireball and the distance from the fireball. Thus, with a pupil of given size at a given distance, a certain amount of energy is distributed over the image area. If the subject is twice as far away, the amount of energy passing through the same pupil will only be one-quarter as great. However, because of the focusing power of the eye, the image area in which the energy falls will only be one-quarter as large. The energy per unit area will therefore be constant except for the attenuations produced by air and other ocular media. Thus, distance alone provides little safeguard against visual damage if one is looking directly at the explosion.

The above point is elaborated by Metcalf and Horn (1959) who stress the small amount of thermal energy required to produce a retinal lesion. They note that 0.04 $cal/cm^2/sec$ delivered at the eye may produce 60-80 $cal/cm^2/sec$ at the retinal image area depending on pupil size, ocular transmission, and angular size of the object. This would result in a retinal lesion and a permanent blind area in the visual field. The effect on vision might be unnoticed, however, unless the lesion were to fall directly on the fovea centralis.

Ham (1962) has conducted recent experiments, using rabbits, to attempt to define the minimal thermal energy which will produce chorioretinal lesions. He used a Zeiss Light Coagulator capable of producing a maximum irradiance on the rabbit fundus of approximately 1100 $cal/cm^2/sec$. An exposure time of 175 microseconds resulted in a total dose of 0.2 cal/cm^2. This energy level produced lesions barely visible by ophthalmoscopic observation which appeared in 3 to 5 minutes following exposure. Under the same conditions, but with the total energy dropped to 0.16 cal/cm^2, no lesions were observed. This energy level appears to represent threshold dose for visible lesions. This threshold dose appears to represent the lowest value determined experimentally to date. It is important to note that this dose value is for energy at the retina and not at the corneal plane.

Flash Blindness

The term flash blindness, as used in this report, refers to the effects of exposure to sudden and intense light which renders the eye temporarily useless. From the point of view of a military pilot, this is the important problem area. It is doubtful that he will experience permanent visual damage unless he is quite close to the burst point or is looking directly at the fireball. However, a burst anywhere within several hundred miles might provide sufficient visible energy to produce flash blindness.

Experimental Investigations of Flash Blindness

Empirical evidence is available as to the effect upon vision of exposure to sudden and very intense light. Several important investigations are described below. The results of these studies show certain very definite trends but are not entirely consistent. The inconsistencies which exist may be due to differences in experimental techniques or, as seems more likely when considering the limited number of subjects in each study, to differences in the characteristics of the visual mechanisms of different individuals. It is known that people vary with respect to dark adaptation time, visual acuity, susceptibility to visual illusions, and any number of other visual performances. It seems likely, then, that individual differences exist concerning susceptibility to flash blindness.

Metcalf and Horn (1958) conducted experiments designed to specify visual recovery time from high intensity flashes of light. A carbon arc was used as a light source to determine the course of visual recovery after exposure to a level of illumination comparable to that likely to be encountered during nuclear operations. Each of the four subjects' pupil was dilated prior to exposure. A 6 mm artificial pupil was used in order to maintain constant pupil size. The subjects were exposed for 0.1 second to illumination ranging from 60 to over 12,000 lumens per square foot. Following exposure, subjects were required to detect the flashing of a 17 minute visual angle circular patch. The primary conclusion of the authors is that exposure to intense light, similar in nature to that which might be encountered in the vicinity of a nuclear detonation, will require a maximum of approximately 170 seconds for recovery to read red-lighted instruments.

The time required to recover visual sensitivity following exposure to high intensity, short duration adapting flashes also has been investigated by Chisum and Hill (1961). In contrast to other investigations, this study used extremely short exposure flashes. Adapting flashes of 33 to 165 microseconds and 9.8 milliseconds in duration with luminances from 4.1 to 8.6 log mL were used. Visual sensitivity was determined by the resolution of gratings requiring acuities of 0.13 and 0.33 at display luminances from -2.50 to 2.25 log mL. The 0.33 acuity level requires the function of cones while the 0.13 acuity level can be resolved by rod vision. The authors found that for a given adapting flash luminance recovery time is a decreasing negatively accelerated function of display luminance. That is, recovery time decreases with an increase in display luminance but at a decreasing rate. Figure 4 illustrates this. It was also found that recovery time decreases with a decrease in the intensity of the adapting flash and with a decrease in the visual acuity requirement of the display. Of these variables, the visual acuity requirement of the display appears to influence recovery time the least. It was found that when the display luminance exceeded 0.5 log mL, recovery at the higher visual acuity requirements was about as rapid as that at the lower visual acuity requirement. The authors conclude that the significance of visual acuity as a factor in the flash blindness problem may be reduced by having display

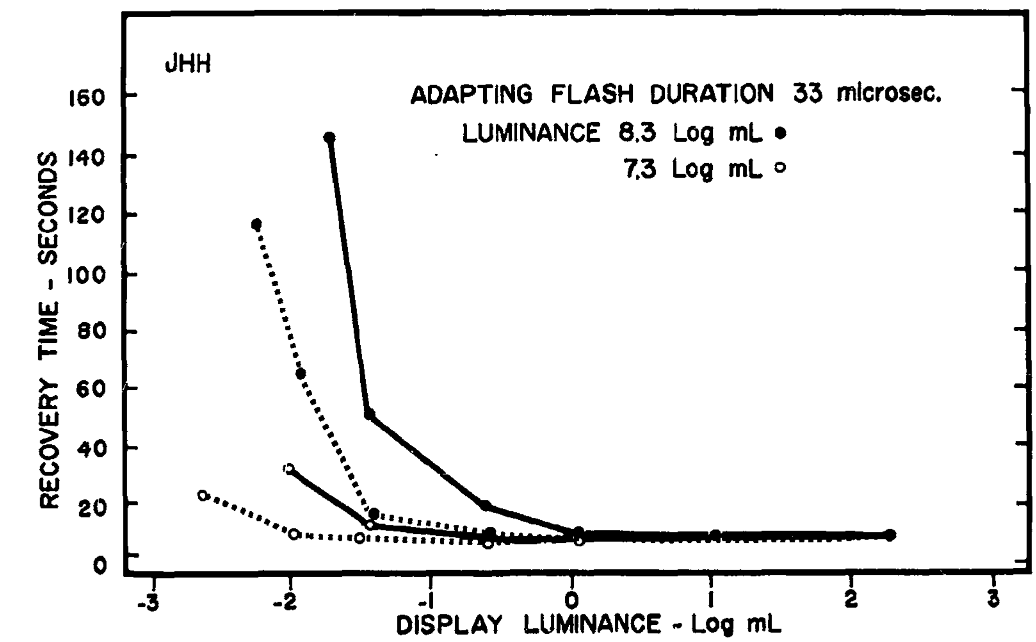

Fig. 4. Effect of increasing display luminance on time to perceive an acuity target following exposure to an adapting flash. (Chisum & Hill, 1961)

luminance above this value.

Chisum and Hill also investigated the relationship between the total energy of the adapting flash and recovery time. It was found that as the total energy in the flash is increased, recovery time at first increases very slowly, then rapidly, and then apparently slowly again. They suggest that the possibility exists that after integrated luminance has reached a level of more than 6 log (mL-sec), no further increase in recovery time will occur, provided irreversible eye damage is not inflicted.

Particularly interesting is the finding of Chisum and Hill that, when the total energy received at the eye remains constant, a decrease in exposure time will reduce the ensuing period of flash blindness. This is not a one-to-one relationship, however. A comparison of two exposure times, 9.8 milliseconds and 165 microseconds, indicates that a sixty-fold decrease in exposure time reduces recovery time by about one-half.

Whiteside (1960) performed an experiment to measure the brightness of an actual nuclear explosion and the amount of flash blindness associated with it. In this experiment, the subject's head was positioned so that the image of the fireball would be formed three degrees on the lateral side of the fovea. The explosion distance was approximately 30 miles. Following exposure, the subject viewed an adaptometer containing test fields at three luminance levels (1.04, 0.41, and 0.14 foot-lamberts). The time was noted at which each test field could be initially discerned through foveal vision and through the afterimage of the fireball. The following recovery times were noted:

	Recovery Time		
Adaptometer luminance	1.04 ft-L	0.41 ft-L	0.14 ft-L
Through fovea	5 sec	17 sec	58 sec
Through fireball afterimage	28 sec	40 sec	89 sec

Calculations following the explosion indicated integrated fireball luminance to 100 microseconds was 4365 candles/cm^2/sec.

Severin (1961) performed an experiment in which four subjects were exposed to light flashes ranging over five levels of luminance from 50 lumens/ft^2 to 5500 lumens/ft^2. Each flash had a duration of 0.15 seconds. Subjects then viewed two patches of 0.06 and 0.013 foot-lamberts. Mean recovery times ranged from 0.6 seconds for the test patch brightness of 0.06 ftL and exposure of 50 lumens/ft^2 to 37.3 seconds for a test patch brightness of 0.013 ftL and exposure of 5500 lumens/ft^2.

The above study recently has been repeated and extended in scope (Severin, Newton & Culver, 1962). Sixteen subjects were used in this instance rather than four as previously. The purpose was to study the degree of inter-subject variability, the form of the recovery curve, and the effect of pupillary size upon recovery time. Again an exposure time of 150 milliseconds was used, although flash intensity was extended to a maximum of 21564 lumens/ft^2. The most impressive finding concerns inter-subject variability. For the maximum exposure, recovery times for the sixteen subjects ranged from 10 to 50 seconds. The authors state that "the individuality of the responses implies that healthy people vary considerably in their ability to handle the sensory overload of this situation."

Comparisons Among Experimental Studies

Five classic experiments have been described above, each of which investigated the effect of high intensity flashes on visual performance. The influence of target brightness (display luminance) upon visual recovery time following exposure also was investigated. Table 1 summarizes the procedures of these studies and the principal results in a manner designed to allow comparisons. It can be seen from Table 1 that a variety of exposure times, flash intensities, and other experimental conditions was used. In order to expedite those comparisons which can be made, however, all entries have been converted to a comparable set of units. Of all entries in this table, total energy received at the eye represents the most meaningful basis for comparison. Brown (1959) states that the total energy of an adapting flash up to several seconds in duration appears to be the critical variable in determinining the shape of a dark adaptation curve.

There are a number of observations which can be drawn based on the data of Table 1. Those which appear most related to this discussion are:

1. Inconsistencies. There are certain inconsistencies apparent in the data. For example, in the experiment of Whiteside, the observer received more energy (1.37×10^7 mL-sec) than the subjects of Metcalf and Horn (5.3×10^5 mL-sec) for the same exposure time (100 millisec) and with a much darker target display (1.12 mL compared to 76 mL), yet both produced a visual recovery time of five seconds. Differences in the experimental procedures might well account for the observed discrepancy, one being a laboratory study and the other being a field study, or the difference might simply be due to differences in the basic visual mechanisms of the observers involved.

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TABLE I

Summary of Literature on Flash

Laboratory Studies

	Source	Flash Intensity (Observer Position)	Exposure Time	Total Energy R'ced at Eye (Corneal Plane)	Pupil Diameter	D
1.	Metcalf & Horn 1958	6.7 log ftL (0.05×10^8 mL)*	100 millisec	(5.2×10^5 mL-sec)	6 mm	
		(0.05×10^8 mL)	100 millisec	(5.2×10^5 mL-sec)		
		(0.05×10^8 mL)	100 millisec	(5.2×10^5 mL-sec)		
		(0.05×10^8 mL)	100 millisec	(5.2×10^5 mL-sec)		
2.	Chisum & Hill 1961	(6.1×10^8 mL)	165 microsec	5 log mL-sec (1×10^5 mL-sec)	5 mm	
		(6.1×10^8 mL)	165 microsec	(1×10^5 mL-sec)		
		(0.1×10^8 mL)	9.8 millisec	(1×10^5 mL-sec)		
3.	Severin 1961	5500 lumens/ft^2 (5.9×10^3 mL)	150 millisec	(8.9×10^2 mL-sec)	7-10 mm	
		(5.9×10^3 mL)	150 millisec	(8.9×10^2 mL-sec)		
4.	Severin, Newton & Culver 1962	232,000 lux (2.3×10^4 mL)	150 millisec	(3.5×10^3 mL-sec)		
				Field Study Using Nuclear Bu		
5.	Whiteside 1960	43650 c/cm^2 (1.37×10^8 mL)	100 millisec	4365 c/cm^2 (1.37×10^7 mL-sec)	4 mm	
		(1.37×10^8 mL)	100 millisec	(1.37×10^7 mL-sec)		
		(1.37×10^8 mL)	100 millisec	(1.37×10^7 mL-sec)		
		(1.37×10^8 mL)	100 millisec	(1.37×10^7 mL-sec)		

*Numbers in parenthesis represent measures calculated or transformed for this table. All other va

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TABLE I

of Literature on Flash Effects

Laboratory Studies

'gy ye ıne)	Pupil Diameter	Display Luminance (Visual Task)	Recovery Time	Visual Task
-sec)	6 mm	71 ftL (76 mL)	5 sec	Respond correctly twice to test stimulus flashing at one-second intervals
-sec)		7 ftL (7.5 mL)	12 sec	7 ftL corresponds to flood-lighted aircraft instruments
-sec)		.45 ftL (.49 mL)	35 sec	.07 ftL corresponds to red-lighted aircraft instruments
-sec)		.07 ftL (.08 mL)	93 sec	
ec)	5 mm	2.25 log mL (180 mL)	2 sec	Determine orientation of acuity grating (reciprocal of visual angle in minutes = 0.33)
ec)		1 mL	15 sec	
ec)		1 mL	28 sec	
-sec)	7-10 mm	.06 ftL (.06 mL)	13 sec	Respond correctly twice to test stimulus flashing at one-second intervals
-sec)		.013 ftL (.014 mL)	37 sec	
-sec)			10-50 secs for 16 subjs.	Respond correctly twice to test stimulus flashing at one-second intervals

Study Using Nuclear Burst

-sec)	4 mm	1.04 ftL (1.12 mL)	5 sec	Perceive a lighted square within a dark area (adaptometer)
-sec)		.41 ftL (.44 mL)	17 sec	
-sec)		.14 ftL (.15 mL)	58 sec	
-sec)		1.04 ftL (1.12 mL)	28 sec**	**This was viewed through the fireball after-image rather than foveally as in the other instances

his table. All other values are from original reports.

It is also possible that the discrepancy might be attributed to differences in the spectral distribution characteristics of the two sources. However, the carbon arc (Metcalf & Horn) is considered to be a reasonably good approximation of an atomic burst (Whiteside) in this respect.

2. Influence of Display Luminance. In four of the five experiments the brightness of the target display was varied. In every instance it can be seen that increasing display luminance produces a substantial decrease in visual recovery time. For instance, in the study of Metcalf and Horn, with all other conditions held constant, an increase in display luminance from 0.07 ftL to 71 ftL produced a decrease in the required visual recovery time from 93 to 5 seconds.

3. Intensity/Time Reciprocity. It has been stated (Pirenne, M.H. as reported in Matoush, 1960) that for short exposure times there is a reciprocity between exposure time and brightness in determining the effect produced. Thus, the duration of flash blindness should depend on the product of brightness and time, or on the integrated brightness. The data of Table 1 indicate that, for extremely short exposure times, a strict reciprocity relationship does not exist. The data of Chisum and Hill indicate that, when total energy received at the eye is held constant, a decrease in exposure time from 9.8 milliseconds to 165 microseconds reduces recovery time from 28 to 15 seconds. A sixty-fold difference in duration for two flashes of equal total energy produces only about a two-fold difference in recovery time.

4. Subject Variability. In only one study of flash blindness has the sample of subjects been large enough to indicate the possible range of individual differences in susceptibility. Severin, Newton, and Culver (1962) used 16 subjects and found that recovery times, following a 3.5×10^3 mL-sec exposure, ranged from 10 to 50 seconds. This represents extensive inter-subject variability and suggests that selection on the

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basis of susceptibility to flash blindness might play a part in future operations in space or in a nuclear environment.

5. Flash Blindness-Retinal Burn Comparison. The data of Table 1 indicate the exposure sources used in flash blindness investigations cover a considerable range of intensities. It would be of interest, primarily for reasons of safety, to relate the energy intensities required to produce varying levels of flash blindness to the energy intensity representing threshold dose for minimal retinal lesions. In determining such relationships several important considerations are necessary. These are:

a. Spectral Characteristics of Exposure Sources. An initial problem arises from the fact that most investigations of retinal burn have expressed source intensity in terms of calorimetric units while investigations of flash blindness have used photometric units. A rigorous translation from one set of units to the other requires precise information concerning the spectral characteristics of the exposure source. The two units can be related with precision only if the sources are comparable, both transmitting in similar bands around 550 millimicrons.

Ham (1962) investigated retinal burn damage using a light consisting of an Osram XBO-2001 high pressure xenon lamp and an optical system closely resembling the Zeiss Light Coagulator. Exposure in the flash blindness study of Chisum and Hill (1961) was produced by a xenon-filled helical flash lamp. The spectral distribution characteristics of these two sources are believed to be quite similar. This being the case photometric units can be converted into thermal units using the following transformation equation provided by Matoush (1960):

$$3.53 \times 10^5 \text{ lumen-sec/ft}^2 = 1 \text{ cal/cm}^2$$

Figure 5 presents the general transformation curve provided by

Metcalf and Horn (1959) which relates illumination intensities to thermal irradiance.

Ham determined that, for a 175 microsecond exposure, approximately 0.2 cal/cm^2 represents threshold dose for minimal retinal lesions in rabbits. The upper limit of the flash intensity used by Chisum and Hill, with a 165 microsecond exposure, was 1 x $10^{4.8}$ mL-sec. Using the equation of Matoush, this can be transformed into thermal units yielding a value of 0.23 cal/cm^2 as the exposure used. At first view, this would indicate that the exposures of Chisum and Hill, involving human subjects, are virtually at the threshold dose for minimal retinal lesions. However, the translation is as yet incomplete.

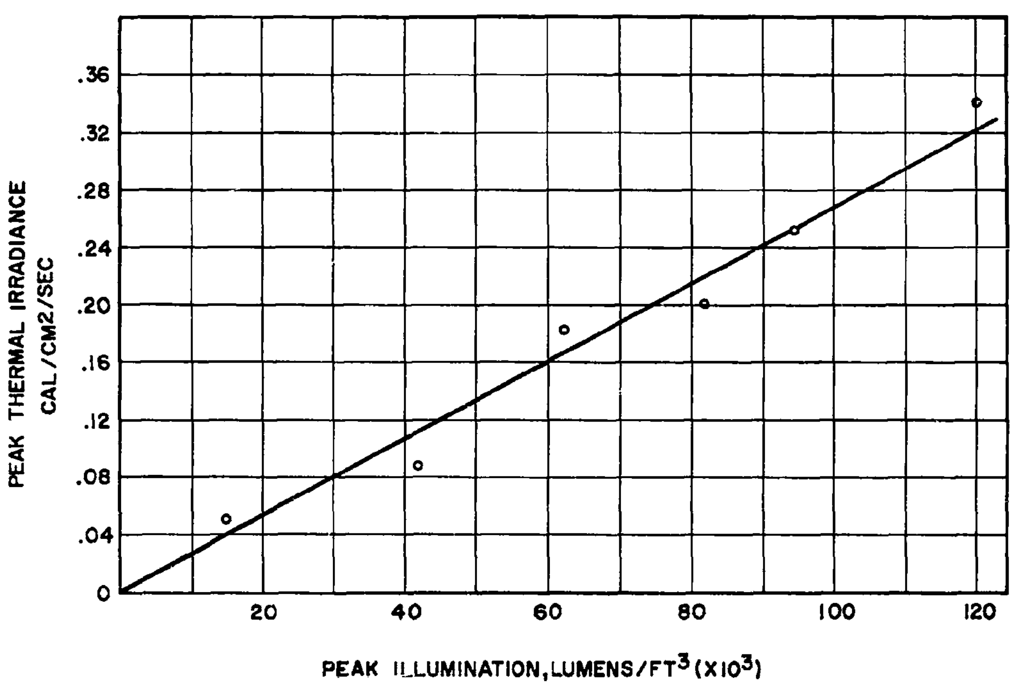

Fig. 5. Empirical relationship of illumination versus thermal irradiance. (Metcalf & Horn, 1959)

b. Comparison of Rabbit and Human Visual Systems. The 0.2 cal/cm^2 threshold value cited by Ham represents irradiance at the retina of the rabbit. Inherent in this statement are additional complications. There are certain similarities between the eye of the rabbit and that of a human. First, susceptibility to exposure damage appears quite similar. Ham believes that 0.2 cal/cm^2 probably also represents threshold dose for minimal lesions in humans. Second, internal transmission is quite similar. One laboratory investigation indicated that the ocular media of the rabbit transmits approximately 10 percent more light than the human ocular media (Geeraets et al, 1960).

There also is an important difference between the eye of a rabbit and that of a human. Focal length of the rabbit eye is 10 mm while that of the human is 17 mm. Since the projected area varies directly as the square of the focal length, a given image presented to the eye of a human will result in a retinal image area three times as large as that of the rabbit. Thus, intensity of stimulation per unit area will be only one-third as great.

c. Measures of Exposure. Ham used an exposure source of known diameter at a fixed distance, thereby allowing calculation of the retinal image size. Knowing exposure value at the corneal plane he thus is able to calculate irradiance at the retina. These are the exposure values he presents. No attempt can be made to compare the work of Chisum and Hill with that of Ham unless exposure values are equated either at the corneal plane or at the retina.

Ham notes that an irradiance at the cornea, using a rabbit eye, of 53.6 cal/cm^2/sec yields a retinal irradiance of 2867 cal/cm^2/sec. The indicated 0.2 cal/cm^2 threshold dose in a 175 microsecond exposure time will yield a value of 1142.9 cal/cm^2/sec at the retina. Comparing this to his previous relation of retinal and corneal irradiance, a value of 21.44 cal/cm^2/sec at the cornea is obtained. For a 175 microsecond exposure time, this value reduces to 0.0037 cal/cm^2. This represents the amount of energy delivered in 175 microseconds to the corneal plane of a rabbit to produce minimal retinal lesions. Area of retinal exposure varied from 1 mm to 100 microns (0.1 mm) in diameter.

Chisum and Hill did not use a completely diffused source in exposing the eye. The flash lamp was five inches in diameter, resulting in a retinal image area of approximately 21 square millimeters. Considering again the work of Ham, we may select a .5 mm diameter as a typical retinal exposure field. This is an exposure area of approximately 0.2 square millimeters. Thus, in the experiment of Chisum and Hill we have approximately 60 times the amount of energy (0.23 cal/cm^2 divided by 0.0037 cal/cm^2) distributed over an area roughly 100 times as large (21 mm^2 divided by 0.2 mm^2). Dividing 60 by 100 yields a factor of approximately 0.6. In other words, the exposure at the retina in the experiment of Chisum and Hill is estimated to be roughly 0.6 that in the experiment of Ham. If these calculations are correct, and there are many assumptions inherent therein, it would be necessary to increase the intensity of the light used by Chisum and Hill only by a factor of two in order to produce minimal but permanent retinal lesions.

The above calculations should be interpreted only as an indication that the light intensities currently used in flash blindness experiments appear to be approaching those used in retinal burn investigations. Both to obtain a better understanding of the phenomenon of flash blindness and to understand safety limitations in flash blindness experiments, experimental work should be undertaken which will provide direct photometric and calorimetric measures of source intensity as presented at the corneal plane of the subject. Ham has spoken of plans to begin experimentation in this direction. He will attempt to determine threshold values for very short exposure periods for retinal image sizes of several millimeters or as large as practicable. These larger image areas will bear more relation to the diffused sources used in flash blindness experiments.

Probability of Foveal Exposure

The severity of visual damage, when occurring as a result of a nuclear flash, depends on whether the flash falls upon the foveal region or upon the periphery. Whiteside (1960) has computed the probability of a flash taking place directly in the line of sight of a pilot operating in a nuclear environment but not anticipating a burst. This is the probability of the image of the fireball being focused directly upon the foveal region. These calculations are based on the assumption that damage is done when some part of the image of a circular fireball overlaps onto the central 1 degree of the fovea. Figure 6 presents these probabilities. If the flash source is represented as a point in random positions, the probability of it falling in the 1 degree foveal field will be the percentage which the area of the foveal field bears to the area of the search field. When the size of the search field is 4 (pi) steradians, the flash may come from any direction. The unrestricted binocular field is estimated to be 1.5 steradians. It is evident from Figure 6 that, even considering a small search field of 40 degrees in which the observer knows the explosion will occur, the likelihood of the flash taking place in the direct line of sight is quite small.

The low probability of direct foveal exposure strengthens the conclusion that the major problem faced, even in a nuclear environment, concerns flash blindness rather than retinal burns.

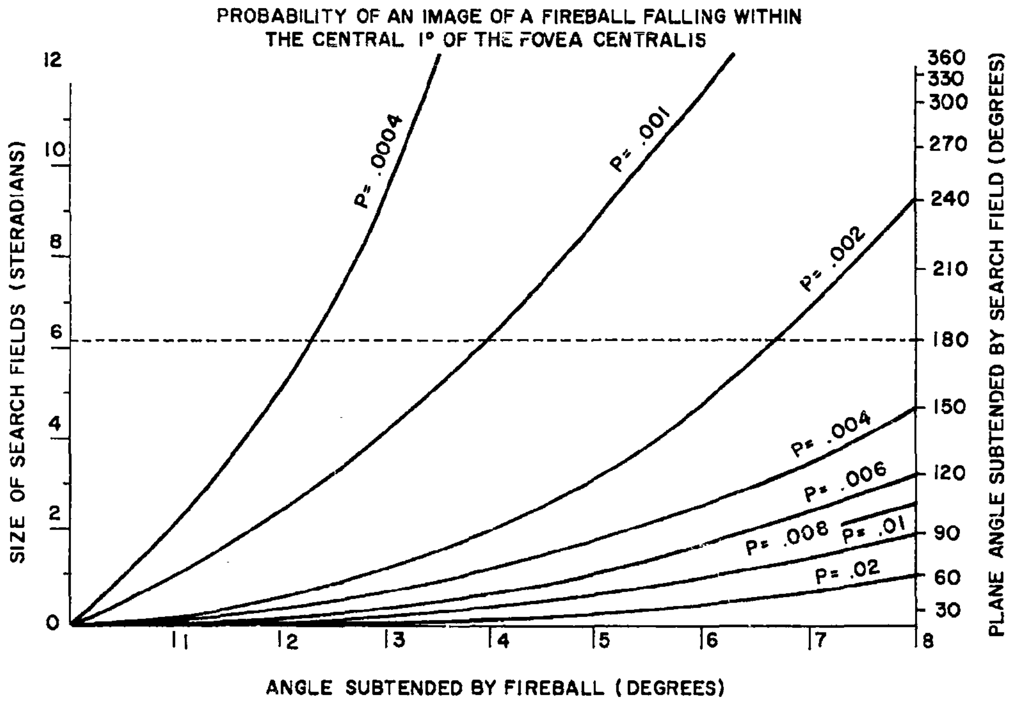

Fig. 6. Probability of focusing directly on fireball image during random search. (Whiteside, 1960)

Effect of Viewing Angle on Exposure

Laboratory investigations of retinal burn damage and flash blindness invariably involve direct stimulation of the retina. Such studies provide much information concerning the direct relationship between exposure intensity and visual damage. They do not, however, provide sufficient information to state the damage likely from a certain type of burst under a specified set of field conditions. For one thing, field conditions such as atmospheric transmission, cloud cover, and terrain reflectivity influence actual exposure. For another, only in a very limited number of instances will a person be looking directly at a burst unless he knows its location in advance.

The probability of direct viewing of an unexpected burst, as noted by Whiteside, is quite small. When the burst is not viewed directly, there obviously is less danger of visual damage. The problem is one of determining the extent to which the danger decreases when an individual is looking at some specified angle from the burst point. No reports have been found which describe laboratory investigations of this problem. However, there have been studies in related areas which provide information relevant to this topic. Investigations of atmospheric optics have produced data which describe the luminance (brightness) of the sky in all quadrants. If the visible radiation from the sun can be considered representative of that from a nuclear burst, and this seems reasonable, these data indicate the extent to which the intensity of exposure decreases as one looks away from the light source.

The Visibility Laboratory of the Scripps Institution of Oceanography, University of California, has for many years conducted research in the field of atmospheric optics. Recent data (Boileau, 1961) from that laboratory probably represent the best available information concerning luminance of the sky. The following discussion is based upon these data.

Effect of Azimuth Change From Source

The primary concern is with the extent to which exposure decreases as an individual looks away from the sun but maintains a constant scan angle above the horizon. Figure 7 presents data illustrating the changes which occur as the line of regard changes in azimuth from the sun. In this figure, all points represent measured values except that at the zero degree azimuth. This value, representing the brightness of the disc of the sun, was calculated by personnel of the Visibility Laboratory using atmospheric transmissivity measures taken on the day of this flight. In this instance, the altitude of the sun is 15 degrees. The altitude of the horizontal scan also is 15 degrees.

Two observations can be made concerning Figure 7. First, the exposure one would receive from viewing the sky at an azimuth of 100 degrees from the sun is exceedingly small when compared to that which would be received through direct viewing of the sun. The brightness of the sky at an azimuth of 100 degrees is 0.00000064 (6.4×10^{-7}) as great as that of the sun. It is true that one would lose dark adaptation completely upon viewing the sky, which was 340 foot lamberts in brightness, but there would be no period of flash blindness.

The second observation relates to the rapidity of the decrease in

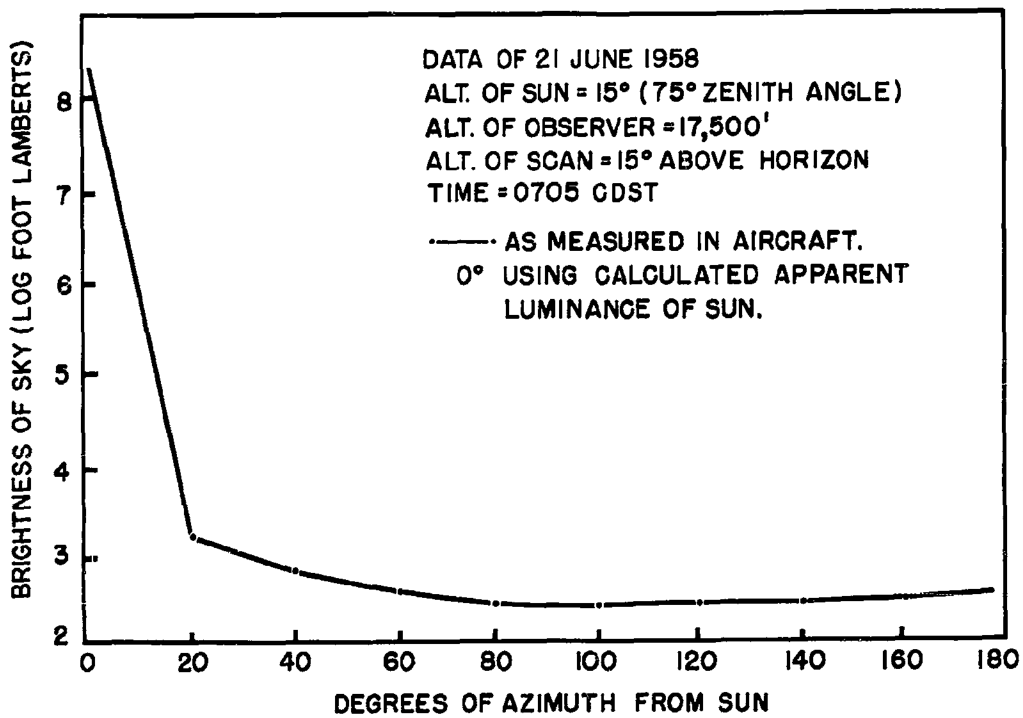

Fig. 7. Change in sky luminance as azimuth from sun changes.

exposure intensity with change in viewing angle. A change in viewing angle of only twenty degrees reduces the intensity of exposure to an acceptable level.

Effect of Elevation of Viewing Angle

The next question concerns the extent to which the intensity of exposure changes as one scans the sky vertically at a given azimuth angle from the sun. Figure 8 illustrates these changes at an azimuth angle of 20 degrees. It can be seen that the brightness of the sky changes from 220 ftL at a zenith angle of 30 degrees

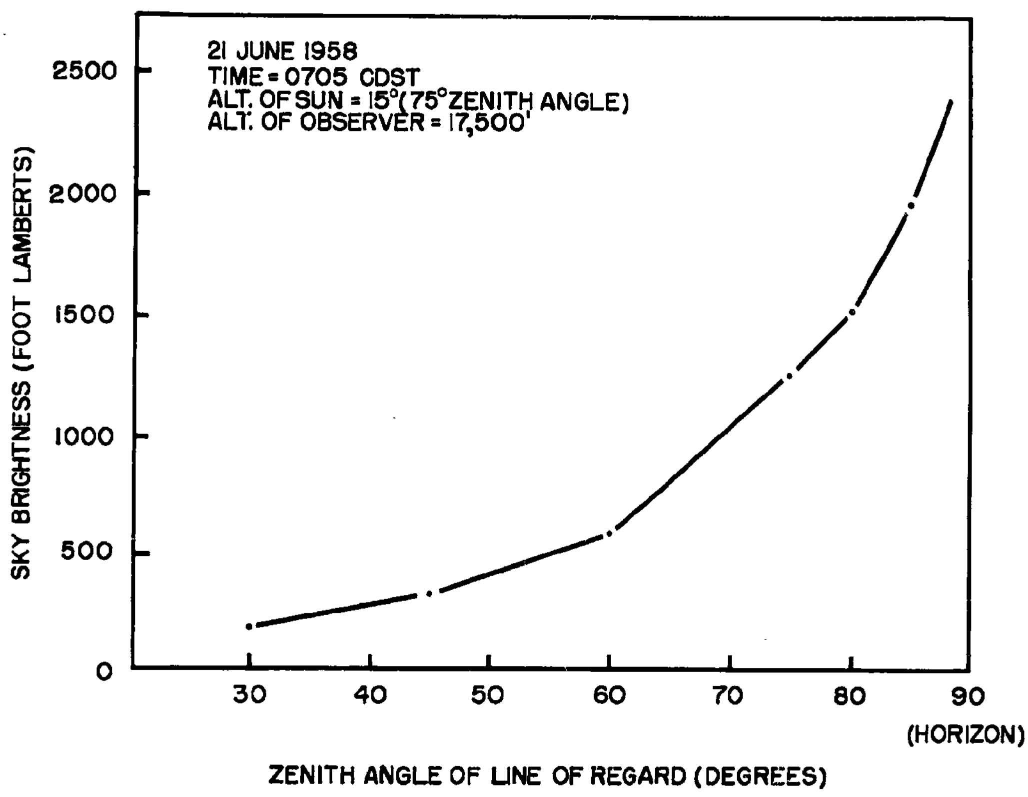

Fig. 8. Change in sky luminance for vertical scan at 20° azimuth.

(60 degrees above the horizon) to a value of 2600 ftL at the horizon. This figure indicates that in this instance, the brightest part of the sky, regardless of proximity to the sun, is at the horizon.

The above analysis would seem to indicate that the chances of a person becoming flash blinded when exposed to a high intensity source such as a nuclear burst are considerably less if he is not looking directly at the burst at the moment of detonation and if he can be trained not to look at the fireball during the period of the burst. However, it should be stressed that this analysis uses data from clear weather conditions only. It yields no information concerning the more traumatic incidents which might occur. For example, if a dark adapted pilot flying a night mission were exposed to the extremely intense visible radiation of a high altitude, high yield burst, he might well be seriously flash blinded regardless of his direction of view.

RESEARCH REQUIREMENTS

Preceding sections of this report have attempted to indicate the extent of current information concerning visual impairment following exposure to high intensity light sources. It is obvious that much remains to be learned concerning this phenomenon. It also is apparent that the military services have a genuine requirement for information concerning retinal burn damage and, in particular, flash blindness. This section describes what appear to be the three basic areas in which information is lacking and suggests procedures for acquiring the missing data.

Stimulus Conditions

The stimulus condition of particular concern here is a nuclear detonation. Through the various nuclear test series which have been held within the last decade and a half, much has been learned concerning the packaging of nuclear weapons and concerning blast damage resulting from them. Surprisingly little has been carefully catalogued in the way of a complete time history of the visible radiation occurring during a burst. Glasstone (1962) states that the surface temperatures of the fireball, upon which the brightness depends, do not vary greatly with the total energy yield of the weapon. Consequently, the observed brightness of the fireball in an airburst is roughly the same. Van Voorhis (1961), in a classified report, presents data concerning the integrated brightness of the fireball for a 1.3 KT weapon at a number of points through time following detonation. The brightness values were calculated from thermal energy measures obtained through photographic techniques. There is a need for the data of Van Voorhis to be verified through direct photometric measures and for such measures to be obtained for weapons having different yields. If nothing else, the time line of the buildup and decay of visible radiation will change as a function of yield.

Glasstone also notes that, for a high altitude detonation, most of the early X-ray energy is absorbed in the large volume of air which has a considerable mass in spite of its low density. Consequently fireball temperatures, although of the order of 10,000° C or more, are much lower than for an explosion at sea level densities. If the temperature of the fireball varies as a function of the altitude of detonation, the character and intensity of the visible radiation also will vary. There thus is a need for a cataloguing of such radiation as a function of altitude of burst.

In summary, it seems that there is little empirically-derived information concerning the spectral character and time history of the visible radiation released during a nuclear burst. There is a need for catalogued data indicating, for various yields and for various burst altitudes, the intensity and the spectral distribution of the visible energy which is released.

Laboratory Research

This report describes five studies which were concerned directly with the problem of flash blindness. There have been many other investigations, to be sure, of the effect of light on the visual mechanisms. However, none seems to be as relevant as these five to the specific problem of flash blindness. Five investigations are not many. As noted, there are certain inconsistencies in the findings, even among these five. It would seem that a considerable amount of additional laboratory research is warranted. This research should investigate a range of light intensities and a range of exposure times.

For instance, only the research of Chisum and Hill (1961) has used exposure times in the microsecond range. Other studies have tended to settle on an exposure time approximating the period of the blink reflex. Exposure time and source intensity should be matched in these studies in such a manner as to provide a complete definition of the dimension of integrated energy received at the eye.

Severin, Newton and Culver (1962) discuss the only study which has used more than a very small number of subjects. With sixteen subjects, rather extensive inter-individual differences in susceptibility to flash blindness were noted. The range of individual differences in susceptibility should be explored and should be related to varying amounts of integrated energy received at the eye.

The effect of drugs on flash blindness susceptibility should be studied. In particular, those which tend to constrict pupillary diameter should be investigated. At present, all flash blindness research information is based on the normal daylight pupil diameter.

In summary, additional laboratory research appears warranted. This research should extend information currently available from those studies which have been conducted. It should also investigate various influences which could tend to increase or decrease individual susceptibility to flash blindness.

Comprehensive Model

Military planners might be expected to be more interested in the application of laboratory findings to military problems than in laboratory data per se. In the operational context the problem is one of expressing the extent of the flash blindness hazard for a given military situation. The translation of laboratory results into solutions for operational problems is not easy, however. For example, empirical studies to date have involved direct stimulation of the eye by the flash source. It is difficult to say what reduction in visual recovery time would occur if the light source were not viewed directly. The influence of specific meteorological conditions on flash blindness also is difficult to assess. If a flash were to take place within extensive cloud cover, a nearby pilot might be extensively blinded regardless of his direction of view.

There appears to be a need for a comprehensive model which will express the extent of flash blindness as a function of source intensity, source altitüde, viewing distance, viewing angle, and meteorological conditions. Only through use of such a model can ready answers be obtained to questions concerning the flash blindness hazard in specific operational situations.

SUMMARY AND CONCLUSIONS

Within recent years increasing interest has been shown, particularly in the military services, in the problem of visual impairment resulting from exposure to intense visible radiation. Intense light can be encountered in space operations and, to an even greater extent, within a nuclear combat environment. If the exposure is sufficient, permanent retinal lesions may be produced. For most exposures, however, the result is simply a period of visual incapacitation, or flash blindness, during which normal visual activities cannot be performed. Even though this period may last but for a few seconds, for certain military missions it could spell the difference between success and failure.

Five recent investigations of flash blindness have been reported in the unclassified literature. Four used artificial laboratory light sources while one used the light from an actual nuclear burst. Although there are inconsistencies among the data of these studies, they indicate, within limits, the extent of the visual impairment experienced following exposure to different light intensities. All studies also indicate the reduction in recovery time which can be accomplished with an increase in the illumination of the visual task being performed.

The five studies cited represent excellent contributions toward an understanding of the flash blindness problem. However, before answers can be provided to questions concerning the extent of the flash blindness hazard to be expected in various military situations, much work remains to be done. First, data concerning the physical stimulus, if it is a nuclear detonation, must be catalogued. At this time, there is no systematic compilation of information concerning the time history and spectral characteristics of the visible radiation from various yield weapons exploded at varying altitudes. Second, additional laboratory research should be undertaken. A complete range of light intensities and exposure times should be explored. The extent of individual differences in susceptibility to flash blindness requires definition. The effect of various influences, such as drugs, psychological set, indoctrination, etc., on this susceptibility also should be investigated. Third, a comprehensive model is required which will indicate the extent of the flash blindness likely to occur in various operational situations. This model should express the extent of flash blindness as a function of such parameters as source intensity, source altitude, viewing distance, viewing angle, and meteorological conditions.

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*Information taken from classified reports pertains only to the structure and functioning of visual mechanisms. No information was taken from these reports pertaining to the nature of nuclear detonations or to nuclear weaponry.