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COMPILATION OF NUCLEAR TEST FLASH BLINDNESS & RETINAL BURN DATA and ANALYTIC EXPRESSIONS FOR CALCULATING SAFE SEPARATION DISTANCES

FINAL REPORT

This work sponsored by the Defense Atomic Support Agency
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Prepared by

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Characteristics of the human eye that affect the eye's sensitivity to thermal radiation, and potential protective measures are summarized. Nuclear bursts at which flash-blindness and retinal burn effects have been documented are identified, and the effects are reviewed and evaluated. Laboratory studies on flash-blindness are briefly reviewed, and wide variations are noted in individual recovery times from effects produced by the same source under the same conditions. Analytical equations derived from analysis of nuclear burst data are presented for calculating the following parameters of thermal radiation: (1) fireball radius as a function of time; (2) time to final thermal maximum, t_f, for air bursts; (3) radiant exposure up to 10 t_f; (4) rate of thermal energy delivery as a function of time; (5) fraction of thermal energy delivered as a function of time; (6) rate of thermal energy delivery at time of first thermal maximum. Criteria based on nuclear test effects are evaluated for prevention of retinal burn. Separation distances, based on the criteria, and calculated by use of the analytical equations are presented graphically for the following conditions: safe viewing by unprotected dark-adapted subjects on the ground of only the first 100 msec of night bursts of yields of 1, 10, 45, 100, and 1000 kt at altitudes from 1 to 20 km; safe viewing for night-adapted visually unprotected subjects coaltitude with the same burst yields. Results are estimated accurate within 25 to 50%.

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Characteristics of the human eye that affect the eye's sensitivity to thermal radiation, and potential protective measures are summarized. Nuclear bursts at which flash-blindness and retinal burn effects have been documented are identified, and the effects are reviewed and evaluated. Laboratory studies on flash-blindness are briefly reviewed, and wide variations are noted in individual recovery times from effects produced by the same source under the same conditions. Analytical equations derived from analysis of nuclear burst data are presented for calculating the following parameters of thermal radiation: (1) fireball radius as a function of time; (2) time to final thermal maximum, t_f, for air bursts; (3) radiant exposure up to 10 t_f; (4) rate of thermal energy delivery as a function of time; (5) fraction of thermal energy delivered as a function of time; (6) rate of thermal energy delivery at time of first thermal maximum. Criteria based on nuclear test effects are evaluated for prevention of retinal burn. Separation distances, based on the criteria, and calculated by use of the analytical equations are presented graphically for the following conditions: safe viewing by unprotected dark-adapted subjects on the ground of only the first 100 msec of night bursts of yields of 1, 10, 45, 100, and 1000 kt at altitudes from 1 to 20 km; safe viewing for night-adapated visually unprotected subjects coaltitude with the same burst yields. Results are estimated accurate within 25 to 50%.

SUMMARY

Characteristics of the human eye that cause sensitivity to thermal radiation, the effects of thermal radiation on the eye, and potential protective measures are summarized. Nuclear bursts at which flash-blindness and retinal effects have been documented are identified, as possible, as are observer locations and conditions. Effects are reviewed for each case, and a summary is presented of information on flash-blindness and retinal burn effects on the human eye as a result of nuclear bursts. Effects of device characteristics and environment are pointed out. Laboratory research in flash-blindness is referenced, and the wide individual variation in recovery times found during several research projects is noted. Retinal burn studies are also referenced.

Analytical equations expressing thermal effects of a nuclear burst as functions of time were derived for this report to provide a means of realistically calculating effects of thermal energy on the human eye. The equations presented, developed by analysis of nuclear burst data, include: (1) fireball radius as a function of yield, time, and burst altitude for air bursts at altitudes up to 20 km; (2) the fraction of thermal energy delivered to a target as a function of time, for bursts in the same altitude range; (3) the rate of energy delivery to a target, as a function of yield, time, and burst altitude. These equations, used in combination with existing analytical techniques for calculating total effective radiant exposure and pulse times, will evaluate thermal energy incident on a human eye, the size of the fireball image in the eye, and the rate of energy delivery at the cornea, at any time after burst.

Three criteria based on nuclear burst effects and laboratory findings were selected as critical values for prevention of retinal burn. Examination of data led to the conclusion that if two of the three criteria are satisfied, no retinal burn will occur.

Separation distances, calculated by use of the analytical equations to satisfy the criteria, are presented graphically for the following conditions:

safe viewing by unprotected dark-adapted subjects on the ground of only the first 100 msec of night air bursts of yields of 1, 10, 45, 100, and 1000 kt at altitudes up to 20 km; safe viewing for subjects (night-adapted and unprotected visually) of only the first 100 msec of the same burst yields when the subjects are at burst altitude. Results are estimated accurate within 25 to 50%.

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INTRODUCTION

1.1 THE PROBLEM

Exposure of the human eye to thermal radiation from a nuclear burst may result in either a temporary loss of visual acuity, termed flash-blindness, or a tissue lesion causing a permanent loss of visual acuity, termed retinal burn. The severity of the latter effect may range from insignificant to serious permanent eye injury.

The effects of thermal radiation on an eye exposed to the flash of a nuclear burst depend on the amount of thermal exposure received by the retina, the rate of energy delivery, and the portion of the eye exposed. These factors depend on the parameters of yield, weapon characteristics, burst conditions, distance and orientation to burst, and atmospheric transmission, as well as on blink reflex time, eye pigmentation, and density or speed of darkening of protective goggles, if they are worn.

Many laboratory tests have been carried out exposing eyes to flashes of light; however, such flashes do not produce exactly the same characteristics of a thermal pulse from a nuclear burst. Animals have been exposed to the flashes from nuclear bursts; however, neither rabbit nor monkey eyes have the same characteristics as human eyes. Consequently, results for humans based on animal exposures have of necessity had "adjustment factors" for conversion, and the accuracy of adjustment is not verifiable. Computer programs have been developed for calculating the exposure to the human eye from a nuclear burst, but such programs are lengthy and most incorporate certain simplifying assumptions. The problem of this report is to derive a relatively simple procedure for calculating minimum distances from nuclear bursts at which retinal burns will not occur, at the same time accounting realistically for nuclear burst thermal characteristics and their effects on the human eye.

1.2 OBJECTIVES AND SCOPE

The objectives of this report are as follows:

1) Review available data on flash-blindness and retinal burns resulting from nuclear tests, and validate (as possible) information published in the various reports;

2) Provide a method for predicting the minimal distances at which thermal radiation will not harm an unprotected eye exposed to the flash from burst of any yield greater than 1 kt.

This analysis derives conclusions based on the effects due to the fraction of the total thermal exposure incident on the cornea before the blink. The amount admitted through the pupil and the retinal image size are calculated in order to determine safe distances. The scope of this analysis, therefore, includes the following:

1) Derivation of an analytical method for calculating the radius of the fireball as a function of time, for any yield greater than 1 kt at any burst altitude below the "singular altitude" (i.e., that altitude above which a nuclear burst does not produce a double thermal pulse);

2) Derivation of an analytical method for calculating the fraction of the total thermal exposure delivered during any period of the thermal pulse;

3) Derivation of analytical expressions for rate of energy delivery as a function of yield, time, and burst altitude air density;

4) Determination of burn criterion for viewing the first 100 msec of a nuclear burst;

5) Derivation of minimum distances at which no retinal burn is expected for an observer at the surface, viewing the first 100 msec of 1-, 10-, 45-, 100-, and 1000-kt bursts at altitudes from 1 to 20 km;

6) Derivation of minimum distances at which no retinal burn will occur from observing the first 100 msec of 1-, 10-, 45-, 100-, and 1000-kt bursts when the observer is at the same altitude as the burst.

1.3 FINDINGS

The end results of this analysis are graphical presentations of distances from which an observer at the surface or at burst altitude will suffer no retinal burn when viewing at night only the first 100 msec of the nuclear flash from bursts of weapons of 1, 10, 45, 100, and 1000 kt at altitudes from 1 to 20 km. Each distance was determined as the closer distances calculated to satisfy the first two conditions, and checked with the third. The conditions are:

1) Image concentration is no greater than 0.02 cal/mm^2.

2) Image radius is no greater than 0.024 mm.

3) Energy delivery rate is no greater than 0.20 cal/cm^2/sec on the cornea at blink time.

Distances for 1000-kt bursts, calculated to satisfy the above criteria, are less than those shown in Figs. 5.2 and 5.4. For safety, the additional condition was imposed that total thermal exposure at 10 t_f not exceed 0.56 cal/cm^2, a value only one-tenth the level expected to cause sustained glowing or flaming of paper or dried grass (due to radiant exposure from a 1000-kt burst*).

The criterion for image concentration is a value less than that which caused the accidental minimal burn suffered by an airman who viewed, at a distance of 16 km, the flash from Shot Simon of Operation UPSHOT-KNOTHOLE. The criterion for image radius is based on statements in the literature and on information from Professor Heinrich Rose,** who stated that no burn will occur unless the image diameter is 0.05 mm, or greater.

Distances for these criteria were determined only after derivation of analytical expressions for (1) the fireball radius as a function of time, yield, and burst altitude; (2) the fraction of the total radiant exposure delivered with time; and (3) rate of energy delivery as a function of yield, time, and burst altitude. The equations derived, along with the expressions used for total radiant exposure, are given with their accuracy limits as compared to nuclear test data in Section 4.

* DASA-1240-II(30), in publication.

** Personal communication.

Results are presented only for a 100-msec blink reflex time (considered average) for a night-adjusted eye (8mm dia. pupil). Distances can now be calculated readily for other blink reflex times and for the daylight-adjusted eye, using the derived expressions.

A presented, all equations are cc sidered unclassified, and, in general, calculated results are within plus or minus 25 to 50% maximum deviation from measured data. It is estimated that both fireball and rate of energy equations could be refined to greater accuracy if appropriate functions of mass-to-yield ratio (classified) and rate of fireball rise were taken into account.

1.4 LIMITATIONS

A semi-empirical analysis is subject to limitations because the analytical expressions derived to fit data are, of course, dependent on data accuracy and quantity. Measurements of the same phenomenon by different investigators can vary by as much as 100%. However, the equations derived for fireball radius, fraction of exposure delivered with time, and rate of energy delivery with time are estimated to be, in general, within $\pm$ 25% of nuclear test data available for this study. It is emphasized that results are valid only for bursts below singular altitude, and cannot be applied to high-altitude bursts, such as Shot Blue Gill of Operation DOMINIC. Further study is required to derive expressions applicable to bursts above singular altitude.

Assuming validity of the criteria used, results presented in this report are estimated accurate within 25 to 50%.

Section 2 of the report describes eye injuries due to thermal radiation and possible protective measures. Section 3 presents a summary of nuclear test data and evaluation of published results, Section 4 presents the analytical equations used to calculate retinal burn criteria, Section 5 presents the final results, and Section 6 offers Conclusions and Recommendations.

Section 2

EYE INJURIES POSSIBLE FROM THERMAL RADIATION, AND PROTECTIVE MEASURES

2.1 INTRODUCTION

Exposure of the human eye to a brilliant flash of light or to thermal radiation from a nuclear burst may produce flash blindness, retinal burn, or no effect, depending on the many factors noted in Section 1.1. The threshold amount of incident thermal energy harmful to the eye is many magnitudes less than the amount sufficient to cause a mild burn on bare skin. This difference is due to the physiological characteristics of the eye. In the following paragraphs, the characteristics of the eye, pertinent to thermal injury, and the reactions of flash blindness and retinal burn are described, and available protection from eye injury is discussed.

2.2 CHARACTERISTICS OF THE EYE INFLUENCING THERMAL INJURY

The physical structure of the eye is responsible for its sensitivity to light. The eye consists of three thin concentric layers, within which are the vitreous body (a transparent jelly), a lens, and fluid. The outer concentric layer of the eye (the sclera and cornea) is protective tissue, and immediately behind the cornea is the iris, which is perforated by the pupil; the middle layer, the choroid (or chorioid), is the vascular membrane for the retina, which is the innermost layer. The external layer of the retina is composed of terminal nerve cells, the rods and cones, which are the receptors of radiation in the visible spectrum. The rods contain rhodopsin and the cones contain iodopsin, both of which are photochemical substances. Recovery of visual acuity after the eye has been exposed to a brilliant flash of light depends upon both the mechanics of vision and eye chemistry, and recovery time as well as the degree of recovery depend on the duration, intensity, and rate of delivery of the energy, and on the ambient light.

Mechanics of vision involves the fact that the eye behaves much like a camera of fixed focal length. The pupil acts like a diaphragm regulating

the amount of entering light that is then focused by the lens to produce an image on the retina of the object viewed. Thus, the retinal exposure is far more highly concentrated than the light incident on the cornea.

The ambient light is a factor affecting retinal exposure because in broad daylight, the pupil of the eye is contracted to about 2 to 3 mm in diameter, while a completely dark-adapted eye will have a pupillary diameter of 7 to 8 mm, depending on age of the individual. As a result, the amount of light that enters the eye from a given source if the environment is dark may be 16 times that in bright daylight. The maximum constriction of the pupil in response to light will reduce the diameter to about 2 mm; thus, a dark-adapted eye has a greater adjustment in returning to normal after exposure to a flash of light than a daylight-adapted eye exposed to the same stimulus.

Eye chemistry involves the fact that the photochemical substances contained in the rods and cones are bleached by exposure to a short, intense flash of light. These substances must regenerate before vision is restored.

Thermal injury to an unprotected eye exposed to a brilliant flash of light falls into two major categories, flash-blindness and retinal burn.

2.3 CHARACTERISTICS OF FLASH-BLINDNESS

"Flash-blindness" is a term used to designate an immediate temporary loss of visual function resulting from exposure of the human eye to a brilliant flash of light. It occurs when the radiant energy delivered to the retina does not raise the tissue above its critical value, and produce a lesion, but is sufficient to cause bleaching of the photochemical substances within the rods and cones. The physiological response includes the initial dazzle effect and the after-image. Dazzle generally is defined as the initial reaction of the eye to bright light, while the after-image is a transient scotoma caused by a visual impression that lasts after the image has ceased to exist. The light-adapted eye depends entirely on cone response, and following bleaching, the iodopsin in the cone regenerates promptly. The completely dark-adapted eye depends on the response of only the rods, and

rhodopsin regeneration in the rods is negligible for several minutes after bleaching. Objects seen in daylight appear much brighter than when seen at night; thus a lesser degree of recovery is necessary for effective daylight vision. To summarize, recovery of effective vision is much faster if eyes are flash-blinded in daylight than when the flash-blindness occurs at night; further, recovery is faster under bright moonlight conditions when there is some cone response, than on a moonless night. It follows that flash-blindness is of longer duration and of more tactical significance after nighttime bursts than after daytime bursts.

2.4 CHARACTERISTICS OF RETINAL BURN

Retinal burn is a physical eye tissue injury that may decrease visual acuity. A retinal burn will occur under only all the following conditions:

a) the eye is facing the direction of the flash;
b) the radiant energy is delivered so rapidly that cellular elements of the choroid and retina absorb heat faster than it can be dissipated by choroid circulation and conduction;
c) the amount of energy absorbed is sufficient to raise the tissue temperature above a critical value.

The size and severity of the lesion and the portion of the retina affected determine the effect on vision. Visual acuity usually is unaffected by slight exposures when the fireball image size, which affects the size of the burn, is limited to the peripheral regions of the retina. In such cases, the victim may experience no symptoms and may be unaware of having sustained a burn, and no loss of vision results. However, minimal lesions (0.05 mm) on the parts of the retina vital to central vision can impair visual acuity. In cases where the exposure is of a sufficiently high irradiation level such that an explosive boiling effect is produced in the tissue, the damaged area on the retina may be larger than the image size, and severe permanent injury will be sustained. Such cases may produce immediate haziness of vision, long after-image, and dizziness or nausea.

2.5 PROTECTION AVAILABLE

Methods of protection from thermal effects of nuclear bursts include trained reaction to take cover (possible only for personnel on the ground), the instinctive reaction of blinking, and shielding the eyes by various means such as restricting the field of vision or wearing goggles or visors that filter the light incident on the eye.

2.5.1 Trained Reaction

Experiments have determined that the average time in which trained personnel could carry out a hands-to-face evasion was 1.2 sec, with 50% of the personnel evading effectively in 1 sec.[1] Such tactics provide no eye protection, since eye damage may occur within the first few milliseconds of exposure to the flash, and will always occur within less than the first second.

2.5.2 The Blink Reflex.

The blink reflex, an instinctive reaction of the eye in response to light stimulus, will to some extent protect the eye viewing a nuclear burst. According to many reports, the human blink has a normal delay time of 80 to 150 millisec (averaging about 100), and lasts from 300 to 400 millisec. For small tactical-yield bursts, pulse times are short (see Section 4), and the blink will offer little protection; for larger yields with longer pulse times and slower energy delivery rates, the blink may be an effective protection if the eyelids remain closed for at least a second after blinking. The effectiveness of the blink reflex will be shown in the development of safe distance contours in Section 4.

2.5.3 Shielding the Eyes.

Numerous types of eye shield have been investigated, including the following:

1) fixed filter goggles;
2) the monocular eye patch;
3) eye-slit devices;
4) curtains or screens; and
5) dynamic devices.

No more comprehensive summary is known of existing and experimental methods of eye shielding than is presented in Ref. 2, although the date of the document is 1965. One simple technique noted is that on long-range missions where navigation is done exclusively by instruments, it is probable that the fireball would occur at a point in space outside the momentary field of view. Under such circumstances, the crew could be protected by a curtain or screen that limits vision to a small segment of the canopy. However, the most promising protection devices appear to be in the field of dynamic devices — those that change optical density as a function of ambient density. This category includes mechanical devices (such as the unsatisfactory electromechanical goggles), electro-optical/magneto-optical devices, the ELF (Explosive Light Filter) System, photoreactive devices, indirectly activated phototropic devices, and indirect viewing techniques. A review of the capabilities of all the operational and developmental devices listed indicates that none is completely satisfactory or foolproof, to date.

Section 3

NUCLEAR TEST DATA

3.1 INTRODUCTION

Flashblindness tests were conducted, and several accidental human retinal burns or injuries occurred during some of the United States nuclear tests. Effects on the eye are functions of incident exposure on the cornea, concentration of exposure in the retinal image, and energy delivery rate. In order to calculate these quantities, the shot yields and environments and locations of observers must be known, and device characteristics that could affect thermal output should be considered. However, some of the recorded data are confused and contradictory, and some of the necessary information was never recorded. Available information and conclusions on shot identification and observer location will precede the discussions of nuclear burst results on flash-blindness and retinal burn accidents from nuclear bursts.

3.2 SHOT IDENTIFICATION AND OBSERVER LOCATION

The Operation RANGER report, Ref. 3, mentions an accidental retinal burn that occurred when, in 1951, one man aboard a SAC plane looked directly at F with one eye covered. The description continues with details of the effects of the burn. Assuming "F" is Shot Fox, yield and burst altitude are identified. Correlating the Ref. 3 data with that of Case 2 listed in Ref. 4, it is concluded that the plane was about 5 miles from burst. However, aircraft altitude remains unknown, a condition that prevents calculation of the the thermal conditions that caused the burn.

It has not been possible to identify the shot that caused the retinal burn listed as Case 1 in Ref. 4.

At Operation BUSTER, in 1951, the flash-blindness tests conducted are described in Ref. 5, which identifies the shots as Baker, Charlie, and Dog, and states that the aircraft in which the test subjects were located was orbiting at 15,000 ft altitude, about 9 miles from each burst.

In an Operation SNAPPER report, Ref. 6, the shots during which flash-blindness tests were conducted are stated to have occurred on 22 April and 1 May (1952), and it is stated that the trailer was located approximately 10 miles from both shots. On those dates, Shots 3 and 4, both air bursts, of Operation TUMBLER were fired, and the yield of the 1 May shot was 30 kt and that of the 22 April shot was 18 kt. Under those circumstances, maintaining the same trailer distance from both shots is rather surprising. Reference 6 also notes that two cases of retinal injury occurred during the tests; therefore, the tests were discontinued. However, no information is given on which shot(s) caused the injuries. Reference 7 provides some details on one accidental retinal burn an observer suffered during the Operation SNAPPER flash-blindness tests, and states that the accident occurred on 1 May. Reference 4 also describes an injury (Case 3) that appears to be the same one mentioned in Ref. 7. Reference 9 refers to the flash-blindness tests conducted at Operation SNAPPER, and states that both shots were of approximately 14-kt yield (less than the yield of Tumbler Shot 4 on 1 May). It is of interest that Shots 3 and 4 of Operation SNAPPER were both of approximately 14-kt yield, and were on low towers. In view of the contradictory and confusing quality of available information, it not possible to firmly identify the two shots during which flash-blindness tests were held at Operation TUMBLER-SNAPPER.

During the Operation UPSHOT-KNOTHOLE Series in 1953, flash-blindness tests were held, and three accidental retinal burns occurred, one during the tests. The shot dates and trailer distances given in Ref. 7 are believed to be accurate: 7.5 miles from Shot Annie, 11 miles from Shot Nancy, 14 miles from Shot Badger, 8 miles from Shot Simon, and 7 miles from Shot Harry. Note, however, that shot numbers and yields quoted in Ref. 7 are incorrect, and there are numerous contradictions in the text of the report, particularly with reference to the retinal burn cases discussed. It is believed that Shot Harry caused the one burn that occurred during the flash-blindness tests, that the officer in a trench within 2 miles of ground zero who suffered a severe retinal burn, against orders viewed with one eye the flash of Shot Simon, and the airman who was injured also viewed the flash of Shot Simon, from a distance of either 7 or 10 miles.

Operation PLUMBBOB flash-blindness tests are documented in Ref. 8. The three shots in 1957 at which men were tested for flash-blindness, and trailer and aircraft distances are given: the trailers were 15,136 yd and 18,304 yd from Shots Wilson and Diablo, respectively, and the aircraft were 19,360 and 32,426 yd from Shots Wilson and Hood, respectively. However, aircraft altitudes are not listed. Thus it is not possible to compare measured peak exposures and irradiances tabulated in the report with calculated values.

At Operation HARDTACK II in 1958, three groups of personnel, oriented at 90, 135, and 180 degrees from ground zero, and at a distance of 5700 ft from Shot Hamilton, were tested for flash-blindness effects immediately after the shot was fired. The information is adequately documented in Ref. 9.

Two cases of retinal burn occurred in 1962, from viewing Shot Blue Gill Operation DOMINIC at a distance of 60.6 km. These cases are described in Ref. 10.

At Operation SUNBEAM, an observer wearing a special visor viewed the flash of Shot Small Boy while in an aircraft at a distance of 9700 ft. Effects are given in Ref. 11. Aircraft altitude is not given.

3.3 FLASH-BLINDNESS NUCLEAR BURST RESULTS

Table 3.1 lists, in chronological order, Operation, Shot, Yield, Height of Burst, and Distance and Environment of Observers for those nuclear bursts at which flash-blindness effects have been noted in available literature. In addition, special device characteristics or shielding that may affect thermal radiation are noted. Note that all the tests took place in Nevada, and except for Shot Small Boy, were prior to 15 September 1961. Yields, burst altitudes, and device characteristics are from Refs. 12 and 13. Special shielding data are from Ref. 14, and other data are from references noted in the preceding discussion. The heights of burst (HOB) are tabulated in both feet (as specified in Refs. 12 and 13) and in kilometers; observer distances noted in Section 3.2 are converted to kilometers. The metric system is used in the analytical calculations of Section 4. Therefore, distances

Table 3.1

Nuclear Bursts at Which Flash-Blindness Effects Were Observed

Operation	Shot	Yield (kt)	HOB Above Surface (ft)	(km)	State of Observers and km Distance from Burst	Notes
War II (1945)	Hiroshima	~ 20	1850	0.564	Day-adapted, at surface	Air burst
	Nagasaki	~ 20	1650-1950	0.503-0.564	Day-adapted, at surface	Air burst
Ranger (1951)	1	22	1435	0.4374	Day-adapted, in a/c at 8.05 km	Air burst
Buster (1951)	Baker	3.5	1118	0.3408	Day-adapted, in a/c at 4.57 km from burst for all 3 shots	Air burst
	Charlie	14	1132	0.3450		Air burst
	Dog	21	1417	0.4319		Air burst
Tumbler (1952)	3	30	3447	1.0506	Dark-adapted, in light-tight trailer at 16.1 km from two shots, probably Tumbler 3 and 4	Air burst
	4	18.5	1040	0.3170		Air burst
Snapper (1952)	3	15.5	300	0.0914		Surface-intersecting (S.I.) on tower
	4	13.9	300	0.0914		S.I. on tower
Upshot-Knothole (1953)	Annie	17.1	300	0.0914	Dark-adapted, in trailer at 12.07 km	S.I. on tower
	Nancy	24	300	0.0914	Dark-adapted, in trailer at 17.7 km	S.I. on tower
	Badger	25	300	0.0914	Dark-adapted, in trailer at 22.53 km	S.I. on tower
	Simon	45	300	0.0914	Dark-adapted, in trailer at 12.874 km	S.I. on tower
	Harry	32	300	0.0914	Dark-adapted, in trailer at 11.265 km	S.I. on tower
Plumbbob (1957)	Wilson	10.3	500	0.1524	Dark-adapted, trailer at 13.84 km, a/c at 17.7 km	Balloon-supported device surrounded by 4 in. of sand, lead and paraffin shield below
	Hood	71	1500	0.4572	Dark-adapted in a/c at 29.65 km	Balloon-supported device, lead and paraffin shield below
	Diablo	17	500	0.1524	Dark-adapted in trailer at 19.4 km	176,000-lb lead and paraffin shield below on tower, S.I.
Hardtack II (1958)	Hamilton	0.00117	50	0.0152	Day-adapted in open at 1.7 km, facing away from burst	Device on wooden tower
Sun Beam (1962)	Small c	low	surface----------		Day-adapted, wearing visor in a/c at 2.96 km	Surface burst

are given in the same system here to permit easier comparison of calculated and test results. The significance of burst environment and device characteristics will be considered in the Summary of nuclear burst effects, Section 3.5.

Most discussions of nuclear test flash-blindness effects consider average results for all observers for all shots. However, the shots varied in yield and burst altitude, parameters that affect thermal exposure and energy delivery rate. Furthermore, in some cases, test device characteristics were of significance in affecting thermal radiation, and the variation of individual reactions is unpredictable. Therefore, effects for each shot are given separately, where available, and individual variations will be noted, where available, as for Operation UPSHOT-KNOTHOLE. Discussion of the results follows, considering each Operation in chronological order.

Hiroshima-Nagasaki. Information on flash-blindness effects at these bursts is almost impossible to obtain or verify. Reference 9 states that "The Ophthalmological Survey Group which studied the Hiroshima-Nagasaki casualties investigated the impairment of visual acuity following the two detonations. No case of flash-blindness lasting for more than about 5 min. was reported among the survivors."

Ranger. The men in planes (without protective goggles) who did not look at the burst had no difficulty in reading instruments at 8 km from Shot F, a 22-kt air burst. Two conditions were responsible for these results: (1) not looking at the burst; (2) diffusion of the glare by the aircraft windows.

Buster. Reference 3 reports that the flash from Shot Baker (3.5 kt) was so slight that no visual impairment was experienced by any observers, and that data obtained from Shot Dog are considered invalid. The following data, obtained at about 14.5 km from Shot Charlie, a daytime 14-kt air burst, are considered valid:

a) Subjects protected with photoelectrically energized goggles experienced no loss of vision following direct observation of the burst;

b) Unprotected subjects experienced temporarily impaired vision ranging from 20/400 to 20/30 immediately after the flash, with recovery within 2 min.;

c) Test subjects facing 180 degrees away from the burst experienced no visual impairment;

d) Protective filters (rose-smoke or red goggles) did not significantly alter the amount of visual impairment experienced by the unprotected subjects. No information is given on:

- The attenuation factor (if any) of the windows through which the subjects observed the shots;
- closure time of the photoelectrically energized goggles;
- transmission properties of the protective filters.

Tumbler-Snapper. Subjects who observed two daytime bursts had dark-adapted eyes and were in a light-tight trailer located about 16.1 km from both bursts. Half the observers (total number unstated) were unprotected, and half wore protective red goggles that were estimated to transmit about 22% of the energy in the visible and infrared spectrum. All observers viewed through portholes that opened between 46 and 52 msec after flash, and closed after 2 sec. The tests were discontinued because of two retinal injuries.

Reference 6 does not identify retinal injury with shot, but does state that none of the individuals wearing goggles was injured. In addition, the tabulated data is not identified by shot, blink times are unknown, and tabulated results disagree with results stated in the text. According to Dr. Heinrich Rose,* published results, particularly on times, are seriously in error due to uncorrected typographical errors in the draft manuscript. Therefore, only general conclusions can be considered reliable, such as the finding that observers wearing red goggles recovered the use of their eyes more rapidly than those who were unprotected.

It should be noted that if the shots observed were Tumbler 3 and 4, both were air bursts; if they were Snapper 3 and 4, they were surface-intersecting bursts (the fireball intersected the surface) on towers.

Upshot-Knothole. A total of 19 dark-adapted subjects in a light-tight trailer were exposed to flashes from five pre-dawn surface-intersecting nuclear

* Personal communication from Dr. Rose, who was at U.S. School of Air Force Medicine at the time of the tests, is now Prof. of Ophthalmology at Stanford University.

bursts fired on 300-ft towers. The subjects viewed the shots with only the left eye, through a port fitted with a shutter and protective filter that screened out all wavelengths except those between 6000 and 9000 Å. Thus, only 20-25% of the light incident on the shutter was incident on the cornea. The shutter opened at 11 msec before zero time, remained open for 1 sec, then closed automatically. Blink times are not known. After each shot, seven or eight men were tested for recovery of ability to read red-flood-lighted and internally red-lighted instruments, and the other four were tested on the nyktometer and adaptometer for recovery time of mesopic and scotopic vision. Table 3.2 shows the maximum and minimum recovery times for three of the tests administered, for the shots in order of increasing yield. Note that the yield of Shot Simon was over 2½ times that of Shot Annie, and that Shots Nancy and Badger were of almost the same yield. Table 3.3 shows the individual variations in recovery time of three subjects who were tested for recovery of ability to read red flood-lighted and internally red-lighted instruments after all five shots. Note the lack of any similar trend in recovery times for these three men.

The data in the two tables illustrate the wide variation in recovery times, and the fact that the average value may be about half that required for some individuals. Since knowledge of the individual eye characteristics is unknown, and the population of data is so small, statistical use of the data is unwise. For safe prediction purposes, maximum (rather than average) values would be more significant.

Plumbbob. Dark-adapted subjects viewed the flashes of three nuclear bursts from a trailer and an aircraft. Some subjects viewed through an electromechanical shutter that transmitted approximately 20% of the total incident light. The shutter acted as a neutral density filter, utilizing two movable glass plates inscribed with a series of alternately opaque and transparent lines, and had a normal closure time of 0.55 msec. Other subjects were stationed behind sandblasted diffusing windows, and one viewed through a narrow-band filter with about 20% transmission.

Shot Wilson: Four subjects in the light-tight trailer at a distance of 13.84 km and four in the aircraft at 17.7 km distance viewed through the

Table 3.2

Maximum and Minimum Recovery Times From Flash-Blindness at Operation UPSHOT-KNOTHOLE

Shot and Distance	No. Men	Instruments (sec)	No. Men	Mesopic* Vis.acuity 0.5 (sec)	No. Men	Scotopic** Vis. acuity 0.01 (min)
Annie (17 kt) 12 km	8	12 - 25 avg: 19.9	3	158 - 420 avg: 248	4	3:00 - 4:15 avg: 3.38
Nancy (24 kt) 17.1 km	8	8 - 40 avg: 21.5	3	56 - 260 avg: 138	3	1:10 - 4:22 avg: 2:51
Badger (25 kt) 22.5 km	8	5 - 25 avg: 15.1	3	65 - 89 avg: 80	3	0:50 - 3:00 avg: 1:52
Harry (32 kt) 11.3 km	8	5.3 - 30 avg: 16.4	---		---	
Simon (45 kt) 12.9 km	8	6 - 27 avg: 16.7	8	47 - 225	4	1:30 - 3:50 avg: 2:13

* Mesopic vision uses both rods and cones. In each case, one of the subjects did not reach the 0.5 acuity level.

** Scotopic vision is that using rods alone. These tests were for a luminance of 0.001 candle/m^2, that of a moonless night sky. Where only 3 subjects are indicated, one did not reach the 0.01 acuity level.

Table 3.3

Times Required by Three Subjects to Recover Ability to Read Red Flood-Lighted and Internally Red-Lighted Instruments

Subject	Shot Annie (sec)	Shot Nancy (sec)	Shot Badger (sec)	Shot Harry (sec)	Shot Simon (sec)
W.K.	20	40	15	8	10
R.S.	17	21	16	23	27
R.B.	25	15	19	14	12

shutters the first 0.55 msec of the flash of the 10.3-kt burst. No measureable recovery time was observable.

Shot Hood: All six subjects were in the aircraft at a distance of 29.6 km from the 71-kt burst. One subject viewed through a shutter that closed at 0.55 msec, and no recovery time was noted. Of the three subjects who viewed through shutters that remained open, one recovered 0.1 visual acuity in 72 sec and 0.3 visual acuity in 90 sec; the other two required 10 and 12 sec to read standard red-lighted aircraft instruments. Two subjects who viewed the flash from behind a sandblasted aircraft window required 90 sec to recover 0.1 visual acuity.

Shot Diablo: Six subjects were in a trailer at 19.4 km from the 17-kt burst. For three subjects who viewed the flash through shutters (two of which closed at 0.55 msec, and one at 0.9 msec), recovery was instantaneous. In addition, no measurable recovery time was noted for the subject who viewed through the narrow-band filter. One subject who viewed through an open shutter behind a sandblasted diffusing window required 6 sec to read standard red-lighted aircraft instruments. One subject behind a sandblasted diffusing window required 20 sec to regain 0.1, 28 sec for 0.3, and 35 sec for 0.5 visual acuity.

Test results provided the following conclusions:

1) The shutters operated effectively and provided flash and burn protection of the eyes at the distances and for the yields tested;

2) Recovery time was shorter when the flash was viewed directly, but the possiblity of permanent damage exists under those conditions;

3) When the flash was viewed through a secondary source (sandblasted window to simulate a cloud), the possibility of permanent damage is almost non-existent, but glare-effect was great, and recovery time could be of critically long duration (depending on the observer's tasks). Neither blink times nor individual eye characteristics were noted.

Hardtack II: At Shot Hamilton (a fractional-kiloton burst), 25 Army and Marine officers were stationed in the open in three groups located 5700 ft

from ground zero. They were oriented at 90, 135, and 180 degrees from the line of sight of the daylight shot on a 50-ft wooden tower. Immediately after the shot, all personnel (who were completely light-adapted and unprotected by goggles) demonstrated normal visual acuity, and no subject reported experiencing dazzle.

It was concluded that dazzle is either non-existent or transitory in nature when the individual is light-adapted, and that the return of photopic vision is rapid when adequate illumination is provided for performance of visual tasks.

Sun Beam: At Shot Small Boy, a rear-seat observer in the cockpit of a F100-F was outfitted with a 1% transmission gold-coated neutral density visor. The aircraft was at 2.96 km distance when, with one eye covered, this subject observed the flash of the daytime burst of a small weapon, and experienced no period of flash-blindness.

3.4 RETINAL BURN NUCLEAR BURST EFFECTS

Table 3.4 lists Operation, Shot, Yield, Height of Burst, Observer distance and environment, and special burst environment characteristics that may have been contributing factors in causing retinal burns in observers. The significance of such factors will be discussed in the summary of Section 3.5. Yields, burst altitudes, and burst characteristics are taken from Refs. 12 and 13. Other data are from the references noted in Section 3.2. Discussion of the cases in chronological order follows:

Hiroshima-Nagasaki: Surveys[15,16] of effects after Shots Hiroshima (about 20 kt at 1850 ft) and Nagasaki (about 20 kt at 1650-1850 ft) in 1945 state that the only instance of retinal burn to have been reported is that noted by Oyama and Sasaki. A 23-yr old girl at 2 km from the hypocenter at Hiroshima was searching the sky, looking for the plane at the time of the flash. She developed symmetrical opacification of both corneas, and permanent central scotomata of both eyes.

Reference 15 states that the faces of many survivors were severely burned, accompanied by loss of skin, and often of the eyebrows and lashes. Yet none

Table 3.4

Nuclear Bursts at Which Retinal Burns Occurred

Operation	Shot	Yield (kt)	HOB Above Surface (ft)	(km)	State of Observer and Distance From Burst	Notes
War II (1945)	Hiroshima	20	1850	0.564	Day-adapted, at surface, about 2.1 km from burst	Air burst, daytime
Ranger (1951)	Fox	22	1435	0.4374	Day-adapted, at 8.05 km in a/c	Air burst, daytime
Tumbler (1952)	3	30	3447	1.0506	Dark-adapted in light-tight trailer, at 16.1 km from two bursts. Tumbler 4 probably caused burn.	Air burst
	4	18.5	1040	0.3170		Air burst
Snapper (1952)	3	15.5	300	0.09144		S.I. on tower
	4	13.9	300	0.09144		S.I. on tower
Upshot-Knothole (1953)	Simon	45	300	0.09144	(1) in trench, unprotected eye at less than 3.2 km. (2) in open, unprotected eyes at 11.26 or 16.1 km	S.I. pre-dawn tower burst
	Harry	32	300	0.09144	In light-tight trailer at 11.26 km, dark adapted, viewing through 20% transmission filter	S.I. pre-dawn tower burst. Darkly-pigmented fundus, longer-than-normal blink time.
Dominic (1962)	Blue Gill	sub-megaton	high altitude	tens of km	Men on Johnston Is., about 60.0 km from Shot Blue-Gill, goggles not worn	High-air night burst with very short pulse and high energy delivery rate.
	Calamity	intermediate	air drop		Conditions not known	Low-air morning burst

examined had permanent corneal opacities attributable to ultraviolet or infrared radiation. It is postulated that this effect may, in part, be due to the facial characteristics of the Japanese, i.e., narrow eye openings and protective overhang of the upper lid. Many people interviewed stated they were looking at the sky, some at the plane, some at the parachute. However, no lesions of the fundus were observed, and only one patient other than the first one mentioned lost vision in an eye. The second case, it was believed, suffered a vitreous hemorrhage. Some Japanese survivors developed cataracts with time; these are thought to be the result of ionizing radiation.

Ranger. In 1951, a 35-yr-old pilot, with his left eye covered, looked directly at Shot F through the window of an aircraft that was 8 km from burst. Viewing the 22-kt flash produced blindness in the exposed eye for about 15 sec, then after 20-25 sec, he was able to hazily see the flight instruments. The hazy condition lasted for 8-10 min. Examination seven months later showed no retinal lesion, but a paracentral scotoma was present in the upper temporal quadrant of his right eye.

Tumbler-Snapper: According to Ref. 5 (published in 1953, a year after the tests), two dark-adapted subjects, wearing no protective goggles, "developed blanched areas of the retina following exposure to the flash. Only one of these men showed an impairment of vision and complained of a scotoma. This man showed a small area of retinal edema with a central blanched area ..... Examination of the retina (of the second man) revealed a small area of retinal edema. Both men were observed until they were completely recovered. Neither has any visual impairment, visual defect, or change in the fundus of the eye." However, Ref. 5 does not identify the shot. Reference 7 describes the nearly round absolute scotoma (about 0.15 mm in diam.) in the left eye of a subject who viewed the burst stated to occur on 1 May 1952, and includes a photo of the healed lesion taken 1½ yr after exposure. Reference 4 describes a retinal burn experienced by a 27-yr old pilot (Case 3) that appears to be the same injury. It is thus probable that a retinal burn was suffered by one dark-adapted subject whose left eye viewed the fireball of an 18.5-kt air burst. He wore no protective goggles, and was in a light-tight trailer,

viewing through a shutter that opened between 46 and 52 msec after the beginning of the flash, and closed after 2 sec. How long the subject viewed the fireball is unknown, since blink times were not measured, nor are eye characteristics mentioned. No further information is available on the other subject.

Upshot-Knothole: Three individuals experienced retinal burns during Operation UPSHOT-KNOTHOLE in 1953.

Case A. A 22-yr old officer (S.H.) in a trench about 3.2 km from Shot Simon, a 45-kt pre-dawn burst on a 300-ft tower, against orders looked at the flash with his left eye, keeping the right eye covered. Visual acuity in the exposed eye dropped immediately to 0.1. The central retinal lesion was clearly defined at examination six weeks later to be about 1.5 mm in diameter, when visual acuity in the exposed eye had improved slightly. References 7 and 4, which describe the injury, give results no later than six weeks after the accident. It is estimated that this accident is the second case listed in Table 2.3 of Ref. 17 (issued 12 years later), which states that acuity of the left eye ultimately reached a level of 0.4.

Case B. References 4 and 7 both describe the injury to an airman who viewed the flash of Shot Simon. According to Ref. 4, he was 19 years old, wore no eye protection, and was 10 miles from the burst. According to Ref. 7, he was preparing to photograph the bomb at a 7-mile distance, and had just sighted the target when the flash occurred. Both reports agree that he noted no symptoms, and the injury was not discovered until one[7] or two[4] months later when a routine physical examination revealed identical bilateral symmetrically placed small lesions. Reference 4 states that 18 months later there was no change in ophthalmic appearance, visual fields, or visual acuity, which was 20/25 in each eye, whereas Ref. 7 gives the acuities as O.D.:20/20; O.S.;20/25. Case 5 of Table 2.3, Ref. 17 is estimated to be the same injury. The burn size is given there and in Ref. 4 as 1.5 mm in diameter, the same size as that for Case A. It is postulated (on the basis of comparison with Case A) that considering visual acuity,

lack of subjective symptoms, and burn location, the stated burn size is large by a factor of 10. Blink time and eye characteristics are unknown.

Case C. References 4 and 7 both describe the retinal injury to a 20-yr old officer (M.C.B.) in a light-tight trailer, at 11.26 km from ground zero, who observed the flash of Shot Harry (32 kt on a 300-ft tower). He was dark-adapted, and only his left eye viewed the shot through special filters designed to transmit 20 to 25% of incident light. He made an effort to keep his eye open, and may not have blinked for one second, the time at which the shutter closed. His fundus was darkly pigmented. A peripheral scotoma was found immediately after the tests, and examination revealed an elliptical lesion about 0.25 mm in diameter. At three months after exposure a positive scotoma was still present, but the edema had disappeared.

Dominic: Two cases of retinal burn that occurred during Operation DOMINIC are described in Ref. 10 which quotes Ref. 18, and in Ref. 17.

Case A. J.W.S., SSgt USAF, was walking on Johnston Is. with his protective lenses adjusted upward when detonation of Shot Blue Gill, a high-altitude burst occurred in Oct. 1962. To quote Ref. 10, "As he was reaching to adjust his glasses, he experienced a bright flash of white light and fell to his knees protecting his eyes. He observed the latter part of the fireball (about 60.6 km away) with, and then without, his lenses, and about a minute later looked at a distant light and noticed it to be blurred. He also noted a dark spot in front of each eye. There were no colored after-images."

He reported to sick call and was transferred that day to Tripler General Hospital with a diagnosis of bilateral macular burns. A report from Tripler[19] states that initial visual acuity through the central scotoma was 20/400 in both eyes, and was 20/100 in both eyes when using a fixation point off center. "The entire macular area was involved. Visual fields revealed an absolute dense central scotoma which was measured at two meters and which had a tail extending upward, up to the 5 degree isopter. Subsequently the

visual acuity has progressively increased and, at the present time (9 November 1962) vision in the right eye is 20/30-2, vision left eye 20/40+1."

In December 1962 the patient was transferred to SAM, Brooks AFB, and his vision continued to improve with time as he increased his ability to see around the defect. By January 16, 1963, the date of Ref. 18, his eccentric visual acuity had improved to 20/25 (both eyes) for distance and 20/20 (both eyes) for near. According to Ref. 17, the lesions initially were approximately 0.35 mm in diameter, located in the fovea, and at six months, absolute central slightly elliptical scotoma measured approximately 1 degree (0.3 mm) bilaterally. All other measurements were within normal limits.

Case B. R.T., A03, USN, also viewed Shot Blue Gill from Johnston Is. According to Ref. 10 quoting Ref. 18, "His goggles were in ready position on his forehead. He states he was looking straight ahead when the nuclear detonation occurred. He then looked up and down rapidly and recalls seeing only a massive white light. He had an immediate after-image of a large, round, white ball. This lasted about one hour, after which he went to sleep. When he awoke it was dark and he noticed the glow of an afterimage that was larger than before. On the next day, he viewed Shot Calamity, a low-altitude nuclear detonation (at about 300 km slant range) and visualized for the first time the black central scotoma that was the same size as the white afterimage which he had seen after the first detonation." He reported to sick call after that, and he was also transferred to Tripler Hospital with diagnosis of bimacular lateral burns, that same day.

According to Ref. 19, "This patient appeared to have a large central area which was almost pure white in color, surrounded by a narrow rim of pale area and a surrounding ring of abnormal retina. In the middle of the white central area, a small speck of black pigment was noted. Visual acuity on this patient was less than 20/400 looking through his central scotoma, and 20/60 when looking

off center from the central scotoma (on the day of his arrival). Visual fields revealed a dense bilateral central scotoma with a small area of functional scotoma, all of which lay within the 5 degree isopter measured at two meters." On 9 November 1962, vision was 20/50-1 in the right eye and 20/80+1 in the left eye.

Reference 10, again quoting Ref. 18, stated that at Tripler, this patient's best visual acuity looking off-center from the central scotoma was 20/60 to 20/70, and there was no objective improvement up to January 16, 1963, while he was under observation at the School of Aerospace Medicine. The bilateral central scotoma are round in contour, and according to Ref. 17, the lesions were initially about 0.5 mm in diameter; at 6 months, the central scotoma had increased slightly in size due to degenerative changes surrounding the central lesion.

In the final section of Ref. 10, the author concludes that despite the subjects' descriptions of their conditions and behavior at the time of nuclear burst, they were actually looking directly at the detonation. "It now appears that R.T. did more directly view the event, and his vision has not improved and that of J.W.S. has greatly improved."

3.5 SUMMARY OF NUCLEAR BURST EFFECTS ON HUMAN EYES

3.5.1 Flash-Blindness.

Unprotected, dark-adapted: The only data available on flash-blindness effects on the dark-adapted unprotected human eye are from Operation TUMBLER-SNAPPER. Those results indicate that viewing from 16 km the fireballs of 30-kt or 18.5-kt low-air bursts for an interval between 46 and 52 sec until blink will require considerable recovery periods and is likely to produce a minimal retinal burn.

Unprotected, day-adapted: Results at several tests indicate that light-adapted subjects oriented away from line-of-sight of the bursts experienced no visual impairment. Those subjects in aircraft who viewed a 14-kt

low-air burst from a distance of about 14.5 km experienced temporarily impaired vision with recovery in 2 min. Other recovery times have been noted as within 5 min.

Protected, day-adapted: It was found that wearing rose-smoke or red goggles did not significantly reduce the 2-min. time required to recover visual acuity after viewing from an aircraft the 14.5-kt burst at a distance of 14.5 km.

An observer in an aircraft viewed through a 1% transmission gold-coated neutral density filter a small yield surface burst from a distance of 2.96 km. He experienced no period of flash-blindness.

Protected, dark-adapted: Experimental data indicate that a 3-min recovery time may be required for scotopic visual acuity of 0.01, for luminance of 0.001 candle/m^2 (moonless night sky) after viewing through protective filters a 25-kt surface-intersecting burst from a distance of 22.5 km. The filters in this case transmitted about 20 to 25% of incident light, and screened out all wavelengths except those between 6000 and 9000 Å. A maximum of 30 sec was required for observers of the same burst, same viewing conditions, to read red flood-lighted and internally red-lighted aircraft instruments. This 25-kt burst is selected as the example due to device characteristics more similar to a weapon than other shots of the same test series. Note, however, that all tower shots produce somewhat different thermal effects than are produced by the air burst of a weapon.

No observable recovery time was required after bursts of 10.3, 17, and 71 kt were viewed for only the first 0.55 msec after flash through a shutter that transmitted approximately 20% of the total incident light. Distances from these bursts were: 13.84 km in a trailer on the ground and 17.7 km in an aircraft from the 10.3-kt balloon-supported burst; 29.6 km in an aircraft from the 71-kt balloon-supported burst; 19.4 km in a trailer on the surface from the 17-kt tower burst. Two subjects who viewed the 71-kt burst through through the shutters until they blinked required 10 to 12 sec to recover ability to read standard red-lighted aircraft instruments, and a third required 90 sec to regain 0.3 visual acuity. Recovery to 0.3 acuity may require up to 28 sec after viewing a burst through a cloud.

It should be noted that due to device characteristics and burst environmental conditions, effects from all three of these bursts are probably atypical of weapon bursts. For instance, it is expected that the burst environment for the Wilson Device (10.3 kt) caused somewhat of an increase in both the peak thermal irradiance and thermal radiation measured at the surface, compared with that from a weapon of the same yield. The combination of device characteristics and shielding below the Diablo device (17 kt) is believed to have considerably reduced the peak thermal irradiance and thermal radiation at the surface, compared to that expected from an unshielded weapon of the same yield. It is estimated that thermal effects from the Hood device (71 kt) as seen at the aircraft may have been similar to those from a weapon of the same yield. Since aircraft altitude is unknown, no comparison of measured and calculated values can be made. It is suggested that results of these tests be considered with respect to measured output, rather than yield.

3.5.2 Retinal Burn.

A minimal burn is believed to have occurred to an unprotected dark-adapted eye viewing the flash and growth of a fireball (until blink) at a distance assumed as the 16 km maximum reported from a 45-kt surface-intersecting burst. The characteristics of this experimental device may have produced thermal radiation different from that expected from this shot. A minimal burn is also believed to have resulted when an unprotected dark-adapted eye viewed from a distance of 16 km an 18.5-kt low-air burst for a period starting between 46 and 52 msec after the flash, and lasting until blink. This experimental device may have produced thermal effects that were not anticipated at that time. A "protected" eye suffered a slightly larger burn (0.25 mm) when it viewed from 11.26 km a 32-kt surface-intersecting burst, for a period estimated longer than 100 msec. Furthermore, this was a darkly pigmented eye, a condition that increases sensitivity to retinal injury.

A severe burn occurred from viewing a 45-kt surface-intersecting burst from a distance of 3.2 km, and a severe burn was caused by viewing a high-altitude burst, one at a height above its singular altitude. Under such conditions, the thermal pulse form is quite different from that of a low-altitude burst, and energy delivery rate is extremely fast.

3.6 REQUIREMENTS OF ANALYSIS

Numerous methods exist for calculating distances at which flash-blindness or retinal burn will or will not occur.

Comprehensive summaries of reports on research in flashblindness may be found in Refs. 2 and 20. A few additional experiments are mentioned here. One study in 1959 showed that a dark-adapted pupil made to constrict by exposure to a flash of light would return to its original size within 1 min.[21] The following studies are representative of those carried out in the past few years:

1) Investigation of recovery times following flashes from a Xenon-filled discharge tube, for exposures varying from 0.04 to 1.4 msec, with a maximum flash energy of 0.012 cal/cm^2 at the retina;[22]

2) Study of recovery times required by naval aviators for various degrees of panel illumination, after exposures to flashes from a Xenon tube;[23]

3) A series of experiments using pilots in aircraft flight simulators for various models of aircraft, to determine loss of aircraft control during flashblindness (Refs. 24, 25, 26, 27). It was concluded in Ref. 27 that there appeared to be little relationship between loss of control in the flight simulator and aircraft.

4) Many laboratory-produced flashes are of extremely short duration, such as those of 150-165 μsec studied in Ref. 28. Exposure to such flashes cannot be representative of exposures to nuclear bursts, nor are the spectral ranges necessarily similar.

5) Reference 29, which details experimental findings on spectral absorption of the retina and choroid, concludes that it is useless to average absorption data on eyes because of individual eye differences due to color and age. For instance, eyes with light-colored irides show least absorption; Negro eyes show absorption greater than 92% at all wavelengths from 340 to 1700 millimicrons, and virtually 100% absorption up to 700 millimicrons.

6) Reference 30 also reports on wide individual variations in recovery times after exposure to flashes.

Numerous studies of retinal burn carried out are summarized in Ref. 2. Various models have been derived for calculating the conditions that will produce retinal burn. Reference 31 presents a recently developed computer program, and Ref. 32 provides additional theoretical findings and discusses a method for computing retinal irradiance. To quote Ref. 32, "There is, then, no single value of radiant exposure that can be named as a threshold."

It becomes obvious that to understand and utilize the nuclear burst data on retinal burns or flashblindness, it is necessary to know the values of the following parameters at blink time: radiant exposure on the cornea, fireball size, image size, image concentration, and peak energy delivery rate. It is estimated that appropriate combination of these parameters will provide criteria for preventing retinal burn from nuclear bursts. The analytical expressions derived in order to calculate values of the above parameters and their expected accuracies are presented in Section 4.

Section 4

ANALYTICAL EXPRESSIONS REQUIRED FOR CALCULATION OF RETINAL BURN CRITERIA

4.1 SELECTION OF CRITERIA

The three parameters selected for evaluation to determine criteria are: 1) minimal image size, 2) maximum energy concentration allowable in the retinal image, 3) maximum peak energy delivery rate allowable.

A minimal image size implies that the image area, I_A, is so small that the surrounding tissue can conduct away energy sufficiently rapidly to prevent the central area from reaching a critical temperature. Image area can be expressed

$$I_A = \pi (R_I)^2 \text{ mm}^2$$

where R_I = Image Radius

$$R_I = \frac{R_{fb}(t^*)\ f}{D} \qquad \text{(A)}$$

and R_{fb} = Radius of fireball at blink time, t^*

$$t^* = \frac{\text{time}}{t_f}$$

t_f = time of final thermal maximum

f = focal length of eye

Energy concentration in the image, IC, can be expressed as follows:

$$IC = \frac{Q\ F(t^*)\ \pi (r_p)^2}{I_A} \text{ cal/mm}^2 \qquad \text{(B)}$$

where Q = radiant exposure incident on the cornea up to $10t_f$

$F(t^*)$ = fraction of radiant exposure delivered before the blink time, t^*

r_p = pupil radius

The thermal pulse of a nuclear burst below its singular altitude will have two major energy maxima. Thermal energy rises very rapidly to the first peak, p_1^* at time t_1, then decreases rapidly to a minimum at time t_m, then rises more slowly to the final maximum, p_f at time t_f, and then decreases to a very low level by time $10t_f$. Thus, rate of energy delivery, p, is a function of yield, time, and burst altitude, and can be expressed at the fireball

$$p(t^*) = f(W,t^*,H)\ 10^{12} \text{ cal/sec}$$

where H = burst altitude in km.

Energy rate of delivery at a target can be expressed

$$p(t^*) = \frac{f(W,t^*,H)\ 10^{12} T \text{ cal/cm}^2\text{/sec}}{4\pi D^2}$$

where D = slant range from fireball to target in cm.

T = transmission of radiant energy through the atmosphere for distance D.

From inspection of the above expressions needed for criteria evaluation, it is apparent that analytical equations are required for the following functions:

(1) Fireball radius as a function of time;
(2) Time to final thermal maximum;
(3) Radiant exposure incident on a target up to $10t_f$;
(4) The fraction of thermal energy delivered to a target, as a function of time;
(5) Rate of energy delivery to a target as a function of time.

The required equations and their derivations follow.

4.2 REQUIRED ANALYTICAL EQUATIONS

4.2.1 Fireball Radius as a Function of Time.

Equations (1) and (2) were derived for calculating fireball radius as a function of time, using data in Ref. 33 for Shots Encore, Gun, and Climax (Operation UPSHOT-KNOTHOLE), Shots Wasp, Moth, Bee, and Wasp Prime

(Operation TEAPOT), Shot Cherokee (Operation REDWING), and Shot Yucca (Operation HARDTACK). In addition, data for Shot Tight Rope was obtained in Refs. 34 and 35, and values at early times (as available in Refs. 36, 37, 38, 39, and 40) for Shots Nambe, Encino, Tanana, Alma and Bighorn were used. The equations were also checked against some late time data in Ref. 41 for Shots Nambe, Yeso, Housatonic, and Harlem, of Operation DOMINIC.

$$R_{fb} = 0.07\ W^{1/3} t^{*.3}\ \rho_b^{-.08}\ \text{km}\quad (t^* \leq 1) \tag{1}$$

$$R_{fb} = 0.07\ W^{1/3} t^{*.16}\ \rho_b^{-.08}\ \text{km}\quad (1 \leq t^* \leq 2.5 \tag{2}$$

where $t^* = \dfrac{t}{t_f}$,

ρ_b = burst height air density (g/liter)

Fireball radii were calculated using equations (1) and (2), with the time for t_f used to calculate t* taken from Ref. 42. Values calculated using this expression for t_f are, in general, within ± 20% of measured times of final maximum for yields greater than 1 kt.

Time for Final Thermal Maximum

$$t_f = 42\ (\rho_b W)^{0.44}\ (\rho_s/\rho_b)^{-\rho_s/\rho_b}\ \text{msec} \tag{3}$$

where ρ_b = burst height air density in g/liter

ρ_s = the "singular" air density such that the double pulse is not produced at burst height air density less than ρ_s

$\rho_s = 0.033\ W^{-\frac{1}{2}}$ g/liter

Calculated fireball radii are within ± 25% of the data for the shots mentioned above. Therefore these equations are considered accurate within ± 25% for yields from 1 kt to about 5000 kt at burst altitudes up to 26 km. It is estimated that, particularly at early times, the use of an appropriate function of mass-to-yield ratio would increase the accuracy of the calculations.

4.2.2 Radiant Exposure.

For distances at which the image radius is very small, it is reasonable to calculate the total radiant exposure as that from a point source. Therefore, the methodology of Ref. 43, a semi-empirical analysis of radiant exposures from air and surface bursts was used for calculating total exposures. This methodology, in general, calculates answers within ± 50% of measured exposures for air and surface bursts. The following concepts and equations (with all distances in km) are used:

A.
$$Q = \frac{100\ W\ I_o\ T_A\ T_H}{4\pi\ D^2} \quad cal/cm^2 \qquad (4)$$

represents the effective radiant exposure or thermal energy emitted up to 10 t_f (ten times the time of final maximum for bursts below singular altitude). The thermal energy emitted after 10 t_f is of very low power level and is emitted very slowly; thus is of little significance with respect to injuries. It is assumed that a nuclear fireball is an isotopic emitter of radiation for both air and surface bursts.

W = yield in kt

I_o = the fraction of total burst energy emitted as thermal radiation up to 10 t_f

T_A = transmission of thermal radiation through the air

T_H = transmission of thermal radiation through oceanic haze

D = slant range from fireball to target.

B. The minimum altitude (HOB) at which the fireball will not touch the surface, and therefore is considered a nuclear air burst is

$$HOB \geq 0.05\ W^{.4}\ km$$

C. The value of I_o is as follows:

a. For an air burst

$$I_o = \frac{1}{1 + W^{0.125}}$$

b. For a surface burst

$$I_o = \frac{1}{2.5 + W^{0.125}}$$

D. The transmission of thermal radiation through air is given by:

$$T_A = e^{-\alpha (\bar{\rho}_s D)^{\beta}}$$

where α = initial, spectral-attenuation coefficient of thermal radiation through air near the source

$\alpha = 0.32\ W^{-0.25}$

$\bar{\rho}_s$ = average relative air density

$\bar{\rho}_s = \bar{\rho}_a / \rho_{std}$, where $\rho_{std} = 1.2923$ g/liter

$\bar{\rho}_a$ = average air density between source (ρ_b) and receiver (ρ_r)

$$\bar{\rho}_a = \frac{\rho_b - \rho_r}{\ln(\rho_b / \rho_r)} \text{ in g/liter}$$

D = slant range from source to target

β = slant range absorption-modification factor, which approximates the shift toward the red in spectral content, and thus represents an adjustment for the predominant fireball emission wavelength as a function of yield.

$$\beta = \frac{1}{1 + W^{-0.11}}$$

E. The transmission of thermal radiation through oceanic haze is given by:

$$T_H = e^{-0.07(D/H)(V_o/V)}$$

where H = airborne target height for a surface burst or air-burst height (in km) for a surface target.

D = slant range

V = actual visibility (in km or mile, as V_o is given)

V_o = the "average" oceanic surface visibility, 10 miles or 16 km.

For air-burst and airborne target heights less than 1.2 km (defined as unit haze thickness) the constant value 1.2 km must be used for H. For all bursts above the oceanic haze, the transmission factor for haze only is

$$T_H = e^{0.07(R/H)} \quad H \geq 1.2 \text{ km}$$

F. From the values of I_o given in (C), above, it is estimated that for surface-intersecting bursts,

$$o = \frac{1}{\left[2.5 - \frac{1.5\,H}{0.05W^{0.4}}\right] + W^{0.125}}$$

where H = height of burst in km.

Use of Eq. (4) will provide the value of total radiant exposure incident on the cornea of an eye at time 10 t_f. Thus, the time of t_f and time of blink are significant parameters of retinal exposure if eyes remain closed after blinking, since after the eyelids are closed, less than 1% of the incident energy is transmitted through them.

Blink reflex times may vary from 60 to 150 msec or more, depending on individuals and environment. The time of 100 msec, which has been observed as the average will be used in this report. For yields of 1 kt or more and for burst altitudes not greater than 20 km ($\rho_b \geq 0.09$ g/liter) the conditions assumed for investigation, a blink time of 100 msec is always less than 10 t_f. Therefore, an expression is required for the fraction of the total thermal energy delivered at any time, up to 10 t_f.

4.2.3 Rate of Thermal Energy Delivery With Time.

An analysis of power vs. time plots from Ref. 44 for Shots Encore, Gun, and Climax of Operation UPSHOT-KNOTHOLE, Shots Wasp and Wasp Prime of Operation TEAPOT, and Shot Cherokee of Operation REDWING provided the required equations for low-altitude bursts. These shots vary in yield from 1.2 kt to several megatons, and all were at burst altitudes below 2 km. The expressions derived, which agree with the data of Ref. 44 within $\pm$ 15% (with 2 exceptions) are:

$$p_1(t^*) = 9.1\ (I_o W)^{0.6118}\ t^{*1.508}\ 10^{12}\ \text{cal/sec}\ (0.2 \le t^* \le 0.5) \qquad (5)$$

$$p_2(t^*) = 5.7\ (I_o W)^{0.6118}\ e^{-1.203 \ln^2 t^*}\ 10^{12}\ \text{cal/sec}\ (.5 \le t \le 2) \qquad (6)$$

$$p_3(t^*) = 9.4\ (I_o W)^{0.6118}\ t^{*-1.555}\ 10^{12}\ \text{cal/sec}\ (2 \le t^* \le 10) \qquad (7)$$

where $t^* = \frac{t}{t_f}$

For any one yield, the pulse configuration changes with increasing burst altitude, and the total pulse duration decreases. There has been insufficient time to determine the availability of all data or to perform a rigorous analysis of the fraction of thermal energy emitted with time by higher-altitude bursts than those mentioned above. However, a few values of power vs. time or power at t_f that have been measured for Shots HA of Operation TEAPOT (Ref. 45), Shot Yucca of Operation HARDTACK I (Refs. 45, 46) and Shot Tightrope of Operation DOMINIC (Ref. 35) were readily available. These three shots are at varying altitudes from about 10 to 30 km. A comparison was made of values at t_f calculated using Eq. (6) with measured values, and it was found that after modifying Eq. (6) with a parameter that reflects the effect of altitude, $e^{.05H}$ (where H is the height of burst in km), calculated and measured results agree within $\pm$ 25% for the three higher-altitude bursts and remain within $\pm$ 15% for the low-altitude bursts. When the same modifying parameter was applied to $p_1(t^*)$ and $p_3(t^*)$, a comparison was made between calculated results and measured data for various values of t* for Shot Tightrope, the only burst for which such data are readily available. It was found that calculated values vary from 52% at t* = 0.2 to 93% at t* = 0.6, to 97% at t* = 1 of values measured by Naval Applied Science Laboratory (NASL). Note that at t* = 0.2, measurements by Air Force Cambridge Research Laboratories and Los Alamos Scientific Laboratory are approximately 55% and measurements by Edgerton, Germeshausen and Grier (EG&G) are almost twice those of NASL. At t* = 0.6, measurements by EG&G are over twice those of NASL, and at t_f, or t* = 1 (using t_f as in Ref. 42), all the measurements are approximately the same. Calculated values from t* = 2 to 10 are approximately twice those measured by NASL. Such variations are not considered

a good fit. However, in view of the data spread, and until further analyses are carried out, equations (8), (9) and (10) are the only available analytical expressions approximating rate of energy delivery with time. They are estimated reasonably accurate at all times up to 10 t* for bursts up to altitudes of about 5 km, and to be within ± 25% of peak energy rate at t_f, or t* = 1, for bursts up to about 25 km.

$$p_1(t^*) = 9.1\ (I_o W)^{0.6118} t^{*1.508}\ e^{.05H}\ 10^{12}\ \text{cal/sec} \qquad (8)$$

$$p_2(t^*) = 5.7(I_o W)^{0.6118} e^{-1.203 \ln^2 t^*}\ e^{.05H} 10^{12} \text{cal/sec} \qquad (9)$$

$$p_3(t^*) = 9.4(I_o W)^{0.6118} t^{*-1.555} e^{.05H} 10^{12}\ \text{cal/sec} \qquad (10)$$

4.2.4 Fraction of Total Thermal Energy as a Function of Time.

Thermal energy emitted up to 10 t_f can be expressed

$$E_{th}(10t_f) = E_{10t^*} = I_o W$$

and

$$E_{10t^*} = I_o WA \int_0^{10t^*} P\, dt^*$$

where $\int_0^{10t^*} P dt^* = \int_0^{10t^*} \left[p_1(t^*) + p_2(t^*) + p_3(t^*)\right] dt^*$

Therefore, $A \int_0^{10t^*} P dt^* = 1$

and $$A = 0.0689\ (I_o W)^{-.6118}$$

The fraction with time of the thermal energy emitted to 10t* is

$$f(t^*) = \frac{E_{10t^*}}{I_o W}$$

After evaluation of the integrals for p_1, p_2, and p_3, Equations (5), (6) and (7), and summing the values, results were plotted for values of t* from 0.2 to 10. The resulting curve for F(t*) shown in Fig. 4.1 was then fitted with the expression

$$F(t^*) = \frac{.253\ t^{*2.508}\left[9.01\ e^{-3.14t^*} - .6 - .016t^*\right]}{\left[.19t^{*2.508} - 9.01\ e^{-3.14t^*} - .6 - .016t^*\right]} \qquad (11)$$

The analytic expression for F(t*) fits the plotted values within $\pm$ 3%.

The modifying factor, $e^{.05H}$, in Eqs. (8), (9), and (10) merely increases the values of p_1, p_2 and p_3 for low-altitude bursts by a constant at any given altitude, and thus does not change the fractional relationship. Therefore, Eq. (11) is considered the best approximation available to calculate the fraction of energy with time for bursts at altitudes from 5 to 20 km, until a more rigorous analysis can be carried out.

4.2.5 Rate of Energy Delivery at Time of First Maximum.

An eye exposed to the first thermal pulse of a nuclear burst receives a very small fraction of thermal energy, but this energy reaches very high levels within an extremely short period of time (microseconds). The time of the first thermal maximum, t_1, as defined in Ref. 42 is

$$t_1 = 0.16\ (\rho_b W)^{1/3}\ e^{0.0076\ km\ (M/W)^{\frac{1}{2}}}\ msec \text{ for } W \geq 1\ kt$$

where M/W = the device mass-to-yield ratio

km = burst altitude

Analysis of data for p_1^* (rate of thermal energy delivery at t_1) resulted in the following equation for p_1^* at the target

$$p_1^* = \frac{1.78\ (l_o W)^{0.6118}\ (M/W)^{\frac{1}{2}}\ t^{*-.605}\ \rho^{-0.8}\ T}{4\pi D^2}\ cal/cm^2/sec \qquad (12)$$

where T = transmission of thermal energy for the distance D (km), as calculated in paragraphs D and E of Section 4.2.2.

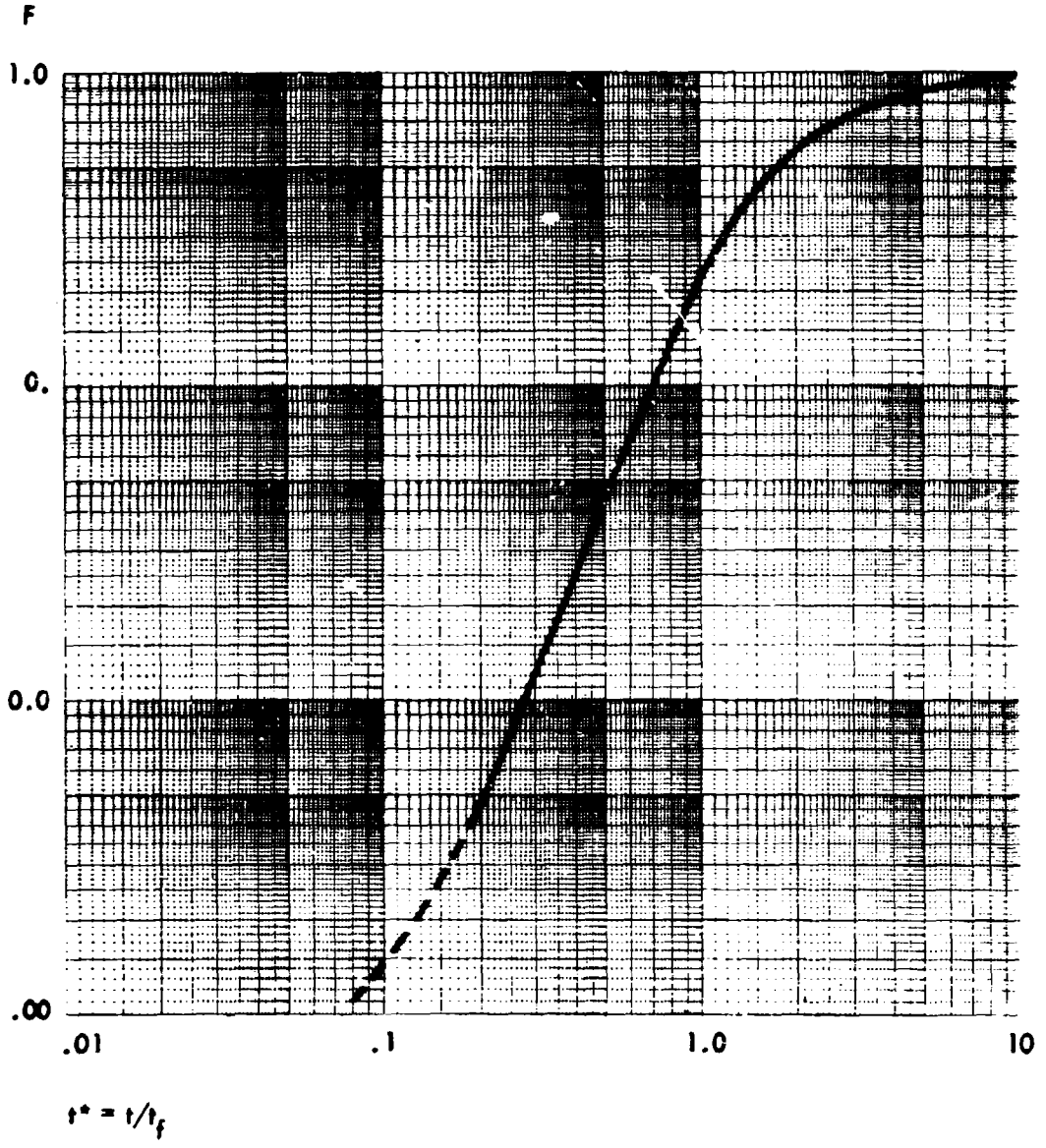

Fig. 4.1 FRACTION OF THERMAL ENERGY EMITTED vs SCALED TIME

This expression was derived from data in Ref. 47 for Shot Rinconada of Operation DOMINIC, from data in Ref. 48 for Shots Santa Fe, DeBaca, Sanford, and Socorro, of Operation HARDTACK II, and from data in Ref. 46 for Shot Yucca of Operation HARDTACK I. Calculated values of p_1^* are within $\pm$ 16% of values reported for the shots referenced above.

4.3 EVALUATION OF CRITERIA FOR PREVENTION OF RETINAL BURNS

4.3.1 Minimal Image Size.

Dr. Heinrich Rose has stated* that a retinal burn will not occur unless the image diameter is at least 0.05 mm. For images of smaller diameter, the surrounding tissue is capable of conducting away sufficient energy rapidly enough to prevent the image area from reaching a critical temperature. The criterion chosen for image size is that if the image radius is less than 0.024 mm, no burn will occur.

4.3.2 Image Concentration

Values were calculated for the image radii and concentrations for the two cases of minimal retinal burn discussed in Section 3.5.2, using the equations presented in Section 4.2. Calculated results, assuming a 100 msec blink reflex are as follows:

1) For Shot Tumbler-Snapper 4, $R_I = 0.191$ mm
   $IC = 0.09$ cal/mm^2

2) For Shot Simon, at 10 mi, (16 km) $R_I = 0.204$ mm
   $IC = 0.025$ cal/mm^2

The value of 0.02 cal/mm^2 was estimated as the maximum allowable concentration. Note that both image radii were larger than the minimal size criterion.

4.3.3 Energy Delivery Rate.

Energy delivery rates at blink times calculated for the same two shots, were found to be:

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* Personal communication.

1) For Shot Tumbler-Snapper 4, $p(t^*) = 0.310$ cal/cm^2/sec

2) For Shot Simon at 16 km, $p(t^*) = 0.205$ cal/cm^2/sec.

From these values, it is estimated that the energy delivery rate should not exceed 0.2 cal/cm^2/sec at the cornea.

Note that the subject was not exposed to p_1^* at the Tumbler-Snapper shot because the shutter did not open until after the time of t_1. Thus the energy rate at time of blink (which was close to t_f) was the peak rate experienced. At Shot Simon, the airman was exposed to thermal energy from the moment the bomb exploded. The calculated energy rate p_1^* at time t_1 for Shot Simon was approximately 0.75 cal/cm^2/sec, an extremely high level for the eye to experience. Furthermore, the calculated image radius at that time was about 0.044 mm. Although the calculated image concentration was less than 0.02 cal/mm^2, only one of the three criteria was satisfied. Thus, it is possible that the first pulse, even though of extremely short duration, probably contributed significantly to this case of retinal burn.

It was concluded that no retinal injury would occur if two of the three criteria were satisfied.

Section 5

SAFE SEPARATION RANGES FROM NUCLEAR BURSTS

This section presents the basic assumptions and calculated distances at which it is expected retinal burn will not occur if air bursts of 1, 10, 45, 100, and 1000 kt were viewed for the first 100 msec.

5.1 BASIC ASSUMPTIONS

A. The following environmental conditions were assumed:

1. Only air bursts are considered, i.e.

$$\text{Height of Burst} \geq 0.05W^{0.4}\text{km}$$

2. Model air densities used are those tabulated vs. altitude in Ref. 49.

3. Bursts are over land, not over oceans; thus, atmospheric haze was not considered. Ranges calculated, therefore, represent "worst case" conditions.

4. Bursts are at night; therefore pupils of observers have 8 mm diam.

B. It is assumed that an individual with no eye protection will blink at 100 msec, and will not open his eyes again until there is no further hazard from thermal energy. The longest such period for the cases considered would be for a 1000-kt burst at 1 km, when it could be necessary for the lids to remain closed for 5 sec to avoid retinal injury.

C. Distances calculated for the co-altitude situations again are "worst case", since no attenuation factor was used to account for aircraft windows, nor for the visors or goggles that pilots wear.

5.2 METHOD OF CALCULATION AND RESULTS

For each yield and burst altitude considered, after the values for t_f and t_l were calculated, using appropriate equations from Section 4.2, the values of t_l^* and t^*_{blink} were determined and fireball radius was calculated for both scaled times, using Eq. (1) or (2) as indicated. Equation (A) was

then used to evaluate the distance D_A at which R_I = 0.024 mm. Equation (B) was then set equal to 0.02, for the second criterion.

In Eq. (B), let

$$q_p = QF\ (t^*)\ \pi\ (r_p)^2$$

Then

$$q_p = 0.02\ \pi\ R_I^2$$

The value of q_p was calculated for distance D_A, using Eqs. (4) and (8).

$$\text{If } q_p \text{ at } D_A > 0.02\ \pi\ R_I^2\ ,$$

Then D_A is the minimum safe distance.

$$\text{If } q_p \text{ at } D_A < 0.02\ \pi\ R_I^2,$$

then values of q_p and $0.02\ \pi\ R_I^2$ were calculated for lesser distances until the two values were approximately equal. At that distance, the value of p(t*) was calculated, to verify that it did not exceed 0.2 cal/cm^2/sec at the cornea. For the 1000-kt bursts, an additional parameter was added, because due to the long pulse time, a very small fraction of the energy is emitted at 100 msec, and "safe" distances became very short. The distances on Figs. 5.2 and 5.4 are such that the total radiant exposure to 10t* never exceeds 0.56 cal/cm^2, a value only one-tenth that expected to cause sustained glowing or flaming of dried grass due to a 1000-kt burst.

Results of the calculations are shown in terms of kilometer slant range for an observer at the surface, and for bursts at various heights up to 20 km in Figs. 5.1 and 5.2. Some curves are not plotted for burst heights above 15 or 20 km. This limitation occurs because as burst altitude increases, the time of t_f decreases, and fireball size has not been verified at times later than $2.5t_f$. Consequently, image size and concentration cannot be calculated, if blink time is later than $2.5t_f$.

Horizontal distances for an observer at the same altitude as the burst are shown in Figs. 5.3 for bursts at altitudes up to 10 km (almost 33,000 ft).

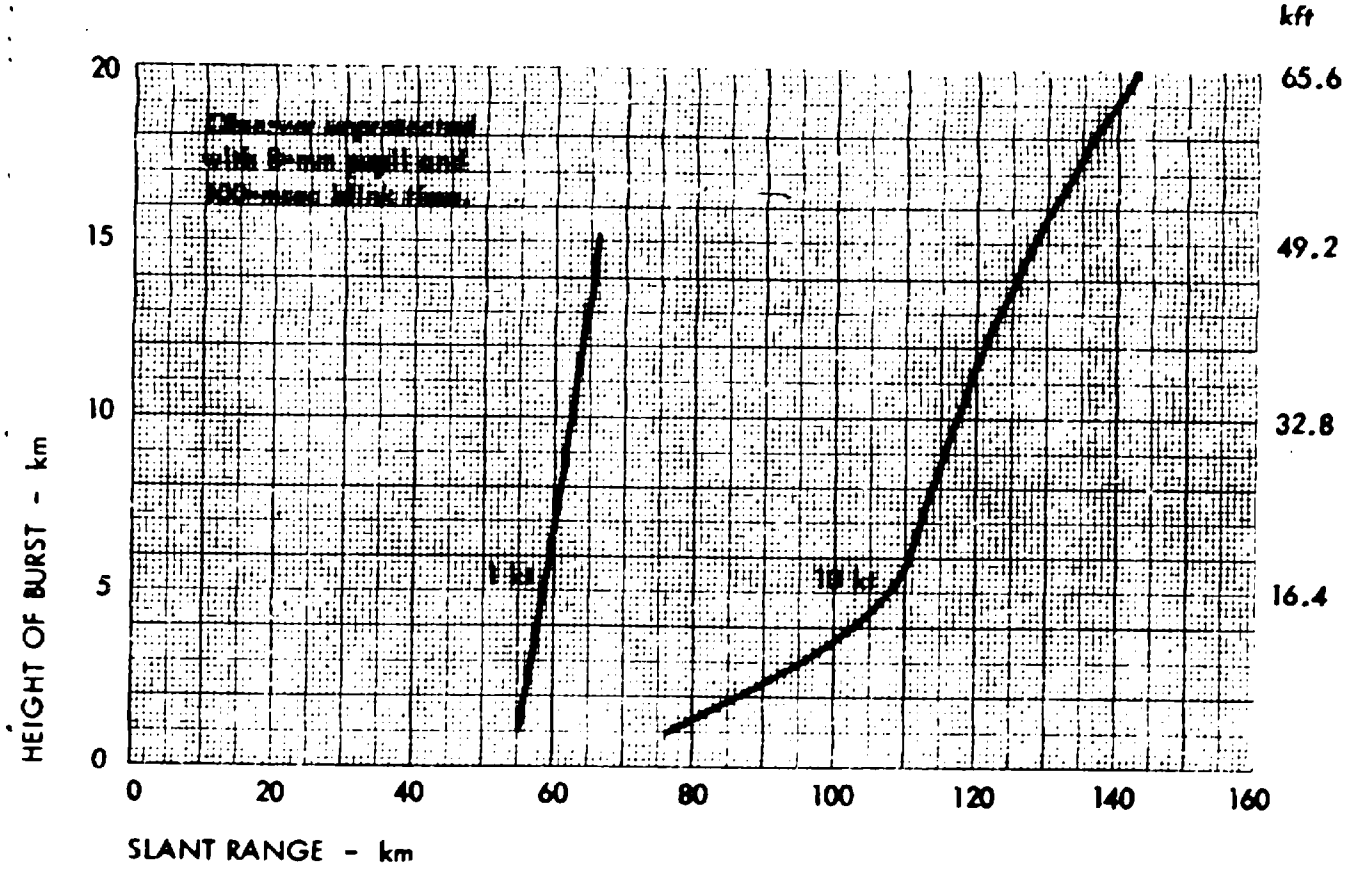

Fig. 5.1 SAFE SEPARATION SLANT RANGE FROM 1- and 10-kt NIGHT BURSTS FOR SURFACE OBSERVER

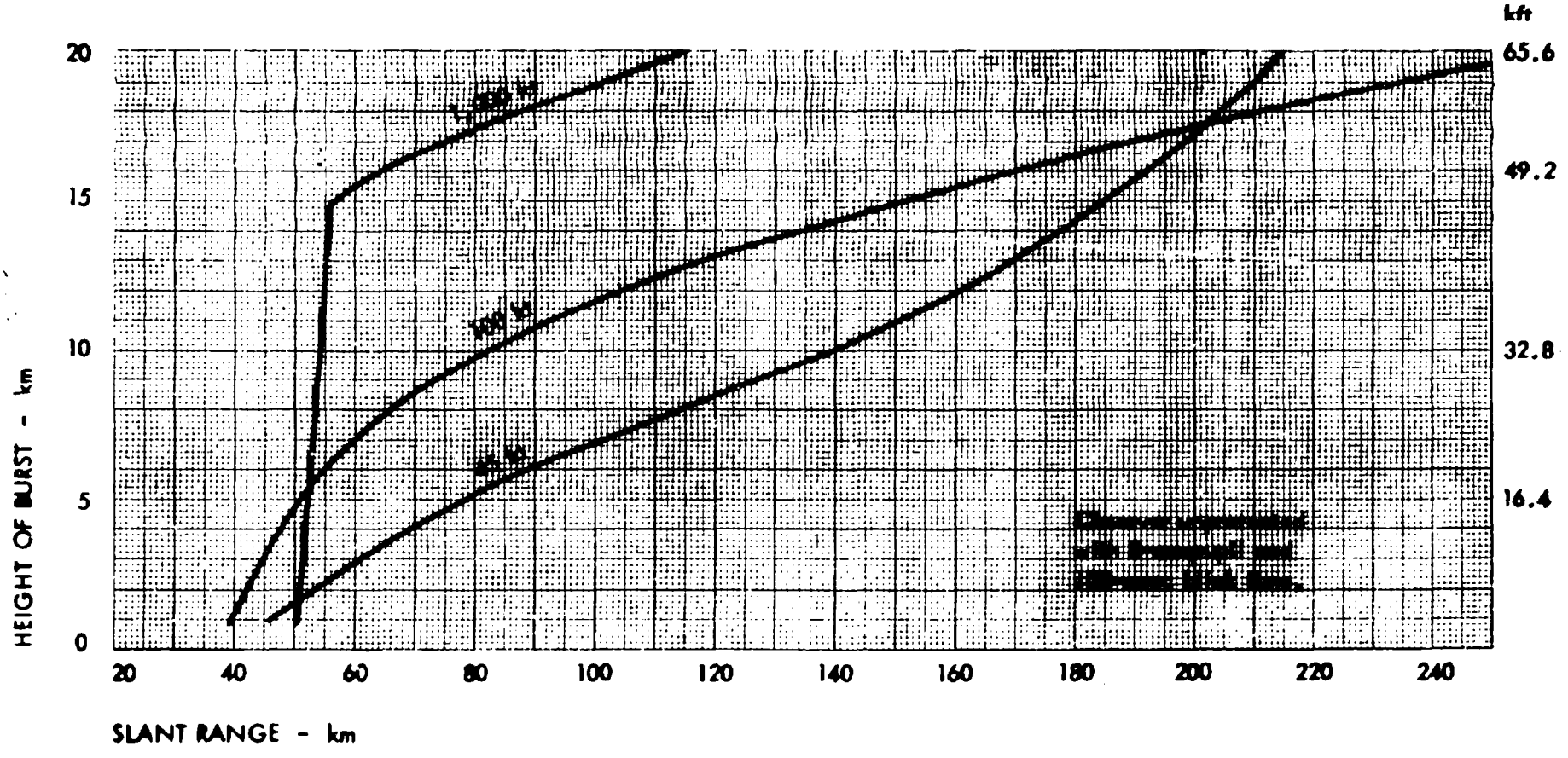

Fig. 5.2 SAFE SEPARATION SLANT RANGE FROM 45-, 100-, and 1000-kt NIGHT BURSTS FOR SURFACE OBSERVER

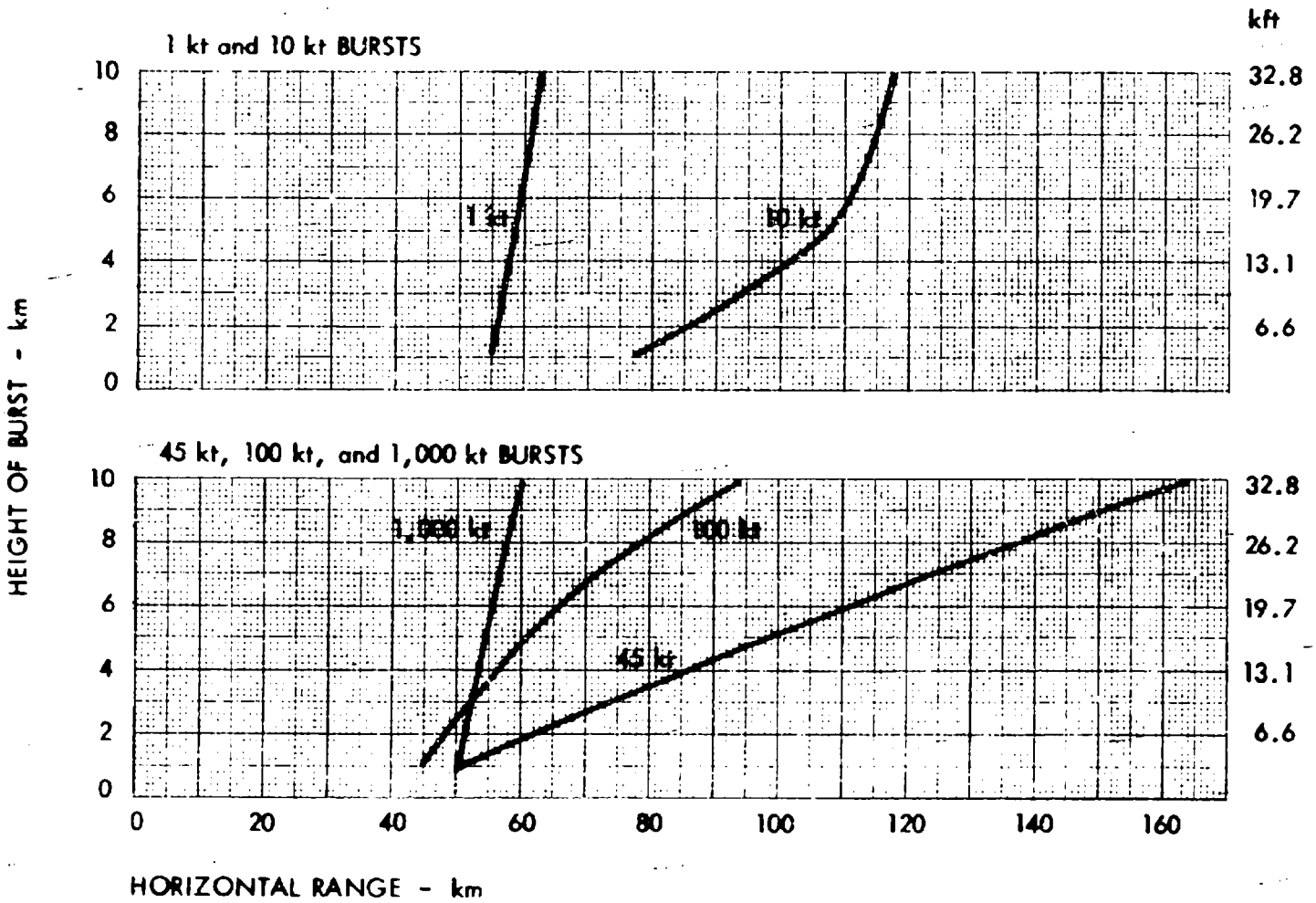

Fig. 5.3 SAFE SEPARATION FOR OBSERVER WITH NIGHT PUPIL (8 mm), 100-msec BLINK TIME, AND COALTITUDE WITH BURST

For viewers at the surface or co-altitude, and for bursts at 3 and 15 km, comparisons were made of the safe distances shown in Section 5 with those for 100 msec blink time in Ref. 31, for dark-adaptation. Assumed conditions differ, somewhat. This report assumes an 8-mm diameter pupil, for dark-adaptation, and average visibility (16 km or 10 miles). Furthermore, it is assumed that the burst is viewed for only the first 100 msec, no matter how long the thermal pulse lasts. Reference 31 assumes a 7-mm pupil diameter, and either 6- or 60-mile visibility. Safe distances appear to reflect criteria, especially for the smaller-yield bursts.

For an observer at the surface:

For 6-mile visibility, and for bursts at both altitudes, safe distances in this report exceed all but that for a 1000-kt burst at 15 km, in Ref. 31.

For 60-mile visibility, safe distances in this report exceed those for 1 and 10 kt, but are less than those for 100 and 1000 kt in Ref. 31.

For an observer co-altitude with the bursts at 3 km (10 kft):

For 6-mile visibility, safe distances in this report exceed all but that for the 1000-kt burst in Ref. 31.

For 60-mile visibility, safe distances for 1 and 10 kt exceed and those for 100 and 1000 kt are less than those in Ref. 31.

The image diameter was found to be the governing factor in determining safe distances for the 1- and 10-kt bursts in this report, since the 100-msec blink time was a minimum of 2t* for 1-kt bursts and 0.8t* for the 10-kt bursts. Thus, the eye views p_1^* in all cases, and $p(t_f)$ for most. For the larger yields, the value of t* is between 0.1 and 0.3 for 1000 kt and between 0.3 and 0.78 for 100 kt. The fraction of energy emitted up to 100 msec is small; thus image concentration and rate of energy delivery are the governing parameters in calculating safe distances.

Criteria values were calculated for all the nuclear tests where eye tests were conducted (where knowledge of conditions permitted calculation). Two of the three criteria were satisfied in each case where personnel were safe, but were not where an injury occurred. These findings tend to validate the calculational technique and criteria selected.

Section 6

CONCLUSIONS AND RECOMMENDATIONS

6.1 CONCLUSIONS

For air bursts at altitudes from 1 to 20 km, the following limitations and accuracy limits apply to the analytic equations presented in Section 4:

1) Values of fireball radius calculated using

$$R_{fb} = 0.07W^{1/3}t^{*.3}\rho_b^{-.08} \text{ km } (t^* \leq 1) \quad (1)$$

$$= 0.07W^{1/3}t^{*.16}\rho_b^{-.08} \text{ km } (1 \leq t^* \leq 2.5) \quad (2)$$

where $t^* = t/t_f$

ρ_b = burst height air density in g/liter, using model air density of 1.16655g/liter at zero km,

are expected to be within $\pm$ 25% of the actual fireball radius (within specified time limits) for yields from 1 kt to about 5000 kt. These equations do not apply to surface bursts.

2) The calculated value of t_f, time of final thermal maximum, agrees with measured data for yields greater than 1 kt within maximum limits of $\pm$ 20% (Ref. 42).

3) The calculated total effective radiant exposure is expected at maximum to be within $\pm$ 50% of that produced by a burst from fractional to multimegaton yield either on the surface or at any altitude (Ref. 43).

4) Values of rate of energy delivery from low-altitude bursts (up to 5 km) calculated using

$$p_1(t^*) = 9.1(I_oW)^{0.6118}t^{*1.508}10^{12} \text{cal/sec } (0.2 \leq t^* \leq 0.5) \quad (5)$$

$$p_2(t^*) = 5.7(I_oW)^{0.6118}e^{-1.203\ln^2 t^*}10^{12} \text{cal/sec } (0.5 \leq t^* \leq 2) \quad (6)$$

$$p_3(t^*) = 9.4(I_oW)^{0.6118}t^{*-1.555}10^{12} \text{cal/sec } (2 \leq t^* \leq 10) \quad (7)$$

are estimated to be within ± 20% of expected rates from a nuclear burst.

For bursts at altitudes from 5 to 20 km, preliminary analysis indicates that energy delivery rates may be calculated using the above equations with a modifying factor, $e^{.05H}$, where H is height of burst in km. Calculated energy delivery rates at t_f using the modified equation

$$p_2(t^*) = 5.7(I_o W)^{0.6118} e^{-1.203 \ln^2 t^*} e^{.05H} 10^{12} \text{ cal/sec} \qquad (9)$$

are estimated to be within ± 25% of those produced by a weapon burst, based on presently available data; however, calculated energy delivery rates at other times vary from 52% to 200% of those measured at Shot Tight Rope, the only burst for which comparative data were readily available.

5) The calculated fraction of total thermal effective energy emitted up to 10 t_f by a low-altitude burst (eq. 11) is estimated to be within ± 20% of that from a weapon burst. Due to the wide data spread in measurements for Shot Tight Rope, and current lack of other data, an accuracy estimate is not possible for bursts between 5 and 20 km.

6) The calculated rate of energy delivery at the target at time of first thermal maximum for bursts up to 20 km is estimated to be within ± 20% of that from a weapon burst, using the equation

$$p_1^* = \frac{1.78(I_o W)^{0.6118} (M/W)^{\frac{1}{2}} t^{*-.605} \rho_b^{-.8} T}{4 \pi D^2} \text{ cal/cm}^2\text{/sec} \qquad (12)$$

It is concluded that calculated values of all thermal effects are within 25 to 50% of those expected from nuclear air bursts at altitudes up to 5 km (16,400 ft). For bursts between 5 and 20 km, calculated time of final maximum, fireball radius at times up to $2.5t_f$, total effective radiant exposure, and energy delivery rate at t_f are also within 25 to 50% of those effects from nuclear bursts.

The criteria selected to prevent retinal burn are based on laboratory data and calculated values for low-altitude bursts that caused retinal injury. Therefore, for bursts up to 5 km, it is expected that no retinal burn will occur to a dark-adapted individual with no visual protection who views the

first 100 msec of a night burst, if he is located at distances calculated as safe (in Section 5). Average visibility conditions (16 km or 10 miles) were used in the calculations.

Safe distances calculated for bursts at altitudes between 5 and 20 km may require a $\pm$ 25% safety factor. The requirement of satisfying at least two out of three criteria reduces the significance of the variation in accuracy of the calculated fraction of energy delivered with time.

6.2 RECOMMENDATIONS

The following recommendations are made as a result of this study:

1) Further analysis of fireball growth with time be carried out to provide a reliable analytical equation for fireball size at any time up to $10t_f$;

2) Further analysis be carried out to derive a verifiable analytical expression for energy delivery rate with time for bursts at any altitude;

3) A rigorous analysis be carried out to derive a reliable evaluation of the fraction of total thermal energy delivered with time, for bursts at altitudes above 5 km;

4) Safe distances be calculated for blink times other than 100 msec;

5) An evaluation be made of the effects of blinking and re-opening the eyes during the thermal pulse of large-yield bursts.

6) Use available retinal burn data to evaluate criteria, then calculate distances at which minimal burns would occur for any yield, for various blink times.

7) Safe distances for fractional-kiloton bursts be evaluated. Fireball radius, and energy delivery rates must be determined. Analytical expressions for pulse times have been solved in Ref. 40.