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# THRESHOLD DISTANCES FOR RETINAL BURNS FROM LOW-YIELD NUCLEAR DETONATIONS

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## FOREWORD

This report was prepared in the Ophthalmology Branch, in support of task No. 630103 and cosponsored by the Defense Atomic Support Agency under project No. 5710, subtask 03.003. The work was performed in January and February 1966. The paper was submitted for publication on 18 March 1966.

This report has been reviewed and is approved.

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## ABSTRACT

A method is given for predicting the threshold distances at which minimal retinal burns will be produced by nuclear detonations. This method relates calculated retinal exposure to experimentally determined burn threshold data. Predicted threshold distances are determined for the human eye exposed to sea-level, air-burst detonations from 0.01 to 10 kt. yield.

The pupil diameter of the human eye is taken to be 2.5 mm. and 6.0 mm., respectively, for day and night conditions, and the effective focal length of the eye is taken to be 17 mm. The average fireball diameter is assumed to be $9.33 \times 10^3 W^{0.4}$ cm. and the effective exposure time is assumed to be $0.064W^{0.5}$ sec. The threshold distance for a bright daylight exposure with clear air (80 km.) visibility varies from about 1.3 to 11 km. as the detonation yield varies from 0.01 to 10 kt. Comparable distances for night exposures vary from 3.8 to 26 km.

Calculations indicate that the use of a fixed filter with 2% transmission will result in retinal exposures more than an order of magnitude below the threshold exposure for these small daylight detonations. For nighttime conditions the retinal exposure is a factor of about 2.5 below the threshold exposure.

# THRESHOLD DISTANCES FOR RETINAL BURNS FROM LOW-YIELD NUCLEAR DETONATIONS

## I. INTRODUCTION

The thermal energy released in a nuclear detonation is sufficient to cause loss of vision in humans who view such detonations without eye protection. This loss of vision may be temporary, as in flashblindness, or permanent, as in retinal burns. The extent and duration of this loss of vision depend on the conditions of exposure.

The basic physical problem in the prediction of retinal burns is the determination of the increase of temperature in the retinal region in which the fireball is imaged. Areas in which the temperature, or time at some critical temperature, exceeds a certain value may be presumed to be irreversibly damaged. However, the nature of the problems and the difficulties in measuring and relating temperature profiles to functional effects have led to an approach by which observed retinal effects are associated with calculated retinal exposures. This approach is based on laboratory investigations which have established the dependence of ophthalmoscopically observable effects on total retinal exposure, exposure time, and image size (fig. 1). The curves in figure 1 are based on the latest and most complete laboratory data available at this time (1).

The use of this method requires the calculation, from known source characteristics, of the retinal exposure, exposure time, and image diameter associated with exposure to a nuclear detonation. The calculations are greatly simplified by using approximations of nuclear detonation characteristics (2, 3, 4).

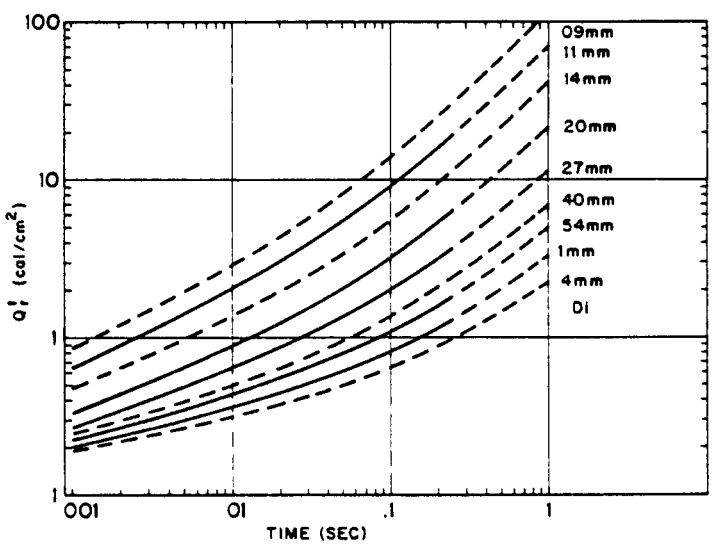


FIGURE 1

*Threshold retinal exposure, $Q_r^t$, versus time for the production of minimal burns in the retina of pigmented rabbits. (Dash lines are interpolated or extrapolated.)*

## II. CALCULATION OF RETINAL EXPOSURE

The retinal exposure resulting from viewing a nuclear detonation can be calculated if the exposure conditions are known. The effective radiant exposure, $Q_r$, of the retina may be expressed as

$$Q_r = \frac{10^{12} apkWT_eT_aT_x}{4\pi f^2 D_{fb}^2} \text{ (cal./cm.}^2\text{)} \qquad (1)$$

The exposure time, t, is

$$t = 2\, t_{max} = 0.064W^{0.5} \text{ (sec.)} \qquad (2)$$

and the image diameter, $D_i$, is given by

$$D_i = \frac{FD_{fb}}{D} \text{ (mm.)} \qquad (3)$$

where

$a = 0.8$ = Fraction of the thermal energy radiated which is located in the spectral region effective in producing retinal damage (350 mμ < Eλ <1500 mμ assuming a 5,800° K. black-body radiator)

$p = 1/3$ = Fraction of total weapon yield converted to thermal energy (low-altitude detonations)

$k$ = Fraction of thermal energy released during time t

$W$ = Yield of the weapon in kilotons

$T_e = 0.8$ = Average transmission of clear media of the eye (assumed 5,800° black-body spectrum)

$T_a$ = Average transmission of the atmosphere

$T_x$ = Average transmission of any material between the eye and the detonation (i.e., aircraft canopy, sunglasses, filters)

$f = \frac{F}{D_P}$ = Ratio of the effective focal length of the eye-lens system to the diameter of the pupil

$D_{fb}$ = Average fireball diameter in centimeters during exposure time t

$D$ = Distance to fireball in centimeters

Retinal exposures have been calculated, utilizing this method, for human eyes exposed to sea-level, air-burst detonations from 0.01 kt. to 10 kt., under both day and night conditions. In these calculations the effective focal length, F, and the bright daylight pupil diameter, $D_P$, of the human eye are taken to be 17 mm. and 2.5 mm., respectively, resulting in a value of $f = 6.8$. The nighttime pupil diameter is taken to be 6 mm., resulting in a value of $f = 2.83$, based on a recent investigation by Alder (5) in which he reports the average pupil diameter under dim cockpit conditions to be 5.9 mm.

The radiant power of a nuclear detonation is less than 45% of the maximum radiant power after an elapsed time of $2t_{max}$, and, along with the apparent surface temperature of the fireball, continues to decrease rapidly. Thus, the energy effective in producing eye hazards is assumed to be radiated in a time $t = 2t_{max} = 0.064W^{0.5}$ sec. This is assumed to be less than the blink reflex time for the yields considered here. During this period of time the fireball emits approximately 47% of the total energy radiated; thus, we have $k = 0.47$. The assumed average fireball diameter is that corresponding to $t_{max}$ or $D_{fb} = 9.33 \times 10^3 W^{0.4}$ cm. (Nuclear detonation characteristics are all from reference 6.)

Substituting the values above in equations 1, 2, and 3 gives the exposure times and other quantities listed in table I, which require only appropriate values for D, $T_a$, and $T_x$ for the determination of $D_i$ and $Q_r$.

Atmospheric transmission was calculated using the equation $T_a = \exp(-\kappa D)$, where D is the distance in km. and $\kappa$ is an average extinction coefficient dependent on visibility. Transmission values were determined for three different conditions of visibility: 20 km. ($\kappa = 0.20$ km.$^{-1}$); 40 km. ($\kappa = 0.10$ km.$^{-1}$); and 80 km. ($\kappa = 0.03$ km.$^{-1}$) (6).

## III. DISCUSSION

Image diameter, retinal exposure, and exposure time were calculated for both day and night exposure conditions for each of the yields

TABLE I

*Exposure time, image diameter, and retinal exposure as functions of yield, distance, atmospheric transmission, and filter transmission (human eye exposed to sea-level air bursts)*

| W (kt.) | t (sec.) | $D_i$ (mm.) | Bright daylight $Q_r$ (cal./cm.$^2$) | Dim cockpit $Q_r$ (cal./cm.$^2$) |
|---|---|---|---|---|
| 0.01 | .0064 | $\frac{2.50 \times 10^4}{D}$ | $.788T_aT_x$ | $4.54T_aT_x$ |
| 0.03 | .0111 | $\frac{3.91 \times 10^4}{D}$ | $.982T_aT_x$ | $5.65T_aT_x$ |
| 0.1 | .0202 | $\frac{6.31 \times 10^4}{D}$ | $1.25T_aT_x$ | $7.19T_aT_x$ |
| 0.3 | .0351 | $\frac{9.81 \times 10^4}{D}$ | $1.56T_aT_x$ | $8.96T_aT_x$ |
| 1.0 | .064 | $\frac{1.59 \times 10^5}{D}$ | $1.98T_aT_x$ | $11.4T_aT_x$ |
| 3.0 | .111 | $\frac{2.46 \times 10^5}{D}$ | $2.48T_aT_x$ | $14.2T_aT_x$ |
| 10.0 | .202 | $\frac{3.98 \times 10^5}{D}$ | $3.13T_aT_x$ | $18.0T_aT_x$ |

listed in table I, for each of the assumed visibilities, and for values of $T_x = 1$ (no intervening filters) and $T_x = 0.02$ (2% transmission fixed filter).

Figure 2 is a plot of retinal exposure and image diameter versus distance for daytime exposure to a 0.01 kt. detonation for visibilities of 20, 40, and 80 km. with no filter and with a 2% fixed filter. Also shown in figure 2 is a plot of the threshold retinal exposure, $Q_r^t$, required to produce a minimal retinal burn. $Q_r^t$ for each distance was determined by using the exposure time and image diameter in conjunction with the threshold curves in figure 1. The distance at which $Q_r^t$ exceeds the retinal exposure, $Q_r$, is the predicted threshold distance for minimal retinal burns. Figure 3 is a plot of the same information for nighttime exposure to a 0.01 kt. detonation and figures 4 through 15 are similar plots for the other detonation yields listed in table I.

This method was used to determine the threshold distance under both day and night exposure conditions and each assumed visibility

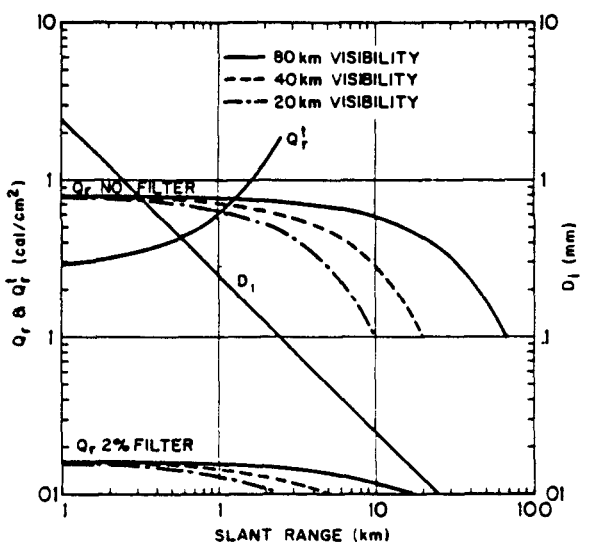


FIGURE 2

*Image diameter, $D_i$, retinal exposure, $Q_r$, and threshold exposure, $Q_r^t$, as functions of distance from a 0.01 kt. detonation for the human eye in bright daylight. Exposure time is 0.0064 sec.*

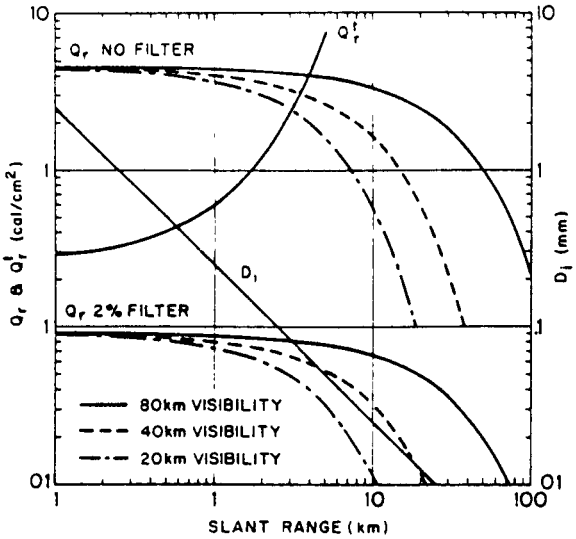


FIGURE 3

*Image diameter, $D_i$, retinal exposure, $Q_r$, and threshold exposure, $Q_r'$, as functions of distance from a 0.01 kt. detonation for the human eye at night. Exposure time is 0.0064 sec.*

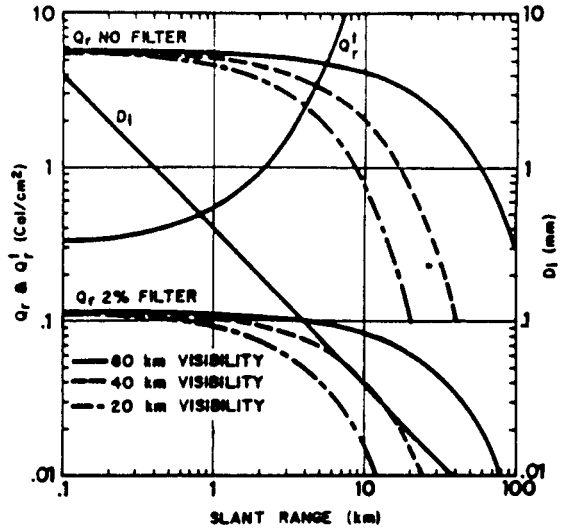


FIGURE 5

*Image diameter, $D_i$, retinal exposure, $Q_r$, and threshold exposure, $Q_r'$, as functions of distance from a 0.03 kt. detonation for the human eye at night. Exposure time is 0.0111 sec.*

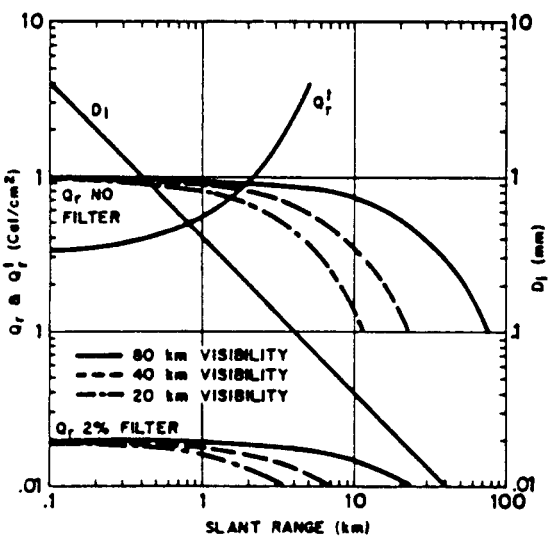


FIGURE 4

*Image diameter, $D_i$, retinal exposure, $Q_r$, and threshold exposure, $Q_r'$, as functions of distance from a 0.03 kt detonation for the human eye in bright daylight. Exposure time is 0.0111 sec.*

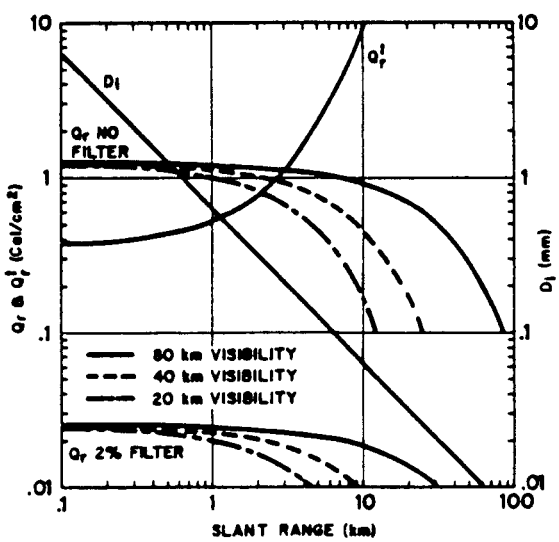


FIGURE 6

*Image diameter, $D_i$, retinal exposure, $Q_r$, and threshold exposure, $Q_r'$, as functions of distance from a 0.1 kt. detonation for the human eye in bright daylight. Exposure time is 0.0202 sec.*

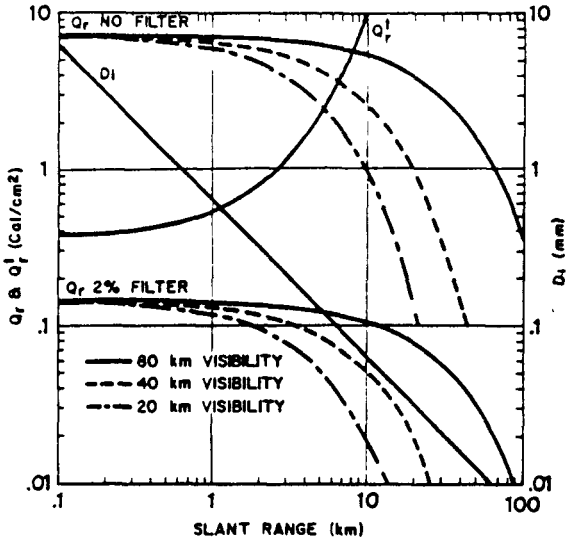


FIGURE 7

*Image diameter, $D_i$, retinal exposure, $Q_r$, and threshold exposure, $Q_r^t$, as functions of distance from a 0.1 kt. detonation for the human eye at night. Exposure time is 0.0202 sec.*

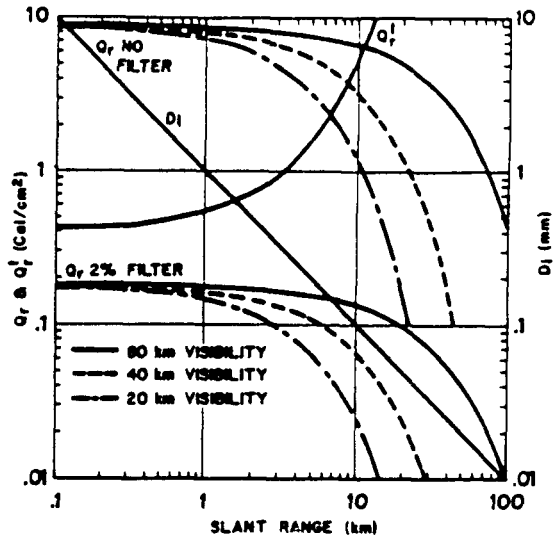


FIGURE 9

*Image diameter, $D_i$, retinal exposure, $Q_r$, and threshold exposure, $Q_r^t$, as functions of distance from a 0.3 kt. detonation for the human eye at night. Exposure time is 0.0351 sec.*

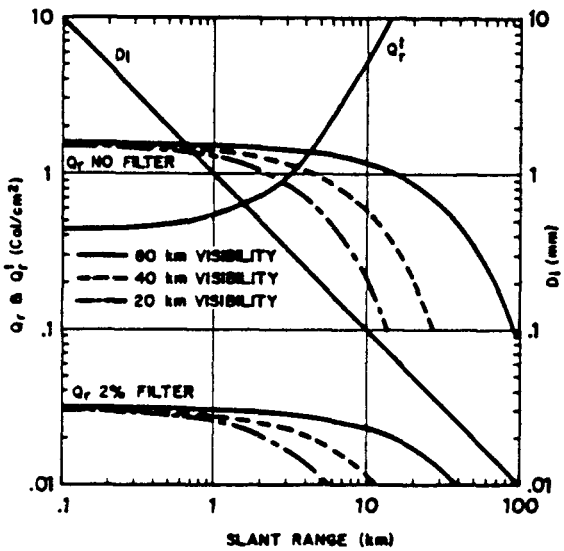


FIGURE 8

*Image diameter, $D_i$, retinal exposure, $Q_r$, and threshold exposure, $Q_r^t$, as functions of distance from a 0.3 kt. detonation for the human eye in bright daylight. Exposure time is 0.0351 sec.*

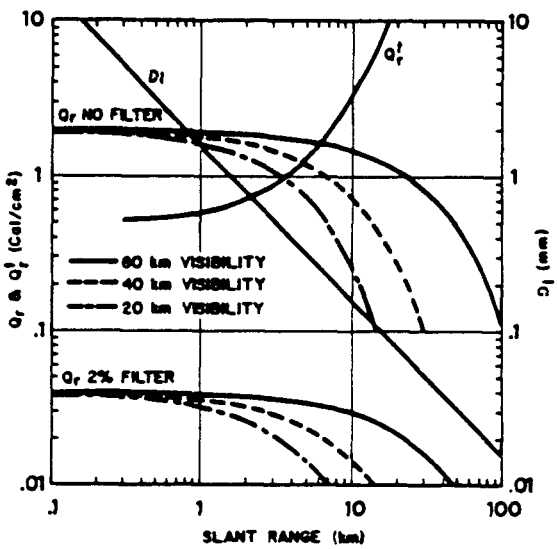


FIGURE 10

*Image diameter, $D_i$, retinal exposure, $Q_r$, and threshold exposure, $Q_r^t$, as functions of distance from a 1.0 kt. detonation for the human eye in bright daylight. Exposure time is 0.064 sec.*

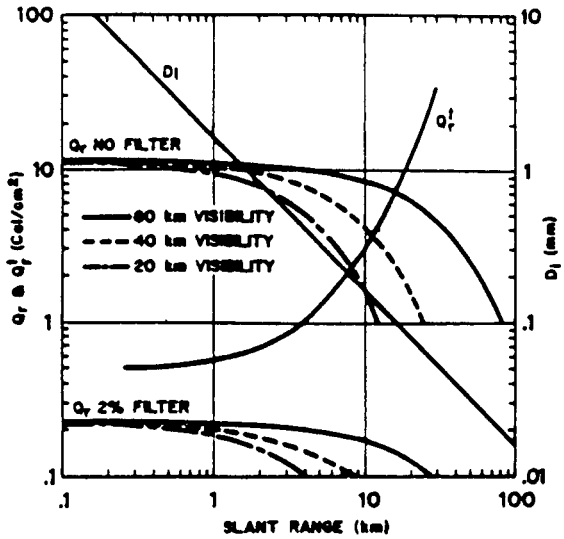


FIGURE 11

*Image diameter, $D_i$, retinal exposure, $Q_r$, and threshold exposure, $Q_r'$, as functions of distance from a 1.0 kt. detonation for the human eye at night. Exposure time is 0.064 sec.*

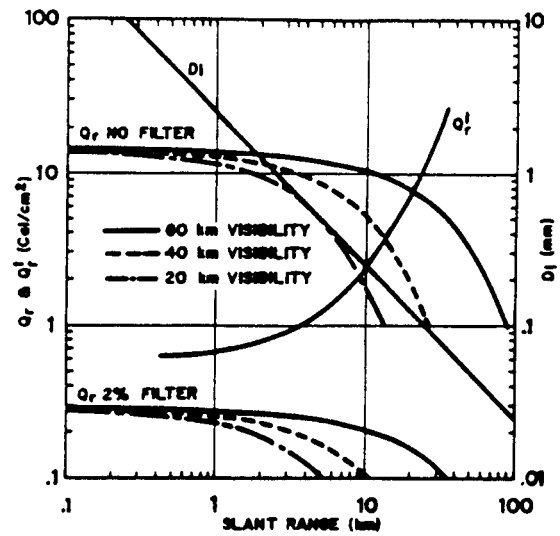


FIGURE 13

*Image diameter, $D_i$, retinal exposure, $Q_r$, and threshold exposure, $Q_r'$, as functions of distance from a 3.0 kt. detonation for the human eye at night. Exposure time is 0.111 sec.*

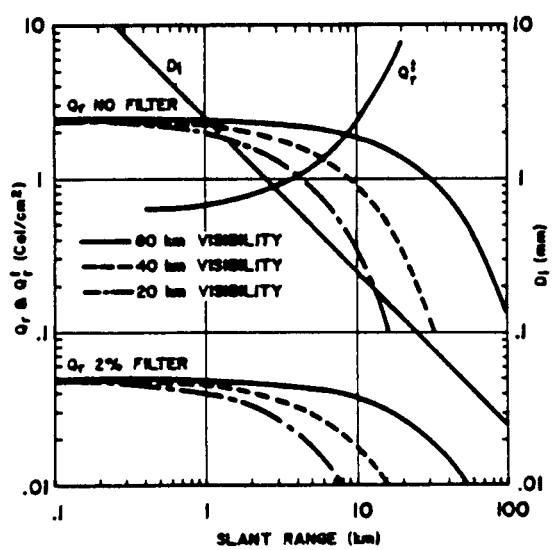


FIGURE 12

*Image diameter, $D_i$, retinal exposure, $Q_r$, and threshold exposure, $Q_r'$, as functions of distance from a 3.0 kt. detonation for the human eye in bright daylight. Exposure time is 0.111 sec.*

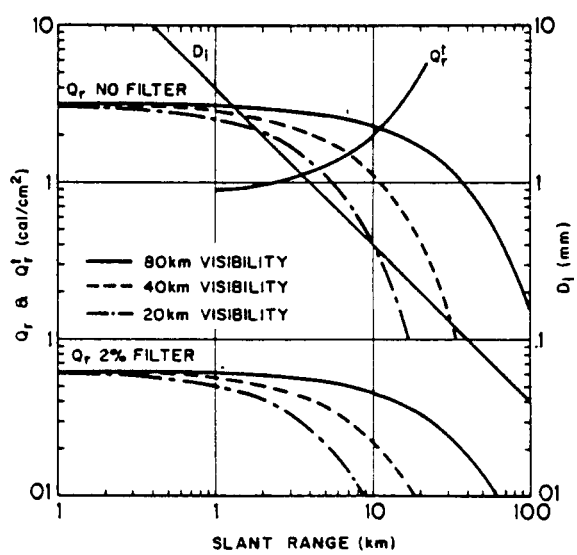


FIGURE 14

*Image diameter, $D_i$, retinal exposure, $Q_r$, and threshold exposure, $Q_r'$, as functions of distance from a 10 kt. detonation for the human eye in bright daylight. Exposure time is 0.202 sec.*

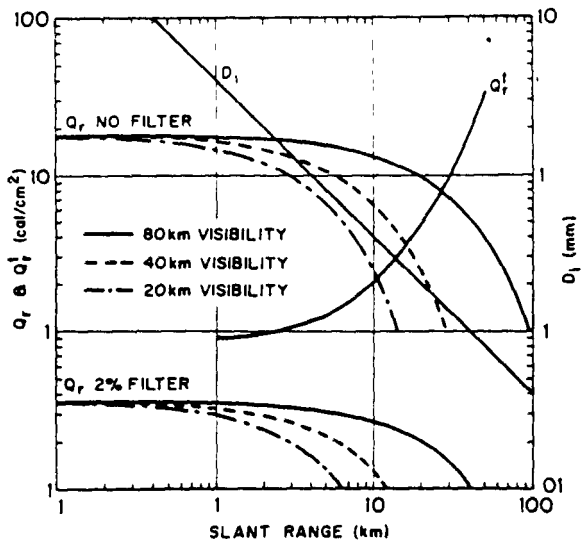


FIGURE 15

*Image diameter, $D_1$, retinal exposure, $Q_r$, and threshold exposure, $Q_r^t$, as functions of distance from a 10 kt. detonation for the human eye at night. Exposure time is 0.202 sec.*

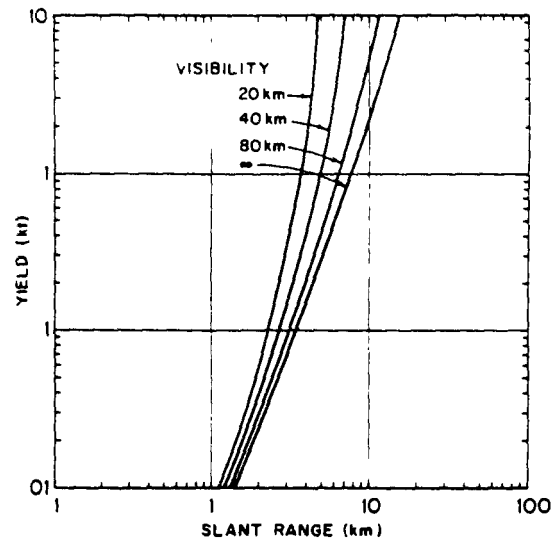


FIGURE 16

*Threshold distance for minimal burn versus yield for human eye in bright daylight with no protection.*

for each yield listed in table I. Figure 16 is a plot of the threshold distance versus yield for the day exposures and figure 17 is a similar plot for the night exposures.

The threshold distance for a bright daylight exposure with clear air (80 km. visibility) varies from about 1.3 to 11 km. as the detonation yield varies from 0.01 to 10 kt. However, when the visibility is limited (20 km.), the threshold varies from about 1.1 to 4.6 km. for the same range of yields. Comparable distances for night exposures vary from 3.8 to 26 km. for clear air and 3.0 to 10.5 km. with limited visibility.

The use of a fixed filter with 2% transmission results in retinal exposures well below burn threshold values for each of the yields considered, as shown in figures 2 through 15. During daylight hours such a filter reduces the retinal exposure more than an order of magnitude below the threshold exposure. For nighttime conditions the retinal exposure is reduced by a factor of approximately 2.5 below the threshold exposure.

The threshold distances reported here are based on the assumption that the absorption properties of the human retina are essentially the same as those for a rabbit—as suggested by the absorption measurements of Geeraets et al. (7). There may be some question concerning this, however, and care must be exercised in using existing animal threshold data to predict retinal damage in humans (8). In addition, the curves in figure 1 show the thermal exposure which will produce a minimal burn, defined as a very slight coagulation of the retinal tissue which becomes ophthalmoscopically visible between 3 and 5 minutes after exposure (1, 9). The exposure required to produce permanent damage is undoubtedly less than that required to produce burns defined in this way. However, there is as yet no satisfactory definition of minimum acceptable damage.

The energy spectrum of the source used in obtaining the threshold exposure curves in figure 1 was deficient in the infrared relative to a 5,800° K. black-body radiation (1) (fig. 18). Since the retina does not appear to absorb energy in the infrared as effectively as energy

in the visible region of the spectrum (7), the threshold curves of figure 1 are somewhat conservative for a 5,800° K. black-body source—a source that in some respects resembles some nuclear detonations. The peak temperature of a low-altitude nuclear detonation, however, is probably between 7,000° and 10,000° K. (6), and the spectral distribution of the energy would more nearly resemble that of the experimental source used.

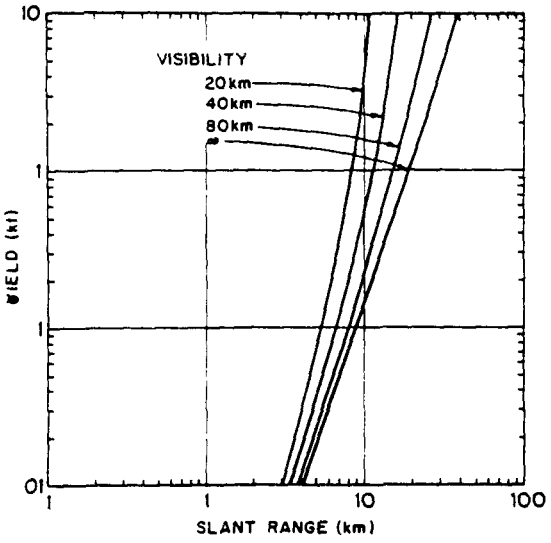


FIGURE 17

*Threshold distance for minimal burns versus yield for human eye at night with no protection.*

The predicted distances for minimal burns shown in figures 16 and 17 obviously cannot be interpreted as the distances at which humans may safely view nuclear detonations without eye protection. A safety factor needs to be introduced. However, the amount of this factor and how it should be introduced have not yet been arbitrated. One possibility is simply to lower the threshold curves for minimal burns by some arbitrary factor generally suggested to be between 5 and 10. Once this factor is selected, it is only necessary to shift the ordinate scale of figure 1 to determine "safe" separation distances.

An increase in detonation altitude with the consequent increase in fireball diameter, energy emission rate, and atmospheric transmission (3, 6, 10) results in threshold distances greater than those shown here. The reader is cautioned against using these curves for other than sea-level, air-burst conditions and for yields beyond the range spanned by these calculations. The basic method of calculation can be used for different detonation altitudes and other yields, but it may be necessary to consider different detonation characteristics for these conditions.

## IV. CONCLUSIONS AND RECOMMENDATIONS

The threshold distances for minimal retinal burns reported here are recommended for use

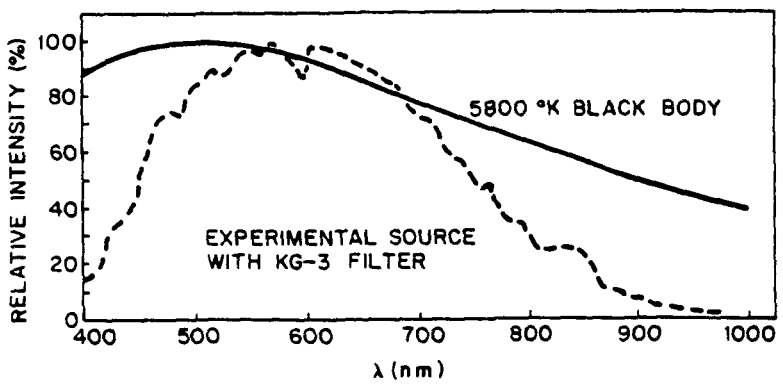


FIGURE 18

*Relative spectral distribution of the exposure source used in obtaining the threshold curves in figure 1 compared to the relative spectral distribution of a 5,800° K. black-body radiator (nm = nano-meters = $10^{-9}$ meters).*

as a guide in establishing interim eye safety criteria. They are believed to be a reasonable and realistic assessment of the eyeburn hazard from small nuclear detonations. The method and technic used here have been used successfully in the past to predict experimentally verified threshold distances for animals, although not for the range of yields covered here (3, 4, 10, 11). Additional work is needed, however, to (1) extend the threshold curves for minimal burns to primates to allow extrapolation to man with more confidence, (2) establish a realistic safety factor and a method of introducing it into the prediction technic used here, and (3) establish a definition of minimum acceptable damage.

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| Nuclear detonations | | | | | | |
| Nuclear eye hazards | | | | | | |
| Retinal burns | | | | | | |
| Threshold distances for retinal burns | | | | | | |

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