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LIFE SCIENCES DIVISION

EVALUATION OF EYE HAZARDS FROM NUCLEAR DETONATIONS

JAMES A. NICKEL

SEPTEMBER 1970

Final Report

Contract No. F-41609-69-C-[illegible]049

USAF School of Aerospace Medicine
Aerospace Medical Division (AFSC)
Brooks Air Force Base, Texas 78235

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EVALUATION OF EYE HAZARDS FROM NUCLEAR DETONATIONS

SENSITIVITY ANALYSIS

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FOREWORD

This report was prepared for the USAF School of Aerospace Medicine, Aerospace Medical Division (AFSC), Brooks Air Force Base under Contract F41609-69-C-0049 and covers the period from July 1969 - August 1970. Mr. Everett O. Richey, Chief, Oculo-Thermal Section, Ophthalmology Branch, USAF School of Aerospace Medicine, was the contract monitor. Grateful acknowledgment is made for the assistance provided by Mr. Richey to this effort.

ABSTRACT

The retinal exposure equation, from which safe separation distances ~~have been~~ calculated, was used as a basis for developing a linearized equation. New scaling laws for the spectral power and fireball radiance were also developed. These equations were used in deriving a variance equation for the safe separation distance. This equation is expressed in terms of the variances of the independent variables: retinal exposure, time of irradiation, yield, observer and burst altitude. The importance of retinal irradiance at the time of cutoff (as effected by blinking or introduction of other shielding) is demonstrated by an analysis of the coefficients in the variance equation, supported by a limited set of calculations. Retinal irradiance is affected by variations in the f-number of the eye and pulse profile of the fireball. The largest variances occur when the cutoff time is near a radiance maximum (approximately a thermal maximum). Small increases in the variance are realized with increased differences in the vertical separation of observer and fireball, but these appear to be of importance only with very low yield weapons.

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LIST of ABBREVIATIONS and SYMBOLS

A, A_o	observer altitude
a_i	radius of spherical aerosol
α, α_i	parameter of Mie scattering ($2\pi a_i/\lambda$)
ds	differential of arc length
E	mean radius of earth
E_c	critical exposure for flashblindness
E_r	exposure received (flashblindness)
F	safety factor in flashblindness equation
f, f_o	f-number of eye
FR	fireball radius
FR*	scaled fireball radius
H, H_o	height of burst
H_r	retinal irradiance
K(d)	efficiency factor for Mie scattering theory
$k, \tilde{k}, k_R, k_H, k_A$	mean value estimates of the atmospheric attenuation coefficient.
k_λ	monochromatic extinction coefficient
k_ρ	extinction coefficient of air due to particulates
L_o	Pythagorean estimate of optical path between fireball and observer (also used once to represent Loschmidt's number)
λ	wavelength
$\underline{\lambda}$	lower bound of radiation wavelength used in calculations
$\overline{\lambda}$	upper bound of radiation wavelength used in calculations
N	radiance
N_i	density of particulates of radius a_i
$N_{\lambda t}$	spectral radiance
n_o	index of refraction of air at standard temperatures and pressure
P	total source power
P*	scaled source power
P_λ	spectral power, wavelength dependent

P_{50}, P_{75}, P_{95}	labels on safe separation distance curves indicating that for normally distributed parameters, the distance will not be exceeded 50, 75 or 95 per cent of the time.
PD	pupil diameter
Q, Q_o	retinal exposure
Q_c	threshold exposure for retinal burns
R, R_o	safe separation distance
r	radius variable in polar coordinate using earth's center as origin.
ρ	density of air
ρ_o	density of air at sea level
S	slant range
σ_A	standard deviation of observer altitude measurements.
σ_H	standard deviation of height of burst measurements.
σ_Q	standard deviation of threshold exposure measurements.
σ_R	standard deviation of safe separation distance measurements
σ_T	standard deviation of time of irradiation measurements
σ_W	standard deviation of weapon yield values
T	temperature (^{o} Kelvin)
T_o	time of irradiation
T_o^*	scaled time of irradiation
T_λ	spectral transmissivity of optical path
T_r	transmissivity of optical path
t	real time
t*	scaled time
t_{1max}	time to first thermal maximum
t_{min}	time to thermal minimum
t_{2max}	time to second thermal maximum
u	scaling parameter defined on unit interval
V	visibility, range of
VB	contribution to variance of safe separation distance by height of burst term

V_λ	visibility function
VW	contribution to variance of safe separation distance by yield term
W, W_o	weapon yield
W_T	thermal yield of weapon
ϕ	angular variable in polar coordinates
ϕ_o	upper bound on angular variable (R_o/E radians)

I

INTRODUCTION

This final report describes the analysis conducted by the Life Sciences Division of Technology Incorporated for the Aerospace Medical Division, Brooks Air Force Base under Contract F41609-69-C-0049. The scope of the contractual effort was to explore the relative magnitude of changes in eye safe separation distance predictions as the input parameters are varied within reasonable limits translating uncertainties in the values of the input data into uncertainties in the value of the predicted safe distances.

It has been demonstrated that an intense flash from a nuclear detonation may be a serious eye hazard at distances much greater than for any other significant effect. Various studies have been undertaken to determine the parameters involved in determining the safe separation distance and developing suitable mathematical models for investigating the relationships. This study extends the safe separation distance of the modeling by Technology Incorporated by considering the sensitivity of the safe separation distance to the input parameters.

With respect to retinal burns, the safe separation distance is defined as the minimum horizontal range from fireball to observer which will prevent the observer from sustaining permanent eye damage before protective action can occur. In the case of flashblindness the safe separation distance is the minimum horizontal distance from the fireball to the observer that will enable the observer to recover the ability to perform a specified visual task within 10 seconds of the initiation of the flash.

In this report, new scaling laws for the fireball parameters and a linearized approximation to the safe separation distance as a function of the input parameters have been developed.

The general details of this investigation are given after the summary in sections III, IV and V. Section VI then presents a more detailed discussion of the parameters and the derivation of the coefficients used in the linearized equation to the safe separation distance and variance equation. Section VII is concerned with approximating the values of the various coefficients.

II

SUMMARY

In order to investigate the sensitivity of the input parameters for the determination of the safe separation distance, new scaling relationships as developed in Air Force Contract F41609-70-R-0007 were used. These scalings compare with previous results but were adjusted to correspond better with test data and theoretical calculations.

The linear, or first order, approximation of the safe separation distance and corresponding variance equation were derived and analyzed to determine the relative importance of the variables. The parameters selected as independent variables in the analyses were threshold exposure, duration of exposure, yield, height of burst and observer altitude

The values of the coefficients in the linear approximation and variance equation are dependent upon the coordinate values about which variations are considered For a given set of conditions, small variations in observer altitude, height of burst and yield are generally the least significant. Retinal exposure, though not treated as an independent variable, is potentially the most significant parameter affecting safe separation distances. The retinal irradiation at cutoff significantly contributes to the variance. Large variances are probable when the observation of the fireball is terminated close to maximum fireball radiance levels.

The changes in the safe separation distance resulting from a 10% increase in the values of critical threshold exposure, time of irradiation and yield for specified scaled times are given in Table1. These values apply if the height of burst and observer altitude are approximately equal, otherwise the indicated values should be increased by a correction factor, the ratio of the Pythagorean length of the optical path to the safe separation distance. It is important to observe that the changes in safe separation distance resulting from a change in time of irradiation or yield depends upon the cutoff time as measured in scaled time. These changes are independent of the choice of safety factor value used in making the initial calculations of the safe separation distance.

TABLE 1

CHANGE IN SAFE SEPARATION DISTANCE CORRESPONDING TO A 10% INCREASE IN THE INDEPENDENT VARIABLE

(nautical miles)

Scaled Time	Threshold Exposure	Time of Irradiation	Yield
0.001	-1.53	+1.65	+0.05
0.01	-1.53	+0.35	-0.50
0.10	-1.53	+0.07	-0.62
0.56	-1.53	+1.72	+0.08
1.0	-1.53	+1.93	+0.17
1.8	-1.53	+1.08	-0.20
10.	-1.53	+0.15	-0.59

The variance of the safe separation distance for flashblindness and retinal burns is approximately proportional to the visibility for fixed yields and cutoff times. Deviations from proportionality become noticeable for low yield devices as the difference between height of burst and observer altitude changes.

A particularly significant factor is cutoff time near a thermal maximum. Small errors in cutoff time at these critical points can be a source of large errors in computed safe separation distances. It follows that if protective devices are used to effect cutoff of the incident radiation at the eye, high reliability of time response is important.

III

LOW ALTITUDE WEAPON SCALING LAWS

The simplest form of low altitude scaling assumes that power and fireball radius can be given as fixed functions of scaled time. This also implies that with well defined fireball edges the radiance should be a fixed function of scaled time. This, and other considerations were used in deriving the scaling laws used in this analysis. These scaling laws are:

$$P = W^{0.6} (\rho_o / \rho)^{0.42} P^* (t^*) \qquad \text{watt} \qquad (1)$$

$$FR = W^{0.3} (\rho_o / \rho)^{0.21} FR^* (t^*) \qquad \text{cm} \qquad (2)$$

$$N = (1/(4\pi^2)) P^* (t^*) / [FR^* (t^*)]^2 \qquad \text{watt/cm}^2 \text{ ster} \qquad (3)$$

$$t = 0.035 W^{0.42} (\rho_o / \rho)^{-0.42} t^* \qquad \text{sec} \qquad (4)$$

The following assumed expressions for power, fireball radius, radiance and time formed the basis for the above laws.

$$P = \int_{\underline{\lambda}}^{\bar{\lambda}} P_\lambda d\lambda = W^a (\rho_o/\rho)^b P^* (t^*) \qquad (5)$$

$$FR = W^c (\rho_o/\rho)^d FR^* (t^*) \qquad (6)$$

$$N = P/(4\pi^2 (FR^2)) = (1/(4\pi^2)) W^{a-2c} (\rho_o/\rho)^{b-2d} P^*(t^*)/[FR^*(t^*)]^2 \qquad (7)$$

$$t = KW^e (\rho_o/\rho)^f t^* = t_{2max} t^* \qquad (8)$$

where

P = total power (watt)

P_λ = spectral power (watt/μ)

W = yield (KT)

ρ_o/ρ = ratio of sea level to burst height density

P^* = scaled power

t^* = scaled time

FR = fireball radius (cm)

FR* = scaled fireball radius

N = radiance (watt/cm^2 ster)

K = constant

$\underline{\lambda}$, $\overline{\lambda}$ = minimum and maximum wavelength for determination of yield.

The exponents a, b, c, d, e and f were determined from consideration of the NASL Dominic field test data and theoretical calculations reported by the AFWL and Lockheed (DASA 1589). Since no detailed first pulse data is provided by the theoretical calculations, the pulse shape was chosen to look like an average of the NASL measurements. DASA 1589 gives an equivalent color temperature history for a wide range of yields and all burst heights up to 20 km for both first and second pulses. These data support the determination of radiance by an equivalent temperature as a function of scaled time, independent of altitude and yield, for burst heights less than 15 km.

Hence, a = 2c and b = 2d. Scaling with altitude from the NASL data is not very sensitive since the range of burst heights is limited. The Lockheed calculations suggest that peak power may be scaled with b = 0.42. Then d = 0.21. The Lockheed calculations also suggest that a = 0.6 from which c = 0.3.

The total thermal yield W_T is given by

$$W_T = \int_t P dt = \int_{t*} W^a (\rho_o/\rho)^b P* (t*) K W^e (\rho_o/\rho)^f dt*$$

$$= K W^{a+e} (\rho_o/\rho)^{b+f} \int P* (t*) dt*. \quad (9)$$

where K is a proportionality constant.

AWFL and Lockheed calculations show a slightly rising thermal yield fraction with increasing burst altitude, while scaling of the Dominic low altitude data shows thermal yield fraction to decrease slowly. Consequently, the thermal yield fraction is assumed independent of air density, that is, b+f = 0 or f = 0.42. The thermal yield fraction as a function of yield is

$$W_T/W = K W^{a+e-1} \int P* (t*) dt*. \quad (10)$$

Time scaling from DASA 1589 gives e = 0.42 which is less than the 0.47 indicated by the NASL measurements. Again because of the wider range of those calculations, it is assumed that e = 0.42. This allows the thermal fraction to increase slowly with yield as $W^{0.02}$. Time to first maximum, $t*_{1max} = 2 \times 10^{-3}$, and time to minimum, $t_{min} = 7.5 \times 10^{-2}$, have not been changed from previous exposure model scalings. These values differ from those obtained with DASA 1589 but safe observer distance calculations are not sensitive to small variations in t_{min} and we have no better information than the NASL measurements for $t_{1\,max}$. The choice of K and the scale assigned to P, determine the thermal yield. The values chosen here for P at the first and second relative maxima, 8.3×10^{12} watt and 2.1×10^{13} watt respectively, are in agreement with both NASL measurements and DASA 1589 calculations. For the P* (t*) shown in Figure 1,

$$\int_0^{t^*_{min}} P^*(t^*)dt^* = 11 \times 10^{10} \text{ joules} \tag{11}$$

and

$$\int_0^{10} P^*(t^*)dt^* = 4.2 \times 10^{13} \text{ joules}$$

If K is taken as 0.035, the thermal yield fraction for the first pulse is

$$100\, W_T/W = 0.09\, W^{0.02}\% \tag{12}$$

and the total thermal yield fraction for both pulses is

$$100\, W_T/W = 35\, W^{0.02}\% \tag{13}$$

From DASA 1589, equivalent color temperatures are about 10^5 °K for the first pulse maximum and 10^4 °K for the second pulse maximum and, as noted before, not very sensitive to yield and altitude. We have therefore used a black body spectral distribution and a temperature T(t*) as shown in Figure 1. The temperature has been adjusted over the range from t* = 10^{-4} to

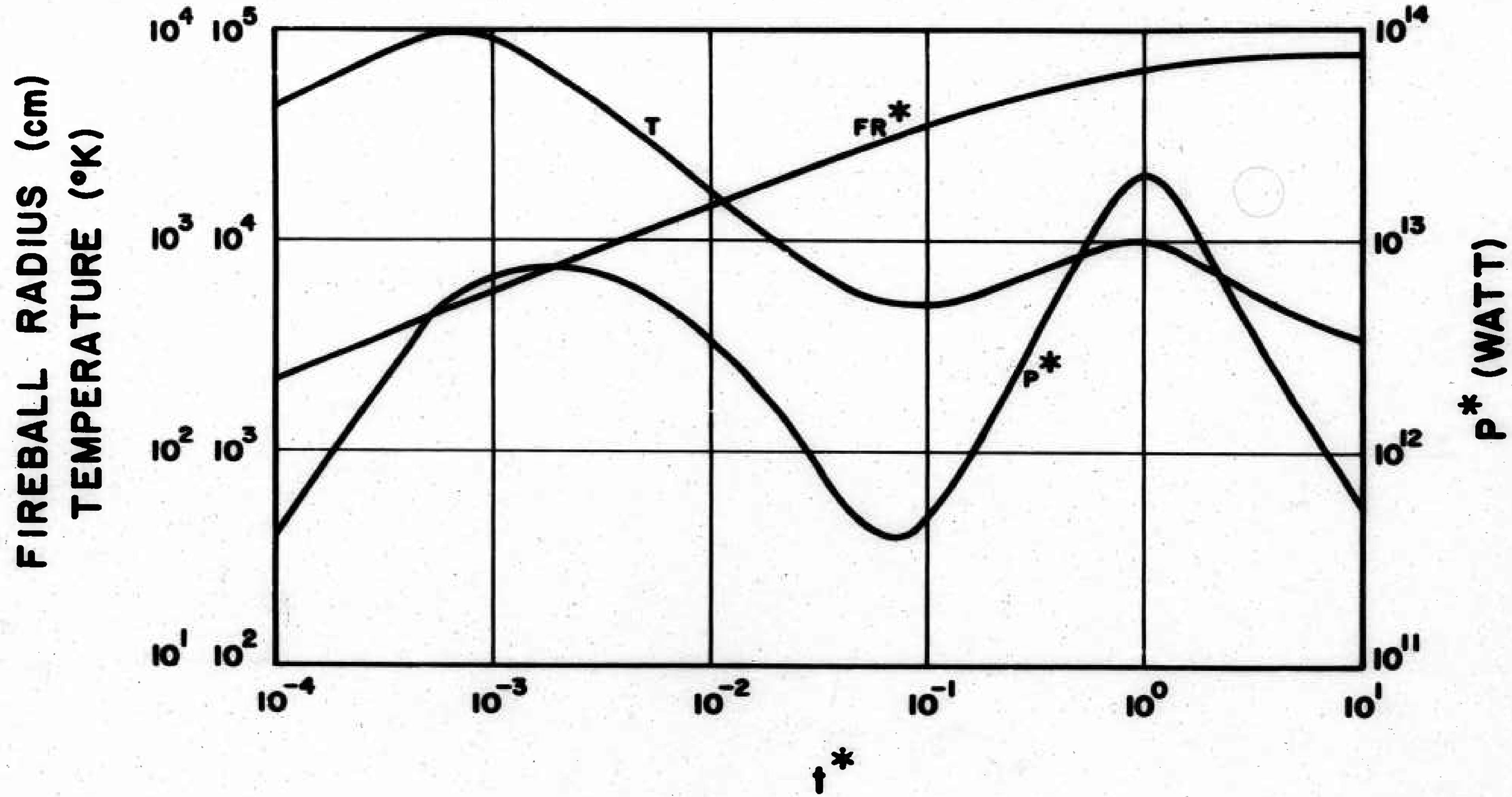

Figure 1. Fireball Radius, Power and Temperature.

$t^* = 10$ so that

$$N = 1.19 \times 10^4 \int_{0.34}^{1.71} d\lambda/[\lambda^5 (e^{1.44x10^4/\lambda T} - 1)] \tag{14}$$

$$= P^* (t^*)/(4\pi^2 [FR^*(t^*)]^2) \qquad \text{watt/cm}^2\text{ster}$$

The limits of integration on wavelength were chosen to correspond to the limits used in the field test measurements.

IV

RETINAL BURNS

A. Safe Separation Distance

The safe separation distance, R, is implicit in the equation for retinal exposure

$$Q = \int_0^{T_o} H_r dt \tag{15}$$

where

H_r = retinal irradiance

T_o = time of irradiance

It is calculated as that value of R for which

$$Q = k_s Q_c \tag{16}$$

where Q_c is the threshold exposure determined from experimental data and k_s is a safety factor. If Q_o is the retinal exposure corresponding to specific values of the safety factor, k_s, and threshold exposure, Q_c, then, corresponding to this value of Q_o, time of irradiance T_o, weapon yield, W_o, height of burst, H_o, and observer altitude A_o, a safe separation distance R_o is determined by equation (15). In order to assess the sensitivity of R to variations in the parameters Q_o, T_o, W_o, H_o and A_o, a linear equation has been derived by means of the implicit function theorem under the assumption that retinal exposure, Q, time of irradiance, t, weapon yield W, height of burst H and observer altitude A are the independent variables. The derived equation is given in equation (17) and the functional forms assumed in the derivation are briefly discussed in Section VI

$$R = R_o - [R_o L_o / (L_o^2 k_R (\phi_o) - (H_o - A_o)^2 k_R)] \{ (Q - Q_o)/Q_o \tag{17}$$

$$- [H_r(T_o)/Q_o] (t - T_o) - 0.42 [1 - T_o H_r(T_o)/Q_o] (W - W_o)/Q_o$$

$$+ [(H_o - A_o) u k_H / L_o - 0.013 (1 - T_o H_r(T_o)/Q_o)] (H - H_o)$$

$$- [(H_o - A_o) u k_A / L_o] (A - A_o) \}$$

where

$L_o^2 = (H_o - A_o)^2 + R_o^2$; This can be interpreted as the Pythagorean estimate of the slant range.

$\phi_o = R_o / E$

E = radius of the earth

k_R, k_H, k_A = are mean value estimates of the extinction coefficient in the transmission term.

u = parameter defined on the unit interval determining the proper mean value estimate.

B. Variance of Safe Separation Distance

Assuming that the parameters used as independent variables in equation (17) are in fact pairwise independent, the variance of the safe separation distance is given by

$$\sigma_R^2 = (R_o L_o)^2 / [L_o^2 k(\phi_o) - (H_o - A_o)^2 k_R]^2 \{ \sigma_Q^2 / Q_o^2 + [H_r^2 (T_o)/Q_o^2] \sigma_T^2 \tag{18}$$

$$+ 0.1764 (1 - T_o H_o(T_o)/Q_o)^2 \sigma_w^2 / W_o^2 + [(H_o - A_o)^2 u^2 k_A^2 / L_o^2] \sigma_A^2$$

$$+ [(H_o - A_o) u k_H / L_o - 0.013 (1 - T_o H_r(T_o)/Q_o)]^2 \sigma_H^2 \}.$$

where

σ_Q = standard deviation of threshold exposure

σ_T = standard deviation of exposure time

σ_W = standard deviation of yield

σ_H = standard deviation of height of burst

σ_A = standard deviation of observer altitude.

If the height of burst and observer altitudes are the same, or if the retinal irradiance is constant over the time of irradiation such that

$$Q_o = T_o H_r(T_o), \tag{19}$$

equations (17) and (18) can be simplified by deletion of the yield term and part of the height of burst coefficient.

C. Variance Estimate for Specific Conditions

Figures 2 through 9 exhibit safe separation distance curves corresponding to an assumed visibility of 60 statute miles for a selected set of yields (0.1, 1, 10, 100, 1000KT), times of irradiance (0.1 and 1.0 seconds), and heights of burst (1kft, 10 kft). Associated with each of these curves are probability curves indicating safe separation distances, where it is assumed that measurements giving rise to these curves are not exact but represent a mean value estimate of these parameters. It has been assumed that the variables used in the calculations are normally distributed variables such that

$$\sigma_Q/Q_o = 0.1$$

$$\sigma_W/W_o = 0.1$$

$$\sigma_A = 0.25 \text{ nautical mile}$$

$$\sigma_H = 0.25 \text{ nautical mile}$$

$$\sigma_T = 0.05 \text{ sec if } T_o = 0.1 \text{ sec}$$

$$\sigma_T = 0.10 \text{ sec if } T_o = 1.0 \text{ sec}$$

Figure 2 contains the safe separation distance curves for yields of 0.1 and 1 KT with a one thousand foot height of burst. These curves are labeled P_{50} (0.1) and P_{50} (1.0) respectively. The subscript 50 indicates that under the assumed normal distribution of the variables, there is a 50% chance that the safe separation distance will not exceed the indicated values. Associated with each yield are two other probability curves corresponding to the safe separation distances below which the true value can be expected to lie 75 and 95% of the time. These curves illustrate that with increased observer altitude, the potential error in the calculated safe separation distance increases.

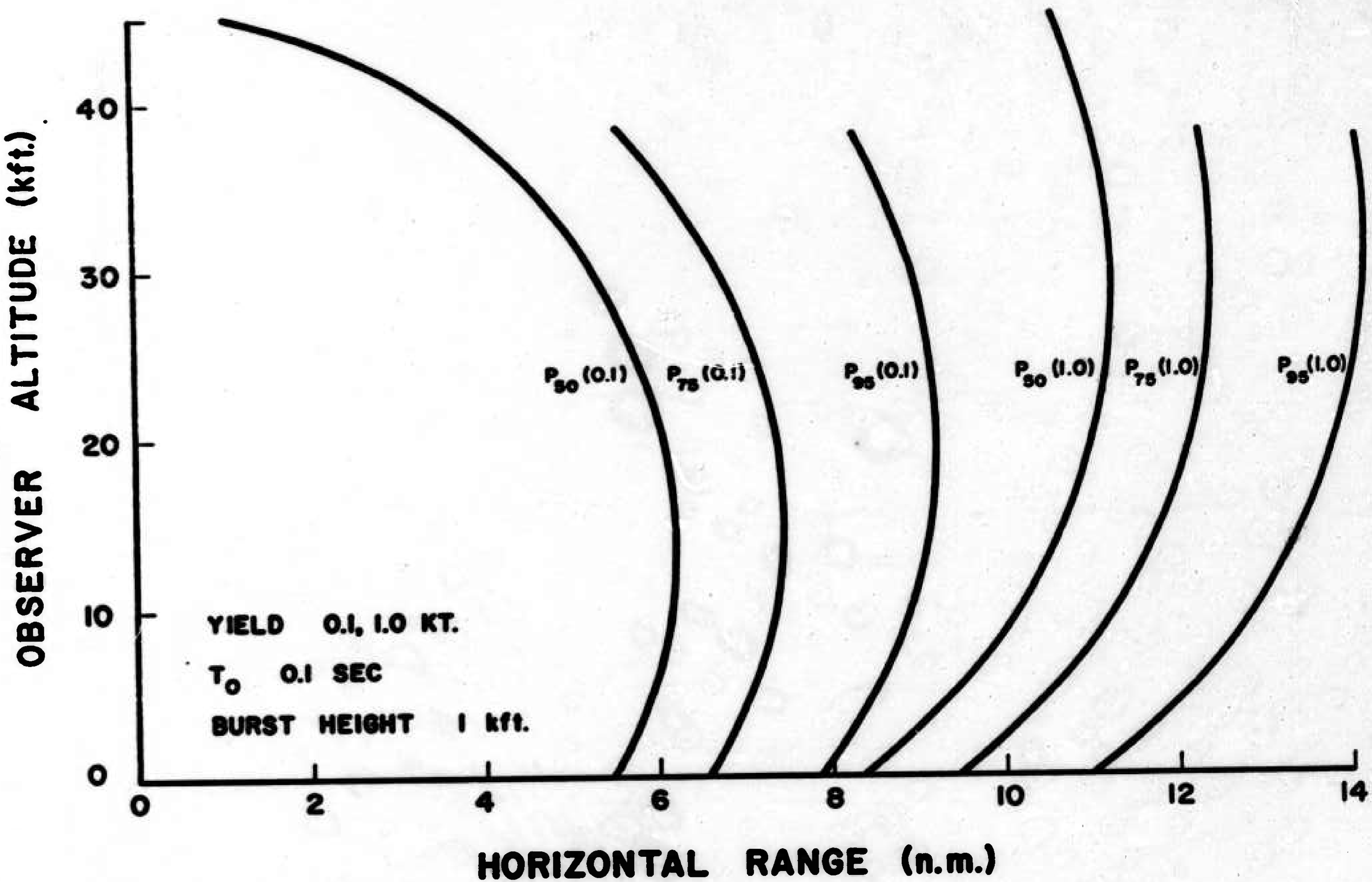

Figure 2. Safe Separation Distance and Probability Boundaries

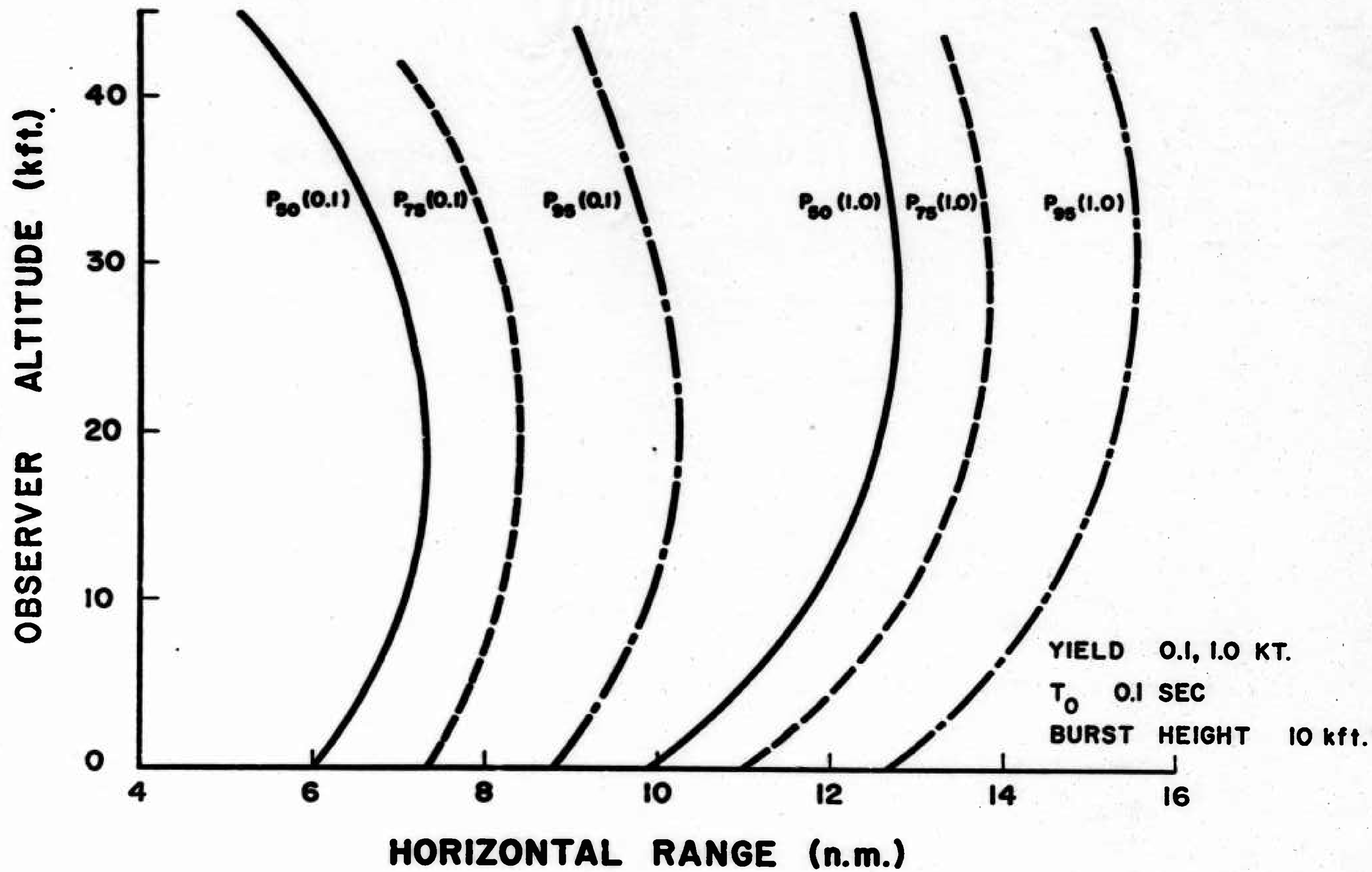

Figure 3. Safe Separation Distance and Probability Boundaries

Figure 3 is similar to Figure 2 except that the height of burst is 10 kft. In both figures, the potential relative error in calculated safe separation distance is large. It should be observed that, as borne out by the standard deviations as given in Table 1, the absolute errors for low altitude bursts are of the same order of magnitude for yields from 0.1 to 1000 KT. The relative error, however, decreases as the safe separation distance increases.

On each of the Figures 4 through 9 are two base curves representing the calculated (mean) value for safe separation distance for the given yield and height of burst. The two curves are distinguished by the assumed mean cutoff times (0.1 and 1.0 seconds) and are again interpreted as the values below which the safe separation distance will occur 50% of the time. Associated with each of these curves are again probability curves bounding the safe separation distance at the indicated probability level. For these yields (10, 100 and 1000 KT), a greater homogeneity of variance was experienced and the dependence on observed height is all but suppressed for the range of calculations made and used in the graphs.

For the 100 KT yield curve with cutoff of the time of irradiance of 0.1 second, the standard deviation is about 20% larger than for other yields and cutoff times. This anomaly occurs when the cutoff time is near a critical point on the radiance curve, grossly affecting the time coefficient in the variance equation. This effect will be realized to some extent whenever the cutoff time occurs near a thermal maximum.

TABLE 1

STANDARD DEVIATION OF THE SAFE SEPARATION DISTANCE

(Nautical Miles)

	Height of Burst (kft)	Observer Altitude (kft) 0	10	20	30	40k
W = 0.1						
T_o = 0.1	1	1.64	1.72	1.92	2.24	
	10	1.69	1.64	1.69	1.86	2.09
W = 1.0						
T_o = 0.1	1	1.63	1.64	1.70	1.78	
	10	1.64	1.63	1.64	1.68	1.77
W = 10						
T_o = 0.1	1	1.69	1.70	1.74	1.78	
	10	1.69	1.69	1.69	1.72	1.75
T_o = 1.0	1	1.66	1.66	1.69	1.74	
	10	1.66	1.66	1.66	1.68	1.70
W = 100						
T_o = 0.1	1	2.16	2.16	2.18	2.22	
	10	2.16	2.16	2.16	2.18	2.21
T_o = 1.0	1	1.64	1.64	1.65	1.67	
	10	1.64	1.64	1.64	1.65	1.66
W = 1000						
T_o = 0.1	1	1.72	1.72	1.73	1.74	
	10	1.72	1.72	1.72	1.73	1.74
T_o = 1.0	1	1.58	1.58	1.58	1.59	
	10	1.58	1.58	1.58	1.58	1.59

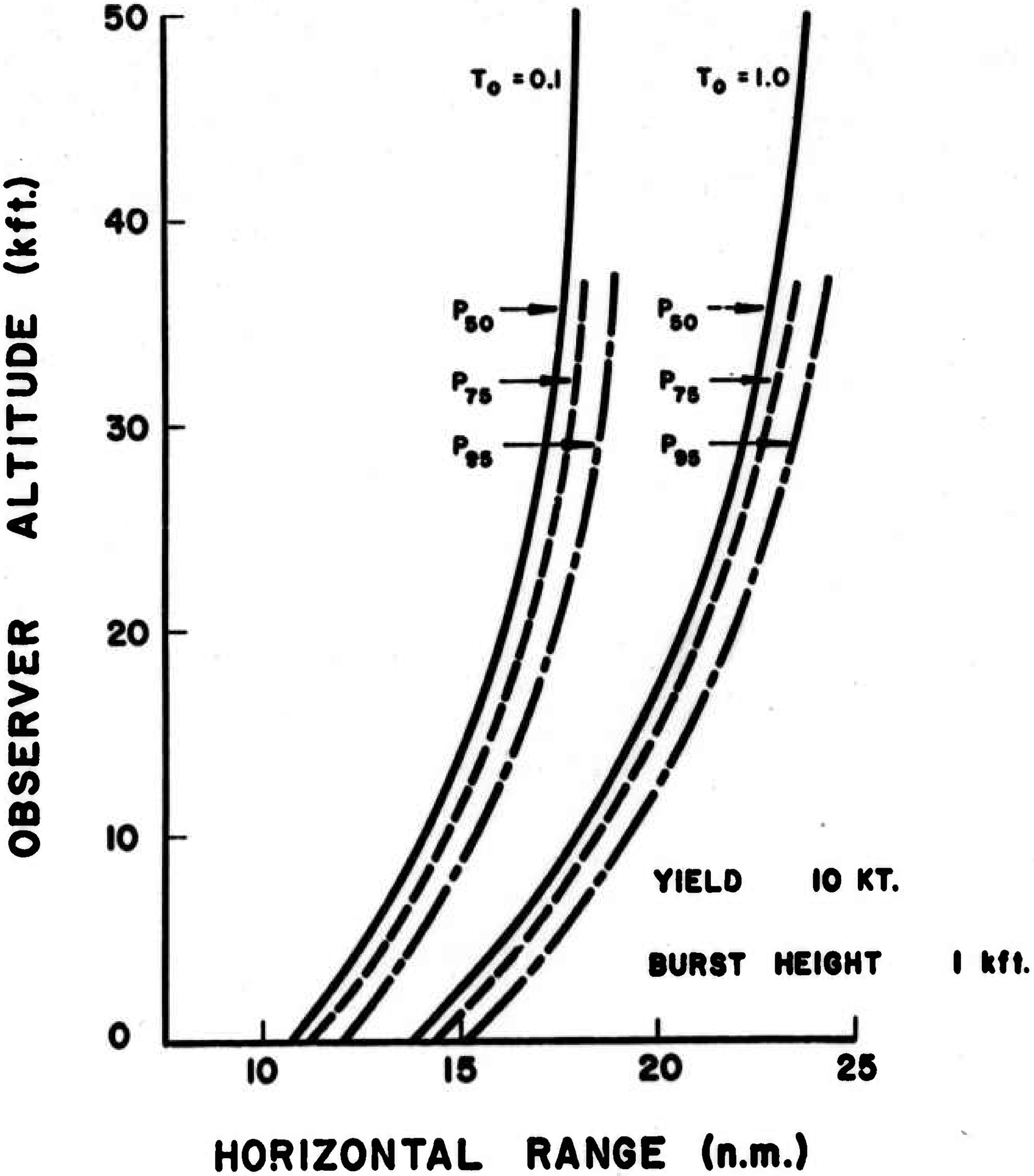

Figure 4. Safe Separation Distance and Probability Boundaries

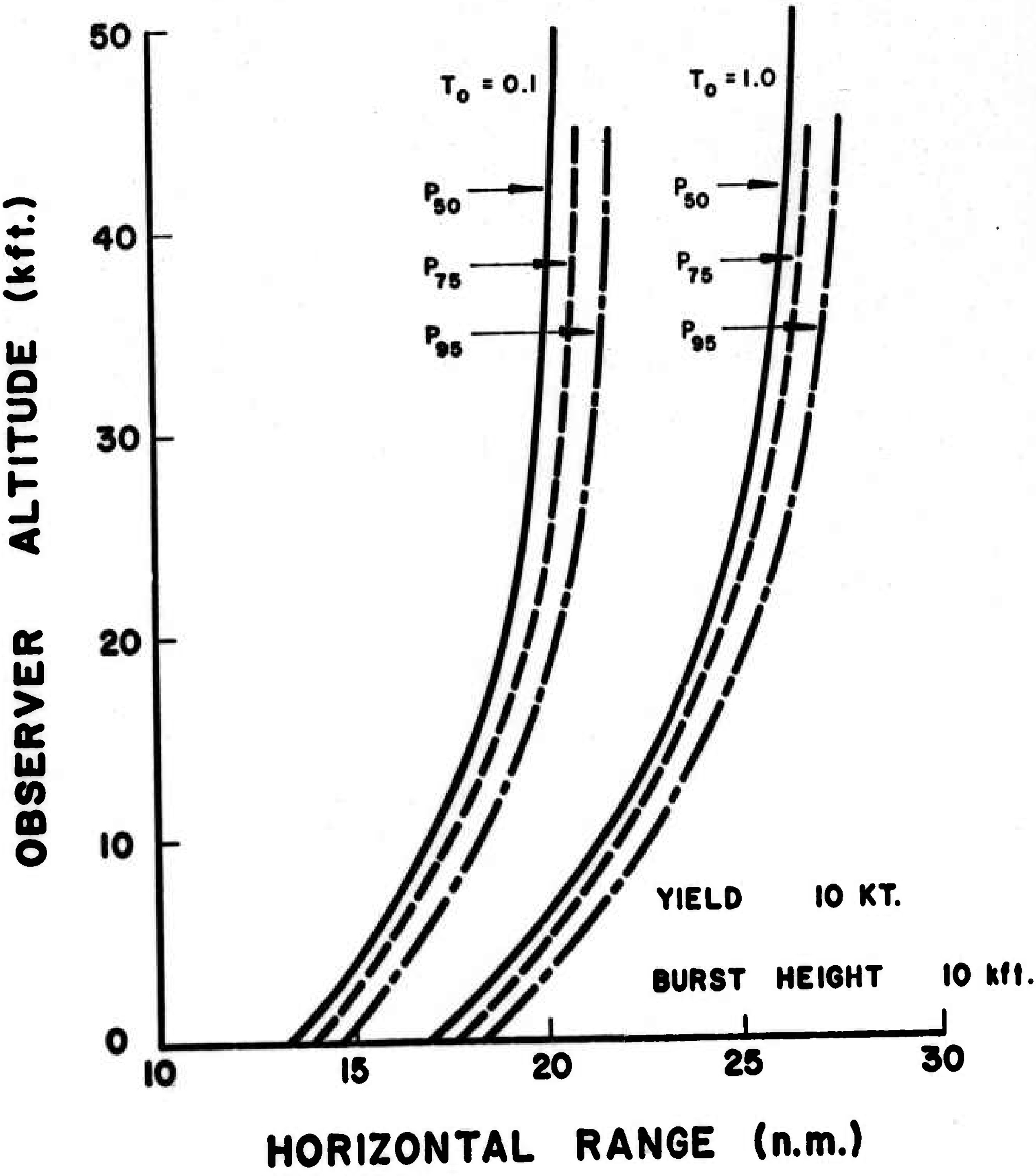

Figure 5. Safe Separation Distance and Probability Boundaries

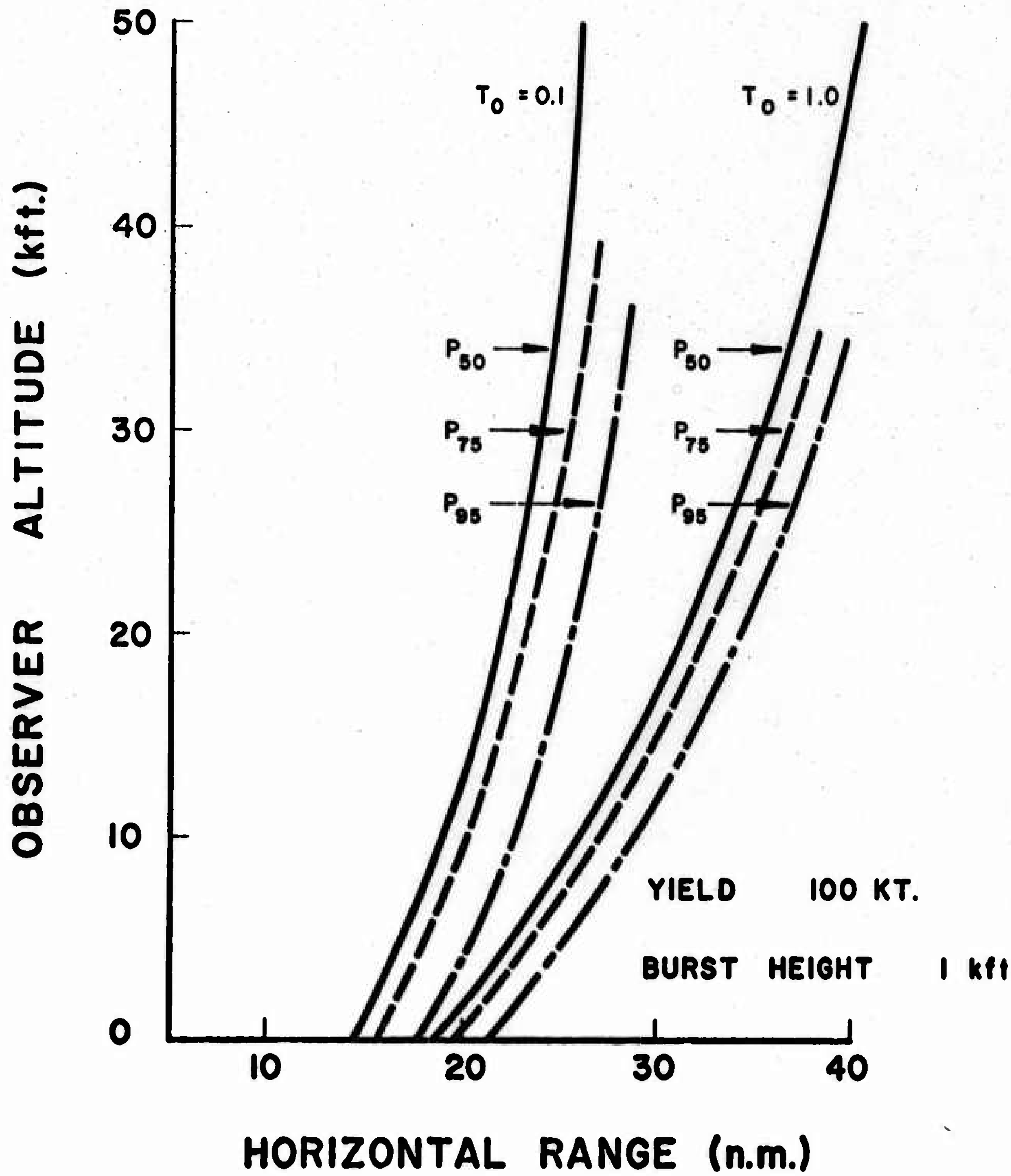

Figure 6. Safe Separation Distance and Probability Boundaries

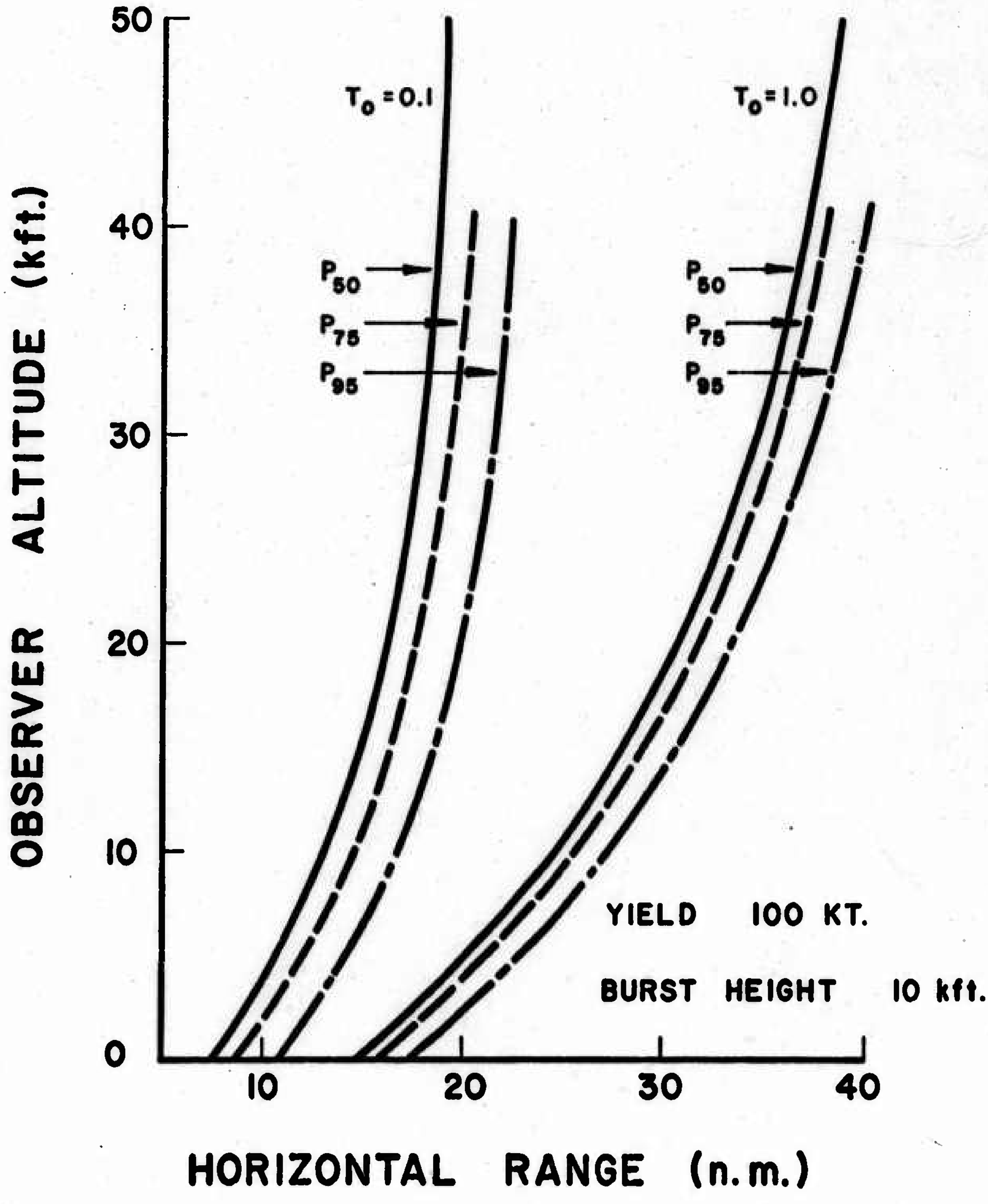

Figure 7. Safe Separation Distance and Probability Boundaries

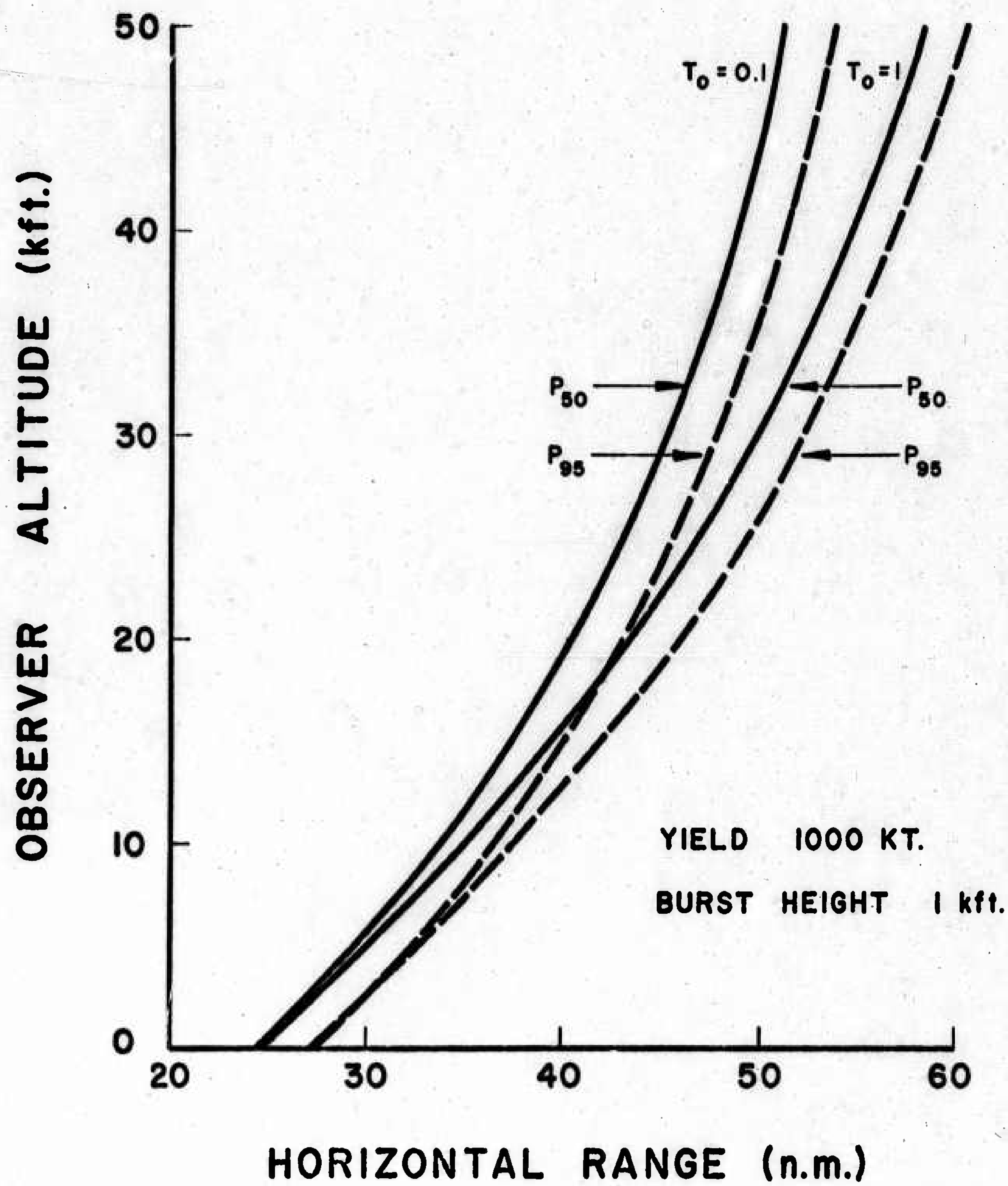

Figure 8. Safe Separation Distance and Probability Boundaries

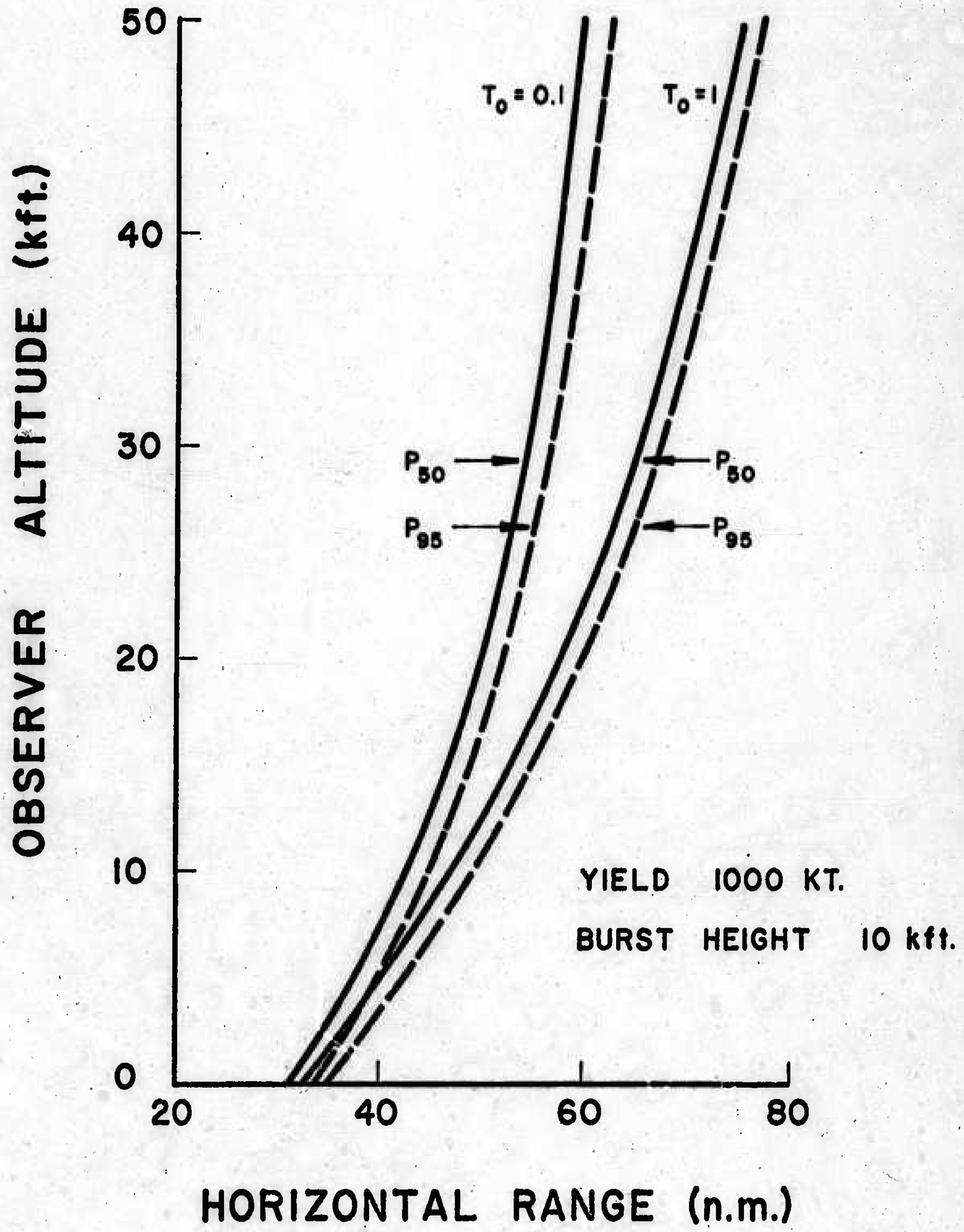

Figure 9. Safe Separation Distance and Probability Boundaries

V

FLASHBLINDNESS

The problem of determining safe separation distances for protection from flashblindness is related to determining safe separation distance for retinal burns in that a threshold exposure, depending on observer-instrument conditions, is used in prescribing the distance. The assumption is made that if the exposure to the retina at a radius of 450μ from the center of the fovea does not exceed a critical value, visual acuity will recover in ten seconds or less. The equation is then

$$F\,E_r \big|_{450\mu} = E_c \big|_{450\mu} \qquad (20)$$

where

F >1 is a safety factor (4 is currently being used)

E_r is exposure received

E_c is the critial exposure of 450μ image for 10 seconds recovery

8×10^5 troland seconds (night)

2×10^7 troland seconds (day)

Estimates of intraocular scattering and atmospheric scattering have been made from experimental data and used for exposure calculations of images with radii in excess of 450μ when the exposure exceeded E_c/F. These estimates can be improved by calculating the retinal image and exposure from a transfer function. The effect of atmospheric scattering on the retinal image of the source is considered to be negligible for high visibility atmospheres.

The optics of the eye are such that beyond 50μ from the edge of the geometrical image, the light intensity may be neglected. We have therefore used the exposures from the image center out to the distance where image radius is 450μ with zero exposure at greater distances. The problem is then to find the slant range S, so that:

$$F E_r = E_c \text{ if radius of image} \geq 450\mu \tag{21}$$

$$S = FR \times 17000/450 \text{ if radius of image} < 450\mu$$

where

FR is the fireball radius and E_r is calculated from

$$E_r = 2.24 \times 10^7 \ (PD_{eff})^2 \sum_j \sum_i V_{\lambda_i} N_{\lambda_i t_j} T_{\lambda_i} \Delta \lambda_i \Delta t_j \tag{22}$$

$$PD_{eff} = PD \sqrt{1 - 0.85 \ PD^2/8 \ + 0.002 \ PD^4/48.} \tag{23}$$

The parameters in these equations are

PD = pupil diameter (see section VIB).

V_{λ_i} = "visibility" function

$N_{\lambda_i t_j}$ = spectral radiance

$T_{\lambda_i}(S)$ = spectral transmissivity of optical path (fireball to cornea only).

Since equation (22) is functionally similar to equation (15) as considered in section IV, a separate analysis has not been made. Similar conclusions may however be drawn. The standard deviation for the safe separation distance is not expected to differ appreciably from that for retinal burns.

VI

FUNCTIONAL PARAMETERS OF THE RETINAL EXPOSURE

The linearized equation for the safe separation distance (equation 17) was derived from the total differential of the retinal exposure equation by using the implicit function theorem. The retinal irradiation, used in equation (15) to define the retinal exposure, is expressed as a functional of the source spectral power, P_λ, fireball radius, FR, f-number of the eye, f, and the transmission terms, T_r, as

$$H_r = \int_{\underline{\lambda}}^{\bar{\lambda}} P_\lambda(W,H,t)\, T_r(H,A,R,\lambda) / (16\pi f^2(t) FR^2(W,H,t))\, d\lambda \quad (24)$$

To calculate the required partial derivatives and investigate their contribution to the linear equation for the safe separation distance and the variance equation, the functional forms of these several functions will now be considered.

A. Source Spectral Power and Fireball Radius

The functional form of the source spectral power and fireball radius were considered in section III with figure 1 providing curves to represent these functions in terms of scaled time. The retinal exposure equation can also be written as a function of source radiance by using equations (3), (24) and (15) giving

$$Q = \pi/4 \int_0^{T_0} \int_{\underline{\lambda}}^{\bar{\lambda}} N T_r / f^2(t)\, d\lambda dt. \quad (25)$$

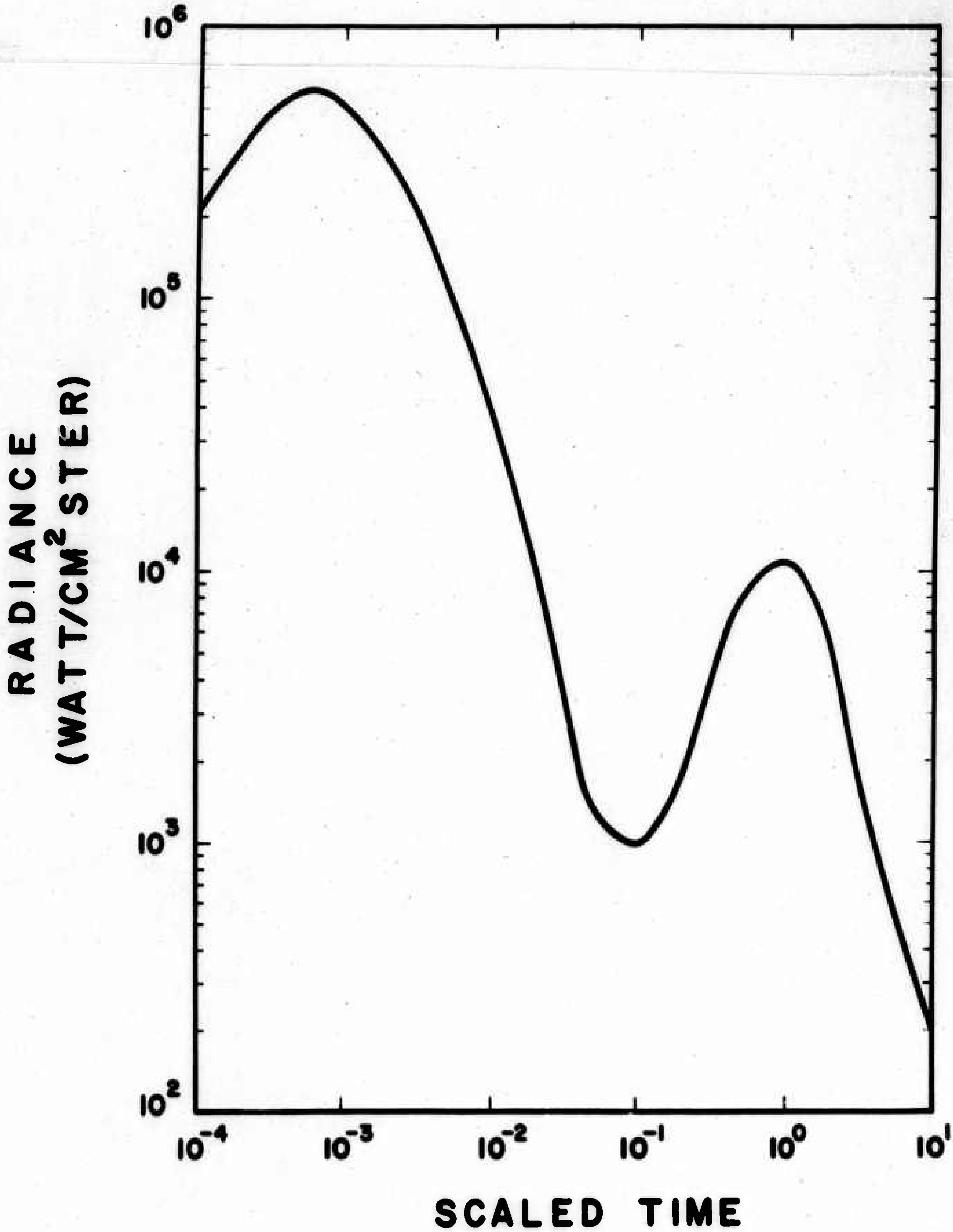

Figure 10. Fireball Radiance.

This form is useful in calculating two of the needed partial derivatives. The data for this curve was taken from the values of P and FR of Figure1, but could have been derived from the fireball temperature curve and radiance equation (14).

B. Pupil Response

Pupil response to the incident radiation enters the exposure calculations through the f-number of the eye. Measurements of pupil response have been made by various researchers since 1760, and has been summarized by Lowenfeld (1). The correlation of experimental measurements relating the square of the f-number and time in the interval between the latent period of no response (lasting 150-300 msec) and the time minimum pupil size is reached (approximately 2 sec.) is good. Thus for this investigation, the following behavior has been assumed,

$$f^2 = f_o^2 \qquad 0 \le t \le 0.3 \text{ sec.}$$

$$f^2 = f_o^2 + 15.35\,(t-0.3) \qquad 0.3 \le t \le (32-f_o^2)/15.35 + 0.3 \qquad (26)$$

$$f^2 = 32 \qquad 0.3 + (32-f_o^2)/15.35 \le t$$

where f_o is the initial f-number of the eye. It is further assumed that the square of the f-number of an eye with a 3mm pupil diameter is 32 (i.e. 17mm focal length).

C. Transmission Term

In addition to radiation wavelength, the transmission term depends on the fireball - observer distance, height of burst and observer altitude. It then contributes to three of the terms in the linearized safe separation distance equation and variance estimate. The attenuation of the radiation emitted from the fireball results primarily from Rayleigh scattering by atmospheric molecules, and particulate scattering such as considered in the Mie theory.

The transmission of radiation for a given wavelength λ is given by

$$T_r = \exp\left(-\int_L k_\lambda \, ds\right) \tag{27}$$

where k_λ is the monochromatic extinction coefficient and the integration is carried out over the optical path of the radiation.

The maximum tranmissivity will be realized for an atmosphere devoid of aerosols and other particulates. In this case the Rayleigh molecular scattering theory would apply and monochromatic extinction coefficient, though not constant, is approximated by

$$k_\lambda \approx [\, 32\pi^3 (n_o-1)^2 \,/\, 3L_o \lambda^4 \,]\, (\rho/\rho_o). \tag{28}$$

In this equation

n_o = index of refraction of air at standard temperature and pressures.

L_o = Loschmidt's number - 2.68726×10^{19} molecules/cm^3

ρ = density of air at height of evaluation.

ρ_o = density of air at standard temperatures and pressures.

λ = wavelength of radiation.

For atmospheres with water aerosols and dust particles the extinction coefficient is modified by the addition of terms such as given in the Mie scattering theory. As a single term it is a summation over the different sized particles and can be written

$$k_p = \sum N_i \pi a_i^2 K(\alpha_i) \tag{29}$$

where

N_i = density of particles of radius a_i (number of particles per unit volume)

α_i = $2 \pi a_i / \lambda$ (dimensionless)

$K(\alpha)$ = an efficiency factor depending upon wavelength of radiation and electromagnetic properties of material forming particle (dimensionless).

Water as a liquid aerosol is a major constituent of our atmosphere, however, the distribution of particle sizes varies considerably. A graph of the efficiency factor for such an aerosol is given in Figure 11. Tabled values of the efficiency factor for various values of α and indices of refraction of the liquid can be found in Middleton.[2]

Dust particles, also constituents of the atmosphere, may be metallic or dielectric, each presenting different scattering coefficients. Curves taken from Hynek[3] showing the relative behavior of metallic and dielectric

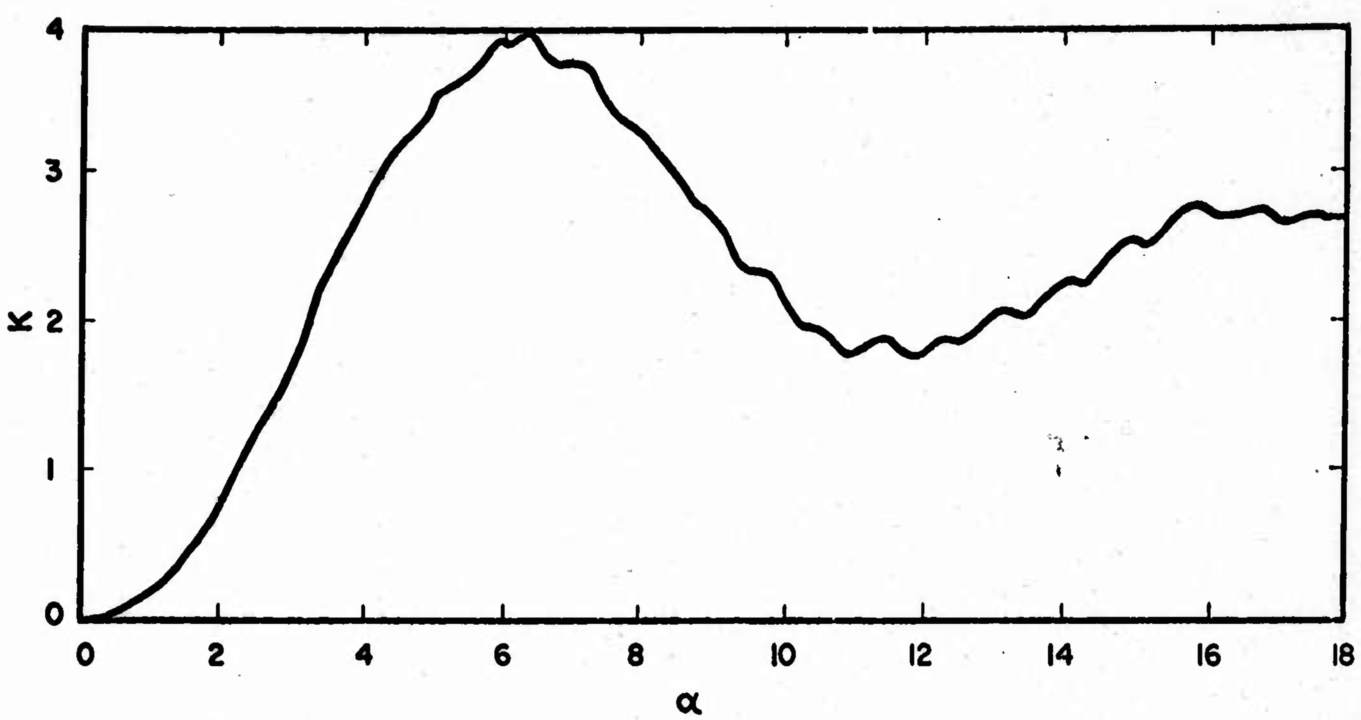

Figure 11. Efficiency Factor for Non-absorbing Spherical Particles

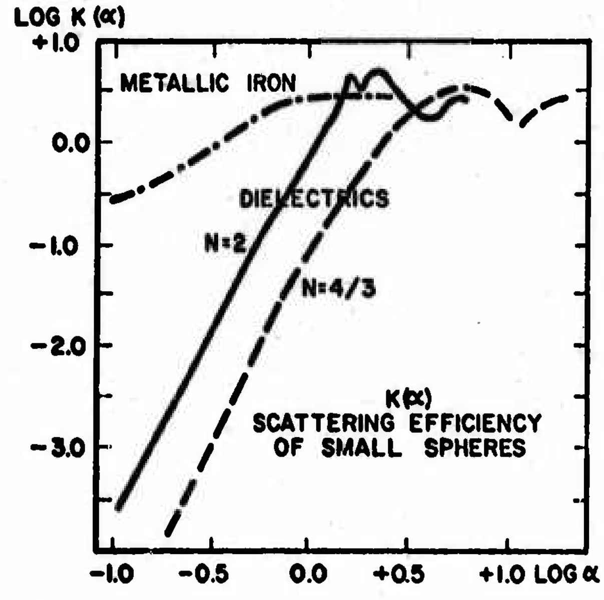

Figure 12. Logarithmic Plot of Efficiency Factor for Dielectrics and Metals

materials are given in Figure 12. Solid particles have an enormous absorbing power if they are of the most efficient size and can contribute substantially to the attenuation of radiation. For example, 0.1 mg of solid matter spread over 1 cm^2 gives nearly complete opacity, while 1 kg of gas per square centimeter is almost completely transparent.

The limitations of using the theoretical formulation for the transmission term in determining the coefficient of the linearized equation are evident. In particular, one must make allowances for variations in the atmospheric density and unknown nature of the aerosol and other particulate distributions. Practical estimates of the attenuation can be made from the definition of visibility as given by Johnson[4] when order of magnitude estimates are necessary. Using this definition and an assumed threshold of brightness contrast of 0.02, the attenuation coefficient, k, and range of visibility, V, then must satisfy the relationship

$$kV = 3.912 \tag{30}$$

This result will be used in determining a value for k to be used in the variance estimates. In evaluating the partial derivatives, however, the variability of k and its relationship to the transmission through equation (27) must be considered.

D. <u>The Partial Derivatives of Retinal Exposure</u>

The linearized equation for the safe separation distance is fundamentally a differential relationship with the coefficients being derived from quotients of partial derivatives. Using equation (25) as the basic equation for retinal exposure, expressions for the partial derivatives can readily be obtained.

1. Time

The partial derivative of the retinal exposure with respect to the time of irradiation is the simplest to obtain, since this time enters the equation only as the upper limit in the final integration. Hence, by the fundamental theorem of calculus

$$\partial Q/\partial T_o = H_r(T_o). \tag{31}$$

This partial derivative indicates that the rate of change of retinal exposure with respect to changes in time of exposure is equal to the retinal irradiance at the time of cutoff, a fact corresponding to the definitions.

2. Yield

Yield dependence is immersed in the functions for source power and fireball radius. However, by transforming the variable of integration from real time to scaled time and taking advantage of the apparent independence of spectral radiance on yield, one gets

$$Q = 0.035(\pi/4)W^{0.42}(\rho/\rho_o)^{0.42} \cdot \int_o^{T^*} \int_{\underline{\lambda}}^{\overline{\lambda}} N(t^*)[\tau_r/f^2(t^*)]d\lambda dt^* \tag{32}$$

where

$$T_o = 0.035\, W^{0.42}\, (\rho/\rho_o)^{0.42}\, T_o{*}. \quad (33)$$

It follows that

$$\partial Q/\partial W\ (0.42/W)[Q - T_o H_r(T_o)]. \quad (34)$$

If the retinal irradiance is constant over the time of exposure, the factor in brackets will vanish identically. This, however, is not the case for nuclear fireballs. As a function of T_o, this factor can be positive or negative, a fact considered again in section VII B.

3. Safe separation distance, height of burst and observer altitude.

To evaluate the partial derivatives with respect to the variables R, H, and A (safe separation distance, height of burst and observer altitude), the transmission terms are brought into play, which in turn involve a line integral evaluated along the optical path. For ease in computation, the variables R, H and A are expressed in polar coordinates with the origin at the center of the earth. Then with E the earth's radius, one defines.

$$\phi_o = R/E \quad (35)$$

$$r = (E+A)(E+H)\sin\phi_o / [(E+H)\sin(\phi_o - \phi) + (E+A)\sin\phi]. \quad (36)$$

In equation (36) $\phi = 0$ prescribes the radial coordinate of the observer and $\phi = \phi_o$ the radial coordinate of the fireball. The differential of arc length along the line of sight is given by:

$$(ds)^2 = [\, r^2 + (dr/d\phi)^2 \,]\ (d\phi)^2 = r^4 \theta^2 \,(d\phi)^2 \tag{37}$$

where

$$\theta = [\sqrt{(H-A)^2 + 2\,(1-\cos\phi_o)\ (E+A)\ (E+H)}\,]/\,[(E+A)\ (E+H)\sin\phi_o]$$

The partial derivative of retinal exposure with respect to the safe separation distance R can be written

$$\partial Q/\partial R = \pi/4 \int_o^{T_o} \int_{\underline{\lambda}}^{\bar{\lambda}} NT_r/f^2 \cdot \partial \ln T_r/\partial R \; d\lambda\, dt \tag{38}$$

with similar expressions in the other two partial derivatives. Since

$$\ln T_r = -\theta \int_o^{\phi_o} r^2 k_\lambda \, d\phi \tag{39}$$

$$\partial(\ln T_r)/\partial R = (-1/E)\{\, 2\theta \int_o^{\phi_o} r\, \partial r/\partial\phi_o \; k_\lambda \, d\phi$$
$$+ \theta\,(E+H)^2 k_\lambda \big|_H + \partial\theta/\partial\phi_o \int_o^{\phi_o} r^2 k_\lambda \, d\phi \,\} \tag{40}$$

$$\partial(\ln T_r)/\partial H = -2\theta \int_o^{\phi_o} r\,(\partial r/\partial H)\, k_\lambda \, d\phi$$
$$\partial\theta/\partial H \int_o^{\phi_o} r^2 k_\lambda \, d\phi \tag{41}$$

$$\partial(\ln T_r)/\partial A = -2\theta \int_o^{\phi_o} r\, \partial r/\partial A \; k_\lambda \, d\phi$$
$$-(\partial\theta/\partial A) \int_o^{\phi_o} r^2 k_\lambda \, d\phi. \tag{42}$$

Since the retinal exposure is an increasing function of time and the length of the radiation interval $(\underline{\lambda}, \overline{\lambda})$, the first mean value thorem for Stieltjes integrals[5] can be applied to equation (38) to yield

$$\partial Q/\partial R = -Q\ \{(2\theta/E) \int_0^{\phi_o} r\,(\partial r/\partial\phi_o)\, k_R d\,\phi\ + \tag{43}$$

$$(E+H)^2\ \partial k_R(H)/E + (1/E)\ \partial\theta/\partial\phi_o \int_0^{\phi_o} r^2 k_R d\,\phi\ \}.$$

The coefficient k_R is that value of the monochromatic extinction coefficient, k_λ, selected from the interval $(\underline{\lambda}, \overline{\lambda})$ to bring about equality. The existence of this value is assured by the above mean value theorem. In this application, k_R, is independent of wavelength.

By use of similar arguments

$$\partial Q/\partial A = -Q\ \{\ 2\theta \int_0^{\phi_o} r(\partial r/\partial A)\ k_A d\phi \tag{44}$$

$$+(\partial\theta/\partial A) \int_0^{\phi_o} r^2 k_A d\,\phi\}$$

where k_A is the appropriate value of monochromatic extinction coefficient to assure equality, again independent of wave length.

The partial derivative with respect to height of burst has an additional term resulting from the dependence of the radiance on this parameter. This additional term is obtained by transforming to scaled time and differentiating as was done for yield. Again, with an appropriate value of k_H,

$$\partial Q/\partial H = -Q \{ 2\theta \int_0^{\phi_0} r(\partial r/\partial H)\, k_H d\phi + (\partial\theta/\partial H) \int_0^{\phi_0} r^2 k_H d\phi \} \qquad (45)$$

$$+ [0.42/(\rho/\rho_0)]\, [\partial(\rho/\rho_0)/\partial H]\, [Q - T_0 H_r (T_0)]$$

Since R, H and A are small relative to the earth's radius, E, some simplifying approximations can be made without significantly affecting the values of the partial derivatives. In particular, terms which are of the order of E^{-1} can be, and have been dropped in the following coefficient evaluations.

VII

ESTIMATES OF COEFFICIENT VALUES

The coefficients appearing in the linearized equation for safe separation distance and the variance equation are not constants but are dependent upon the parameter values near the conditions about which the behavior is to be assessed. In this section, estimates of the coefficient values are made for use in estimating the total variance in the safe separation distance calculations.

A. Threshold Exposure

The coefficient of threshold exposure as it appears in the linearized equations is the reciprocal of the partial derivative of threshold exposure with respect to the safe separation distance. This term squared is the coefficient of the threshold exposure variance in the variance equation. If the values of the atmospheric attenuation coefficient k_R (H) and k_R are approximately equal, the threshold exposure coefficient can be written in a simplified form, that is

$$R_o\sqrt{(H_o-A_o)^2+R_o^2}/(\{[(H_o-A_o)^2+R_o^2]k(\phi) - (H_o-A_o)^2 k_R\}Q) \approx \sqrt{(H_o-A_0)^2+R_o^2}/(kR_oQ) \qquad (46)$$

In this latter expression, k is also a mean value estimate for the atmospheric attenuation, independent of the radiation wavelength. By assuming a 60 mile visibility, and using equation (30) to estimate k, k^{-1} is 15.34 miles, the value used in making the following estimates.

In evaluating the variance, the factor $1/Q$ in equation (46) is associated with the standard deviation of the threshold exposure σ_Q to give the ratio σ_Q/Q. The standard deviation σ_Q is a measure of the dispersion of threshold exposure values experienced by the hypothetical population receiving retinal burns. Since this population is limited, animal data has been used to estimate the values of σ_Q/Q. The Life Sciences division of Technology Incorporated has carried out experimental studies to determine the threshold exposure for retinal burns in rabbits[6] and later in primates.[7] Problems of correlating the animal data to human eye response and pulse profiles of nuclear detonations still remained. Complications arise in that the threshold is not only a function of image size, intensity and exposure duration, but also appears to depend upon retinal temperature.

TABLE 2

RATIOS OF STANDARD DEVIATION TO THRESHOLD EXPOSURE FOR 5 HOUR BURN THRESHOLDS ON MACACCA MULATTAS

Image Diameter mm	Exposure Time (msec) 2	10	40	100	1000	Average; fixed image dia.
1.46		.046	.031	.053	.100	.06
0.72	.028	.150	.068	.111	.137	.10
0.35	.036	.074	.059	.068	.102	.07
0.25	.002	.031	.040	.058	.068	.04
0.12	.016	.051	.030	.035	.040	.03
Average; fixed exposure time.	.02	.07	.06	.07	.09	.06

The ratios of standard deviation to threshold exposures exhibited in Table 2 were derived from five hour burn threshold data taken from experiments on Macacca Mulattas as reported by Miller.[8] The optical structure of the monkey's image forming media is scaled proportionally to that of the human, hence it is assumed that the ratios of standard deviation to threshold exposure is the same. To be on the conservative side, it has been assumed that

$$\sigma_Q/Q \approx 0.10 \qquad (47)$$

This value corresponds to the largest average for the image diameters in Table 2.

B. Retinal Irradiance

Retinal irradiance contributes to the coefficient for the time of irradiation and also enters into the equations through a factor modifying the coefficients of yield and height of burst. Retinal irradiance defined in equation (24) can be approximated by

$$H_r \approx [\pi N^*(t^*)/4f^2(t^*)]\int_{\underline{\lambda}}^{\overline{\lambda}} T_r d\lambda \qquad (48)$$

This relationship allows the use of the source radiance of Figure 10 in discussing the behavior of the terms influenced by retinal irradiance.

The effects of time variation can be estimated by observing that

$$[H_r(T_o)/Q_o]^2 \quad \sigma_T^2 \approx [H_r(T_o)\Delta T_o/Q_o]^2. \qquad (49)$$

The expression $H_r(T_o)\Delta T_o$ is the last term in the Riemann sum representing the integral for Q_o. The ratio $H_r(T_o)/Q_o$ for times in excess of 30 milli-units scaled time is plotted in Figure 13. From this curve it is evident that for a given time increment, the maximum contribution to the variance will occur in the neighborhood of the second thermal maximum. If Δt is taken to be 0.1 second, the contribution by the expression in equation (49) is 0.04. If, however, the variation in Δt is 0.5 second, this term has a value of 1, evidence of the importance of fast reliable time mechanisms for cutting off the radiation.

Retinal irradiance is the primary element through which the time of irradiation induces variations in the safe separation distance. This in turn can be modified by pupil response. By using the time scaling equation (4) and setting $t_{2\,max} \leq 0.3$ sec, ($t^* = 1$),

$$W\,(\rho/\rho_o) \leq 167 \qquad (50)$$

defines the region where safe observer distance determined by the second power peak will be affected. For values of W and ρ/ρ_o below the hyperbola of equation (50), the pupil will not begin to shut down until after t_{2max}. At sea level the effect begins at about 167 KT and at a 15 km height of burst at about 1 MT. If t_{min}=0.3 sec, the pupil response will effect the entire second pulse. This would occur for a sea level yield of about 80 MT.

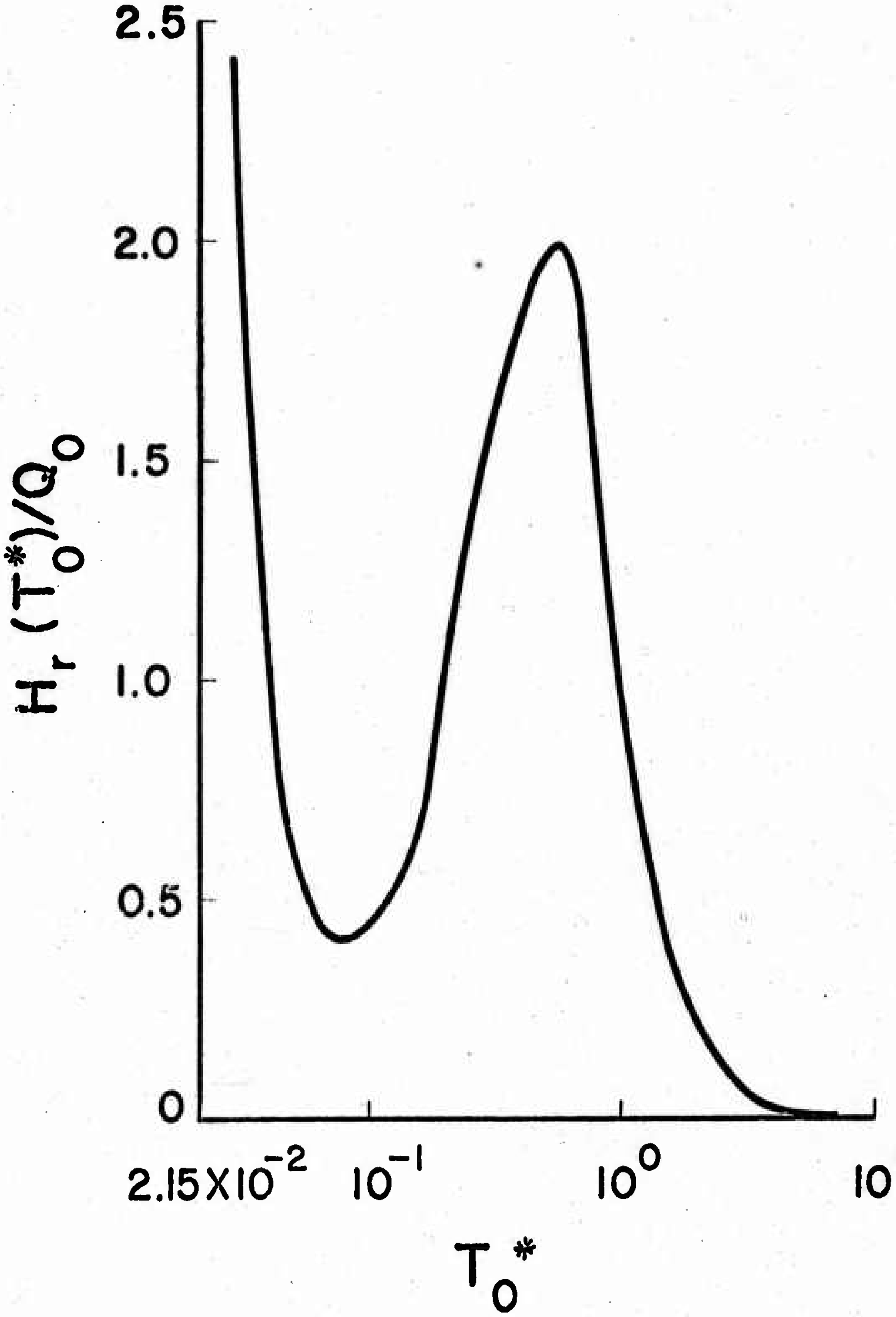

Figure 13. Irradiance - Exposure Quotient

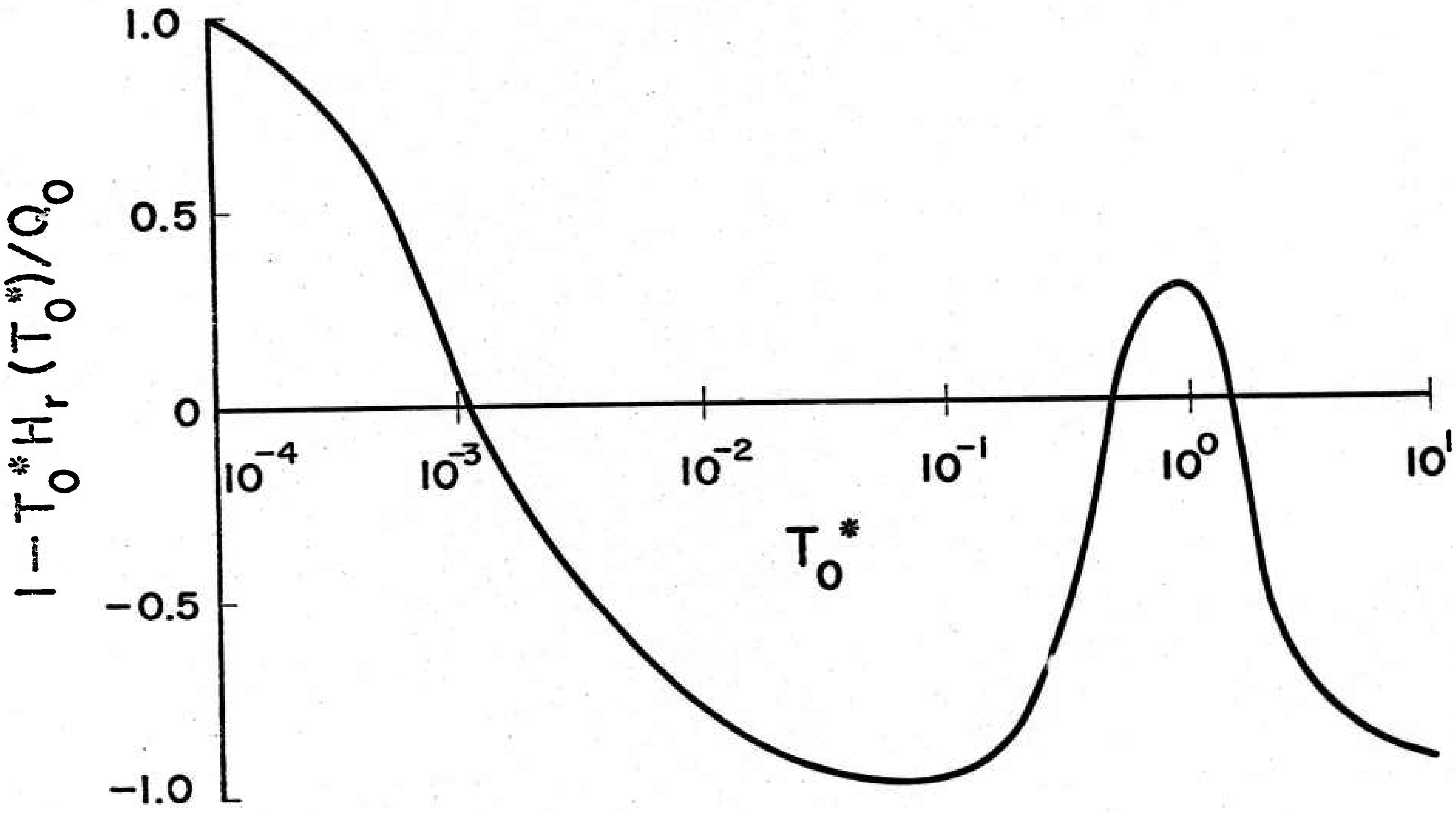

Figure 14. Time Dependent Correction Factor

The retinal irradiance also enters into the equations as a modifier of the yield and height of burst coefficients through the dimensionless number.

$$1 - T_o H_r(T_o)/Q_o \tag{51}$$

This quantity is plotted as a function of the scaled time of irradiation in Figure 14, and is seen to be bounded between plus and minus one with positive values occuring only when near a time of maximum radiance. The possible change in sign has an influence on whether, for a given cutoff time, increasing the yield increases or decreases the safe separation distance. This kind of behavior is expected when one considers that changes in yield, according to the scaling relationships, will change the real times of thermal maximums.

For scaled times in excess of 5×10^{-4}, this modifier suppresses the contribution to the total variance from weapon yield and height of burst, except when the cutoff time is near the thermal minimum or for times in excess of three units scaled time.

C. Yield

The contribution to the variance by yield is given by

$$VW = 0.1764\{[(H_o - A_o)^2 + R_o^2]/[R_o^2 k^2]^2\}. \tag{52}$$
$$(1 - T_o H_r(T_o)/Q_o)^2 \ \sigma_W^2/W_o^2$$

Each factor of this expression has been discussed except the ratio σ_W^2/W_o^2. To determine a representative value for this ratio, let ΔW be the maximum deviation of yield from the design yield, that is

$$W_o - \Delta W \leq W \leq W_o + \Delta W. \tag{53}$$

According to small sample statistical theory, the standard deviation can be approximated by one sixth of the total range, hence if

$$\Delta W = \epsilon W_o \tag{54}$$

it follows that

$$\sigma_W \approx \epsilon W_o / 3. \tag{55}$$

If $\epsilon \leq 0.3$, $\sigma_W^2 / W_o^2 < 0.01$ and the variance contribution by yield satisfies

$$VW \leq 0.001764[(H_o - A_o)^2 + R_o^2]/(R_o^2 k^2)^2 \tag{56}$$

D. Height of Burst

The coefficient for the variance contribution by burst altitude has two terms, each contributing a particular functional behavior. Letting u be a scalar defined on the unit interval, the total contribution is given by

$$VB = (1/R_o^2) \; [\; (H_o - A_o)\, u - 0.2 \sqrt{(H_o - A_o)^2 + R_o^2} \; \cdot$$

$$(1 - T_o H_r(T_o)/Q_o \;)]^2 \sigma_H^2. \tag{57}$$

Using figure 14, it is evident that the contributions are additive if the cutoff time (in scaled time) is in excess of 10^{-3} but less than 0.45 or in excess of 1.5. The variance contribution will be the largest for scaled times near 10^{-1} or if in excess of 5. This provides an upper bound

$$VB \leq (1/R_o^2) \left[(H_o - A_o) + 0.2\sqrt{(H_o - A_o)^2 + R_o^2} \right]^2 \sigma_H^2 . \tag{58}$$

It is assumed the standard deviation of burst altitude is 0.25 nautical miles corresponding to the assertion that the height of burst will be measured to within 1000 feet, 50% of the time.

E. Observer Altitude

The contribution to total variance induced by errors in the observer altitude is probably the simplest expression. The unknown parameter in the estimation is u, a number taken from the unit interval. Assuming a standard deviation of 0.25 nautical miles, the variance contribution due to variations in observer altitude are bounded by

$$[(H_o - A_o)^2 u^2 / R_o^2] \sigma_A^2 \leq 0.0625 \; (H_o - A_o)^2 / R_o^2 . \tag{59}$$

As the difference between the height of burst and observer altitude is reduced relative to the safe separation distance, the relevance of this term also decreases.

VIII

CONCLUSIONS

Some characteristics of the safe separation distance, can be qualitatively determined from the linearized equation. The more significant effects are:

1) An increase in the allowable threshold exposure, permits a decrease in the safe separation distance.

2) An increase in exposure time requires a corresponding increase in the safe separation distance.

3) Changes in yield have a conditional response, in that an increase in yield corresponds to an increase in the safe separation distance if the cutoff time is near that of a thermal maximum (or maximum radiance), but a decrease for other cutoff times.

4) Errors in measuring the height of burst and observer altitude are of lesser significance than errors in measuring threshold exposure, time of irradiation and yield for low altitude bursts.

5) For fixed height of burst a decrease in observer altitude results in a decrease in the safe separation distance.

6) Further modifications on the safe separation distance result from variations in the height of burst. An increased height of burst; when the time of cutoff is near a thermal maximum, corresponds

to an increased safe separation distance, from that stated in paragraph 5 above, but for other times a decrease. This effect is generally very small for low altitude bursts.

7) Weapon yield effects and part of the height of burst effects drop out of the linearized and viariance equations when the retinal irradiance is constant. This simplification and its implications provide arguments for adequately representing the radiance profiles in experimental studi[illegible].

Continued physiological investigation and mathematical analysis are needed to understand better the factors determining threshold exposure and retinal irradiance. These investigations should include the effect of random changes in the f-number of the eye, radiance profile, including intensity of radiation, and rates of change, as well as image size and energy density.

As the mechanisms producing retinal burns and flashblindness are more precisely defined, threshold values and the parameters causing variations of the threshold values will also be more precisely specified. Some experimental data with primates has provided evidence that retinal temperature rise may be a suitable criterion for retinal burns. If this is further substantiated, the threshold investigations may concentrate on correlating the incident radiation profile to heat production in the eye. Similarly, studies on the chemistry of flashblindness need to be correlated with the safe separation studies resulting in better defined thresholds.

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Unclassified
Security Classification

DOCUMENT CONTROL DATA - R&D

(Security classification of title, body of abstract and indexing annotation must be entered when the overall report is classified)

1. ORIGINATING ACTIVITY (Corporate author) Technology Incorporated, Life Sciences Division 8531 N. New Braunfels Avenue San Antonio, Texas 78216	2a. REPORT SECURITY CLASSIFICATION Unclassified 2b. GROUP

3. REPORT TITLE

EVALUATION OF EYE HAZARDS FROM NUCLEAR DETONATIONS

4. DESCRIPTIVE NOTES (Type of report and inclusive dates)

Final Report 1 August 1969 - 31 August 1970

5. AUTHOR(S) (Last name, first name, initial)

Nickel, James A.

6. REPORT DATE	7a. TOTAL NO. OF PAGES	7b. NO. OF REFS
September 1970	50	8

8a. CONTRACT OR GRANT NO. F41609-69-C-0049 b. PROJECT NO. AM-9-10690/6301 c. d.	9a. ORIGINATOR'S REPORT NUMBER(S) 9b. OTHER REPORT NO(S) (Any other numbers that may be assigned this report)

10. AVAILABILITY/LIMITATION NOTICES

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

11. SUPPLEMENTARY NOTES	12. SPONSORING MILITARY ACTIVITY
	Aerospace Medical Division Brooks Air Force Base

13. ABSTRACT

The retinal exposure equation, from which safe separation distances have been calculated, was used as a basis for developing a linearized equation. New scaling laws for the spectral power and fireball radiance were also developed. These equations were used in deriving a variance equation for the safe separation distance. This equation is expressed in terms of the variances of the independent variables: retinal exposure, time of irradiation, yield, observer and burst altitude. The importance of retinal irradiance at the time of cutoff (as effected by blinking or introduction of other shielding) is demonstrated by an analysis of the coefficients in the variance equation, supported by a limited set of calculations. Retinal irradiance is affected by variations in the f-number of the eye and pulse profile of the fireball. The largest variances occur when the cutoff time is near a radiance maximum (approximately a thermal maximum). Small increases in the variance are realized with increased differences in the vertical separation of observer and fireball, but these appear to be of importance only with very low yield weapons.

DD FORM 1473

Unclassified
Security Classification

14. KEY WORDS	LINK A ROLE	LINK A WT	LINK B ROLE	LINK B WT	LINK C ROLE	LINK C WT
Retinal Burn						
Safe Separation Distance						
Variance of Safe Separation Distance						
Weapon Scaling Laws						
Flashblindness						

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