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CROSSOVER CURVES FOR THERMAL AND GAMMA RADIATION

B. L. Miller, 5132

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ABSTRACT

The report considers the criteria which determine the thermal and gamma radiation received at various distances from a free-air detonation of a nuclear device. Curves are drawn showing the crossover points for which specific levels of thermal and gamma radiation occur at the same slant range and relating these coincident radiation levels to conditions of yield and atmospheric attenuation.

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INTRODUCTION

Before a nuclear weapon can be used effectively upon a given target, the vulnerability of the target to the three principal forms of energy released from a nuclear detonation (blast, thermal radiation, and gamma radiation) must be analyzed. One of the prime considerations in such an analysis is the establishment of kill levels for each of these forms of energy. In reality it is a combination of these energy forms which affects the destruction of a given target; however, a given nuclear device is frequently exploited with respect to that energy type which alone will maximize the desired result. If the nature of the target is such that thermal or gamma radiation is preferred, one must ascertain which of these two energy types will provide kill levels having the greater radius of effect.

The yield and geometry of the weapon, the altitude of burst, and the ambient atmospheric conditions determine the radii inside which the gamma and thermal energies exceed the previously determined lethal levels. Curves relating the thermal and gamma energies to distance from the burst point and parameterized by the above influencing factors are presently available for fully exposed targets. For a given set of conditions (fixed parameters) it is possible from these curves to determine whether gamma or thermal radiation will have the greater radius of effect for unshielded targets. The relative value of the thermal energy to the gamma energy, however, can be expressed in a more informative and more readily useable form by means of crossover curves. Basically these curves express the relationship between the yield of a given nuclear weapon and the ratio of the levels of thermal to gamma radiation which are produced at the same distance from the burst point. Again there will be a family of curves resulting from a variation in weapon type, atmospheric condition, and height of burst. This report discusses the development, interpretation, and use of these curves.

PARTITION AND VARIATION OF ENERGY FROM AN ATOMIC BOMB DETONATION

Thermal Radiation

The effectiveness of thermal radiation is measured by the amount of thermal energy incident upon a unit area oriented normally to the radius vector from the point of detonation. (Hereafter this areal density of thermal radiation will be referred to as the thermal exposure.) The term 'thermal energy' is usually loosely defined to include all energy lying within the wavelength range from far ultraviolet to far infrared. If black-body radiation is assumed, this energy accounts for nearly all of the extranuclear, electromagnetic energy which is radiated between the instant of detonation and the time the fireball disappears. The thermal exposure will depend upon the amount of thermal energy released from the bomb and upon the atmospheric attenuation of this energy between the burst point and the unit area intercepting this radiation. This is expressed mathematically as*

$$Q = Yf(h, Y)\frac{e^{-\sigma r}}{4\pi r^2}, \qquad (1)$$

where

Q = thermal exposure on the target,
r = distance from target to burst point,
Y = radiochemical yield,
σ = representative value of the atmospheric attenuation coefficient within the wavelength range of thermal energy, and
$f(h, Y)$ = fraction of radiochemical yield appearing as thermal radiation and expressed as a function of yield, Y, and altitude of burst, h.

In the derivation of Equation 1 the atmosphere is considered to be a homogeneous and an isotropic medium, and the contribution of scattered radiation is neglected. Also the derivation

*See Appendix A.

of Equation 1 is based upon the assumption of a point source. However, the equation is practicable for a finite source which is small compared with its distance from the target.

The thermal energy depends upon the yield and the altitude, h, at which the detonation occurs. For air bursts in which the fireball does not touch the ground it is generally assumed that for yields less than 100 kt the value of f(h, Y) is about 0.33. For altitudes of burst less than 50,000 feet the change in this fraction with height of burst is insignificant.[1] For values of Y and h greater than these limits, f(h, Y) may be determined from experimental curves of thermal yield versus radiochemical yield and from curves of thermal yield versus height of burst for a fixed radiochemical yield. The function f(h, Y) does not account for the reduction in thermal radiation resulting from partial dust shielding of the fireball for low air bursts.

A generally used and easily conceived term for expressing atmospheric attenuation is 'visibility'. Assume that the value for the visibility in a given atmosphere is determined in accordance with the following conditions:[2]

1. The representative atmospheric attenuation coefficient for visible light is equal to σ.
2. Visibility is determined along a horizontal direction.
3. The observed object subtends an angle of at least several degrees at the point of observation.
4. The luminance of the background is large.
5. There is a 90-percent probability of detecting the object.

When these conditions are fulfilled, σ may be expressed in terms of visibility values as

$$\sigma = \frac{\beta}{V}, \qquad (2)$$

where, when σ and the visibility V are expressed in terms of the same units, β equals ln 50 or 3.9.[3]

The substitution of Equation 2 into Equation 1 results in

$$Q = Yf(Y, h)\frac{e^{-\frac{\beta}{V}r}}{4\pi r^2} \qquad (3)$$

$$= \frac{Q_o}{r^2} Ye^{-\frac{\beta r}{V}}, \qquad (3a)$$

where

$$Q_o = \frac{f(h, Y)}{4\pi} .$$

The quantity Q_o may be interpreted as the thermal exposure at a unit distance, disregarding attenuation, from the burst point of a weapon of unit yield.

Gamma Radiation

Gamma radiation effectiveness is measured by the number of roentgens which is an index of the amount of energy absorbed per unit mass of air. The energy absorbed in turn depends upon the total energy incident on this unit mass of air and upon the absorbing qualities of the air. It is the initial gamma radiation which is of concern, that is, the gamma radiation that is emitted from the bomb within the first minute or two from the instant of detonation.* This initial radiation comprises over 90 percent of all of the emitted gamma radiation.* The total amount of energy released in gamma radiation depends directly upon yield and weapon efficiency. Also, the intensity of gamma radiation at a given distance from the burst point depends upon the absorption of the intervening medium.

The dissipation of gamma ray energy per unit volume of the atmospheric medium can be expressed as†

$$S = \frac{c\mu}{4\pi r^2} Y\, g(w)\, e^{-c\mu r} , \qquad (4)$$

where

S = density of energy absorption in air at the target,

r = distance from the target to the burst point,

Y = radiochemical yield,

μ = representative, total, linear absorption coefficient for air under NTP‡ conditions,

c = ratio of existing atmospheric density, ρ, to the air density, ρ_o, under NTP conditions, and

$g(w)$ = fraction of the radiochemical yield appearing as gamma radiation and expressed as a function of weapon type, w.

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*Ref 4, pp 21-25
†See Appendix B
‡Normal temperature and pressure of 0°C and 760mm of Hg.

The validity of Equation 4 depends upon the degree to which the following conditions are approximated:

1. The source is a point emitter.
2. There is no scattering of the gamma radiation; ie, all attenuation is due to absorption.
3. The mass absorption coefficient, μ/ρ_o is a constant. This condition is well satisfied for gamma photon energies of the order of magnitude of one mev and for an attenuating medium comprising atoms of low atomic weight (< 100).

It is assumed, also, that ρ is not dependent upon r; therefore Equation 4 does not allow for the variation of ρ as a consequence of the shock wave. For small distances from the burst point the shock wave arrives well in advance of the major fraction of the gamma radiation. For such close-in targets the effective value of ρ will be smaller than the ambient atmospheric density, and the values of S will be larger than Equation 4 predicts.

The expression for S in Equation 4 may be converted to roentgens by dividing by the factor $k\rho$ or $kc\rho_o$. The factor, k, is the number of roentgens equivalent to the energy absorbed by a gram mass of air or by any atmospheric medium composed of atoms having relatively low atomic weight. Equation 4 may be written as

$$S = \frac{S_o}{r^2} Y e^{-c\mu r}, \tag{5}$$

where

$$S_o = \frac{\mu\, g(w)}{4\pi k \rho_o}. \tag{5a}$$

The constant S_o is the energy density (in roentgens) of gamma radiation absorbed in an atmospheric medium, assuming no attenuation prior to this, at a unit distance from the burst point of a weapon having unit yield.

Development of Curves

Equations 3 and 5 can be combined to eliminate r between them. Substituting the value for r obtained from the ratio of Equation 3 into Equation 5 results in

$$Y/S = \frac{1}{S_o}\left[\frac{V \ln \frac{Q/Q_o}{S/S_o}}{c\mu V - \beta}\right]^2 \left[\frac{Q/Q_o}{S/S_o}\right]^{\frac{c\mu V}{c\mu V - \beta}} \qquad (6)$$

To facilitate the interpretation of this expression in graphical form, two groups of curves have been constructed. Both groups consist of three families of curves with each family parameterized by the ambient atmospheric density expressed as a fraction, c, of the air density under NTP conditions. The individual curves of each family in Group I are plots of Y/S versus V, and they are parameterized by the ratio, K, of Q/Q_o to S/S_o. In Group II, Y/S is plotted against Q/S, and the parameter characterizing each curve is the visibility, V.

The values 0.6, 0.8, and 1.0 were selected for the parameter, c. This range will cover any expected atmospheric conditions existing anywhere on the surface of the earth. Also, c = 0.8 corresponds to an altitude of 7400 feet, and c = 0.6 corresponds to 16,400 feet in a standard atmosphere. For the visibility to be expressed in miles and the slant range in yards the previous value of β (3.9) becomes 2.22×10^{-3} mi/yd. The average value of μ computed from the Buster-Jangle data[5] is 2.72×10^{-3} per yard. This value is in fair agreement with the roentgen slant range curves on p 23 of Ref 4 and the data from the Tumbler-Snapper series of shots.[6,7] A representative value of S_o, 1.23×10^9 roentgen-yd^2/kt, for a standard implosion-type weapon was obtained from the curve for zero atmospheric attenuation as given in Ref 4, and again this value was in accordance with the values determined from the Buster-Jangle and Tumbler-Snapper series. The customary unit for expressing Q is calories per square centimeter; therefore, Q_o assumes the value of 3.17×10^6 cal-yd^2/cm^2-kt from Equation 3a.

To apply the crossover curves to conditions of weapon type and detonation other than those for which the curves were originally plotted, the scales and values of the parameters must be altered in accordance with the change in f(Y, h) and g(w), and the value of the parameter, K, must be changed by the ratio of g(w) to f(Y, h). In Group II the scale for Y/S is again affected by g(w), and the scale for Q/S is affected by the ratio of g(w) to f(Y, h). The curves plotted in Figs. 1-6 are based on the assumption of a low-yield (< 100 kt), standard implosion-type weapon (Mk 4, 5, or 6) burst at an altitude of less than 50,000 feet. Within these limits, g(w) and f(Y, h) will have the constant values represented by $g_o(w)$ and $f_o(Y, h)$. The value for $f_o(Y, h)$ will be one third. The value for $g_o(w)$ is obtained from Equation 5a. Inserting the above values of μ and S_o, and values of 83.8 ergs/gm(air)-roentgen for k, and 933 gm/yd^3 for ρ_o gives $g_o(w)$ a value of 0.0106. For particular types and sizes of attenuating materials comprising a given atmospheric medium a relationship exists between the

atmospheric density, ρ, and the visibility, V. However, it can be shown* that there is a negligible increase in ρ when a sufficient amount of an aerosol is added to the air to limit the visibility to the lowest value considered for the curves.

The values of Q and S are influenced by several factors. First, it is not known what casualty effect may be desired by the Military; second, the values of Q and S necessary to produce a specified effect are far from definite; and third, the values may be affected by shielding and disposition of the target elements. As a consequence the curves in Group I are drawn for various pairs of Q and S. Within each pair, Q is compatible with S on the basis that either the thermal exposure or gamma radiation will alone produce the desired degree of casualties. To have a dimensionless parameter that will facilitate plotting and interpreting the curves, the ratio, K, of Q/Q_o to S/S_o is used in place of Q/S. Physically, K is the ratio of the atmospheric transmission per unit distance for thermal radiation to that for gamma radiation. Table I gives the pairings of Q and S and the associated values for the parameter, K.

TABLE I

Free-Air Values of Thermal Exposure and Gamma Dosage Required to Produce Comparable Biological Incapacitation

Q(cal/cm^2)	S(roentgens)	K
8	400	7.8
20	1000	
7	400	6.8
6	400	5.8
8	600	5.2
10	1000	3.88
50	5000	
6	1000	2.33
18.4	5000	1.43
12.9	5000	1.00
5	5000	0.388

The values of Q and S listed in Table I were determined from several references.[4, 8, 9] Recent experimentation has resulted in the estimate that a dose of 5000 roentgens resulting from a nuclear detonation would produce incapacitation in a human within the order of minutes after

*See Appendix C.

the exposure. The last three values for K in Table I were chosen primarily to illustrate the trend in the curves of Group I.

INTERPRETATION AND USE OF THE CURVES

Consider the Group I curves (Figs. 1, 2, and 3). First, the parameters applicable to a particular target must be established. This step requires sufficient meteorological knowledge about the target region to permit the value of c to be determined. The vulnerability of the target must be carefully ascertained before values can be assigned to Q and S, the criteria for thermal and gamma radiation damage, respectively. This procedure determines K, and a specific working curve is now available. Several examples may serve to interpret these curves and to demonstrate their applicability to the solution of various types of problems.

Example 1

Given: Meteorological conditions over the target are such that c = 0.8 and the visibility is 25 miles. Target requires at least a Q of 50 cal/cm^2 or an S of 5000 roentgens for the desired degree of damage.

Find: What weapon yield will produce crossover—that is, 50 cal/cm^2 and 5000 roentgens at the same slant range?

Solution: Table I indicates that the value of K associated with Q = 50 cal/cm^2 and S = 5000 roentgens is 3.88. From Fig. 2 (c = 0.8) and for an abscissa value of 25, the corresponding ordinate on the K = 3.88 curve is 1.39 $\frac{kt}{1000r}$. Since the desired gamma radiation is 5000 roentgens, this ordinate value represents a yield of 5 x 1.39 or 7 kt as the size weapon necessary to fulfill the conditions of the problem.

Example 2

Given: The meteorological conditions over the target area imply a c of 1.0 and a visibility of 2 miles. The available weapon has a predicted yield of 10 kt. The target requires at least a Q of 6 cal/cm^2 or an S of 1000 roentgens.

Find: Which of the two forms of radiation will have the greater radius with respect to the specified levels of Q and S on a fully exposed target?

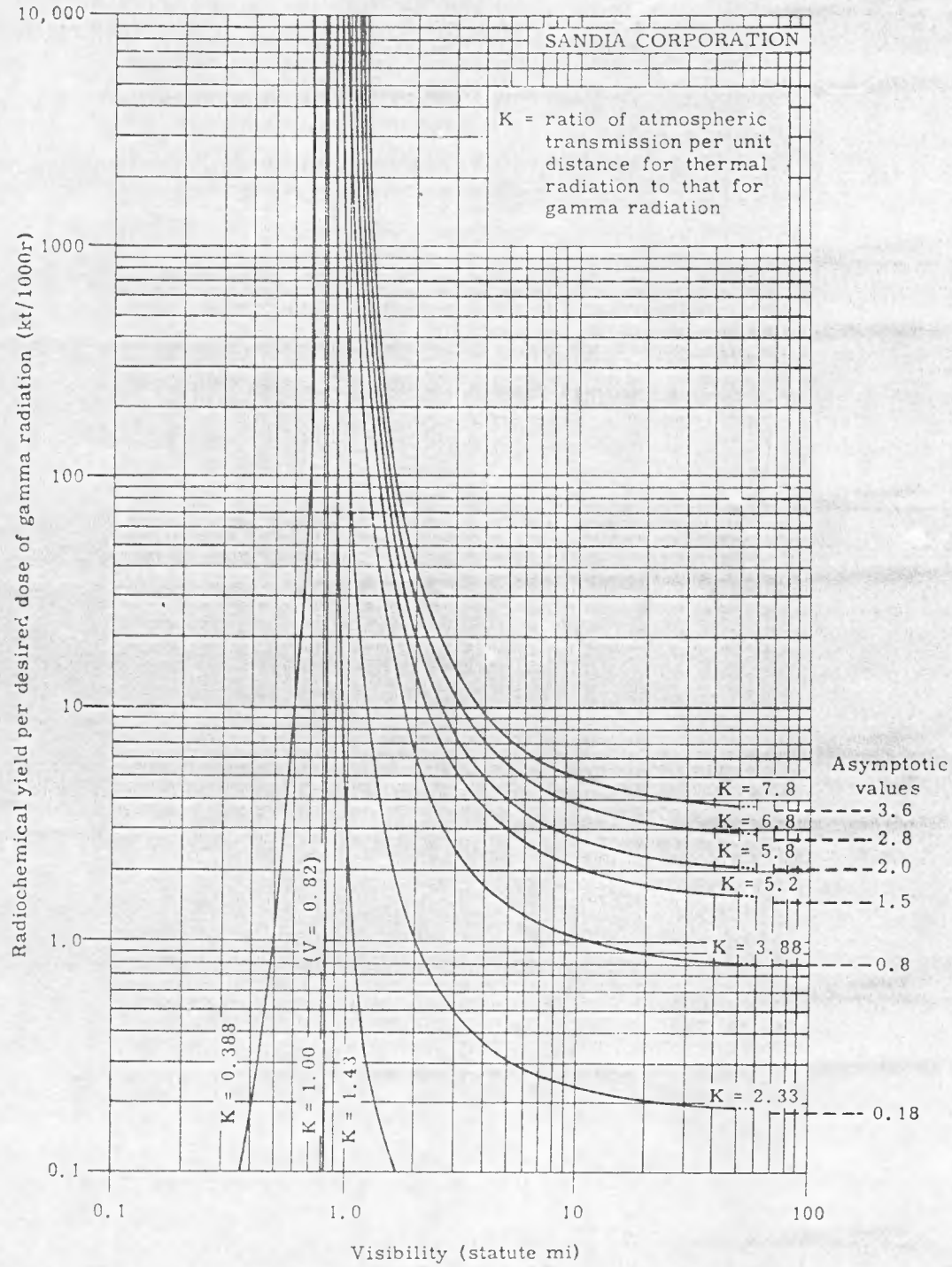

Fig. 1 -- Radiochemical yield (per 1000r of desired gamma radiation) necessary to produce equivalent effects from thermal and gamma radiation at a given slant range versus visibility —Group I; ambient atmospheric density is equal to air density at normal temperature and pressure

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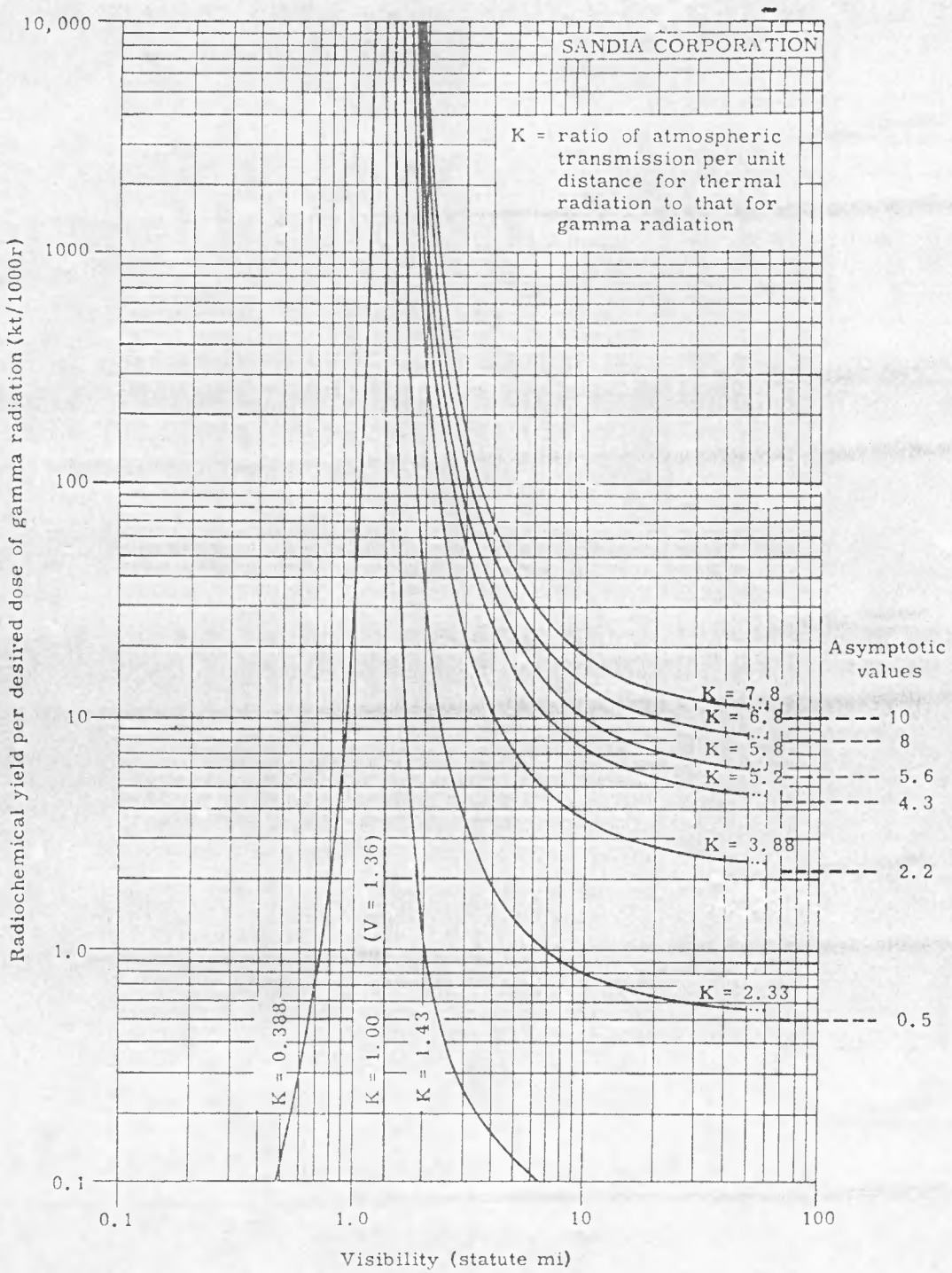

Fig. 2 -- Radiochemical yield (per 1000r of desired gamma radiation) necessary to produce equivalent effects from thermal and gamma radiation at a given slant range versus visibility—Group I; ambient atmospheric density is 0.8 of the air density at normal temperature and pressure

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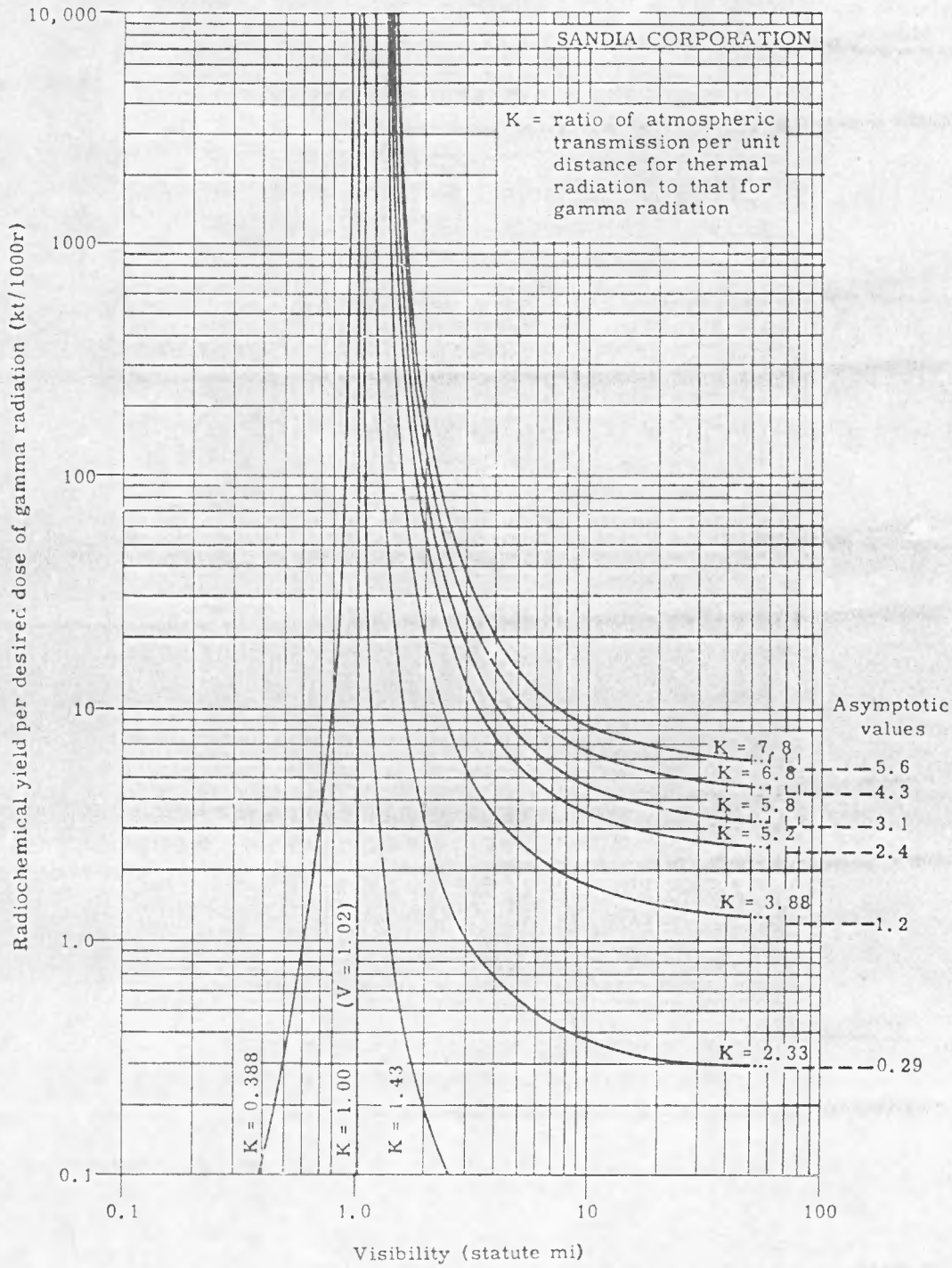

Fig. 3 -- Radiochemical yield (per 1000r of desired gamma radiation) necessary to produce equivalent effects from thermal and gamma radiation at a given slant range versus visibility—Group I; ambient atmospheric density is 0.6 of the air density at normal temperature and pressure

Solution: For c = 1.0, Fig. 1 is used. Table I indicates that the working curve associated with the given values of Q and S should be that whose parameter is K = 2.33. Since the desired amount of gamma radiation is 1000 roentgens the ordinate scale reads directly in kt of yield. Crossover for these radiations from a 10-kt weapon (ordinate value of 10) would occur at a visibility given by the abscissa value of 1.2. The gamma radiation attenuation is insignificantly affected by the visibility; but for the two-mile visibility at the target the thermal radiation is attenuated less rapidly than is necessary to give crossover for the 10-kt weapon. Therefore at that slant range where the gamma radiation is 1000 roentgens the thermal exposure will be greater than 6 cal/cm^2, or the 6-cal/cm^2 level will occur at a greater slant range than will the 1000 roentgens. This implies that the thermal radiation will give a greater coverage of the target.

Remarks: Suppose that there be a target visibility of one mile instead of two miles. The thermal radiation is now attenuated more than is necessary to give crossover for 6 cal/cm^2 and 1000 roentgens from a 10-kt weapon. This means that at the slant range at which the 1000-roentgen level occurs the thermal exposure will be less than 6 cal/cm^2, and gamma radiation is preferred.

Note that all of the curves in Figs. 1, 2, and 3 approach a vertical asymptote which is the limiting value of V, in Equation 6, as the ratio, K, approaches unity—that is,

$$V = \frac{\beta}{c\mu}, \tag{7}$$

when the atmospheric attenuation of thermal radiation is equivalent to that for gamma radiation. The curves for which K > 1 also approach horizontal asymptotes. These asymptotic values given in Figs. 1, 2, and 3 were obtained by taking the limiting value of Y/S, in Equation 5, as V approached infinity; therefore,

$$\lim_{V \to \infty} Y/S = \frac{1}{S_o} \left(\frac{\ln K}{c\mu}\right)^2 K . \tag{8}$$

The physical significance of these horizontal asymptotes is best examined by means of another example.

Example 3

Given: The meteorological conditions of the target indicate c = 0.6. The situation calls for a 5-kt weapon and the target requires at least 1000 roentgens or 20 cal/cm^2.

Find: What is the visibility necessary for crossover?

Solution: Reference to Fig. 3 (c = 0.6) and the curve designated by K = 7.8 indicates that the ordinate value 5 corresponding to a 5-kt yield lies below the asymptote of the K = 7.8 curve. This implies that no visibility, however large, is sufficient for the slant range coincidence of 1000 roentgens and 20 cal/cm^2. The ordinate value 5 lies between the asymptotes for the K = 5.8 and K = 5.2 curves; therefore, the 1000-roentgen level will be coincident with a thermal level lying between 15 cal/cm^2 and 12 cal/cm^2.

In general, any point in Figs. 1, 2, and 3 lying to the right of a curve as characterized by a given value of Q and S indicates that for the particular yield and visibility associated with this point the thermal energy will be more damaging than the gamma radiation. Conversely, if the point falls to the left of the curve, gamma radiation is to be preferred to thermal radiation. For values of K greater than unity, increases in yields above those values necessary for crossover will favor thermal radiation. For values of K less than unity, the gamma radiation will have a greater effect-coverage with increased yield above the crossover value. Once it is known which form of energy has the greater coverage one needs merely to refer to or construct a set of curves relating yield, exposure level, and slant range for the preferred radiation to determine the maximum radius of effect for unshielded targets.

Group I curves readily indicate the sensitivity of crossover yields to variations in visibility, a relationship which is not so easily seen in the curves of Group II. However, since observed visibility is a rather tenuous concept, it is of interest to use discrete values of visibility as parameters and employ values of Q/S for the abscissa. Such curves are shown in Figs. 4, 5, and 6. The advantage in this altered representation can best be illustrated by an example.

Example 4

Given: Assume the same conditions of Example 2—that is, c = 1.0, V = 2 miles, Y = 10 kt, and the desired values of Q and S are 6 cal/cm^2 and 1000 roentgens respectively.

Find: What thermal exposure level coincides with S = 1000 roentgens and what gamma radiation level occurs with 6 cal/cm^2?

Solution: Since S = 1000 roentgens, the ordinate values will be equal numerically to yield in kt. In Fig. 4 (c = 1.0), the abscissa value associated with an ordinate value of 10 (Y = 10 kt) on the two-mile visibility curve is 12—that is,

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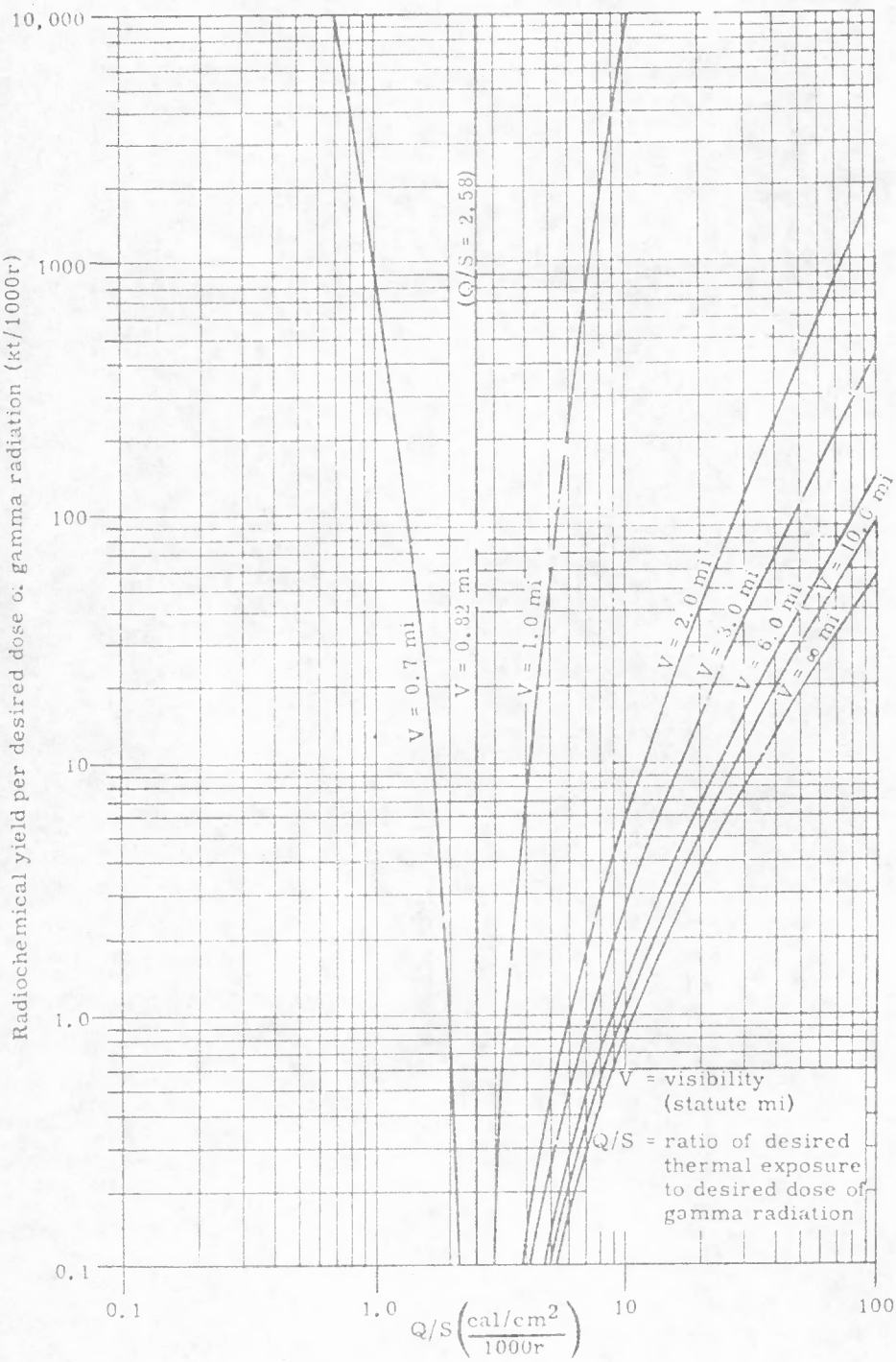

Fig. 4 -- Radiochemical yield (per 1000r of desired gamma radiation) necessary to produce equivalent effects at a given slant range versus ratio of desired thermal-to-gamma criteria—Group II; ambient atmospheric density is equal to air density at normal temperature and pressure

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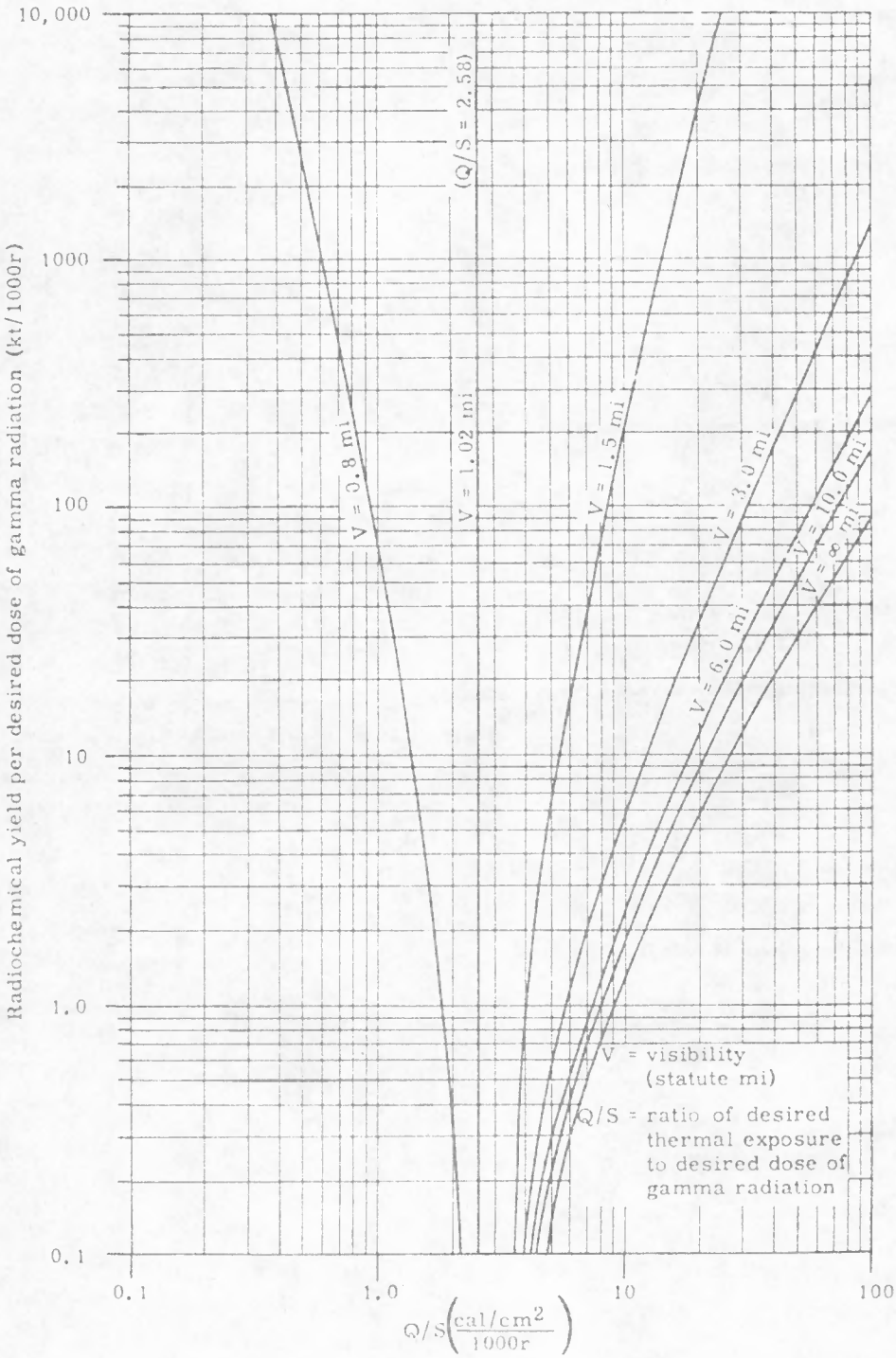

Fig. 5 -- Radiochemical yield (per 1000r of desired gamma radiation) necessary to produce equivalent effects at a given slant range versus ratio of desired thermal-to-gamma criteria—Group II; ambient atmospheric density is 0.8 of the air density at normal temperature and pressure

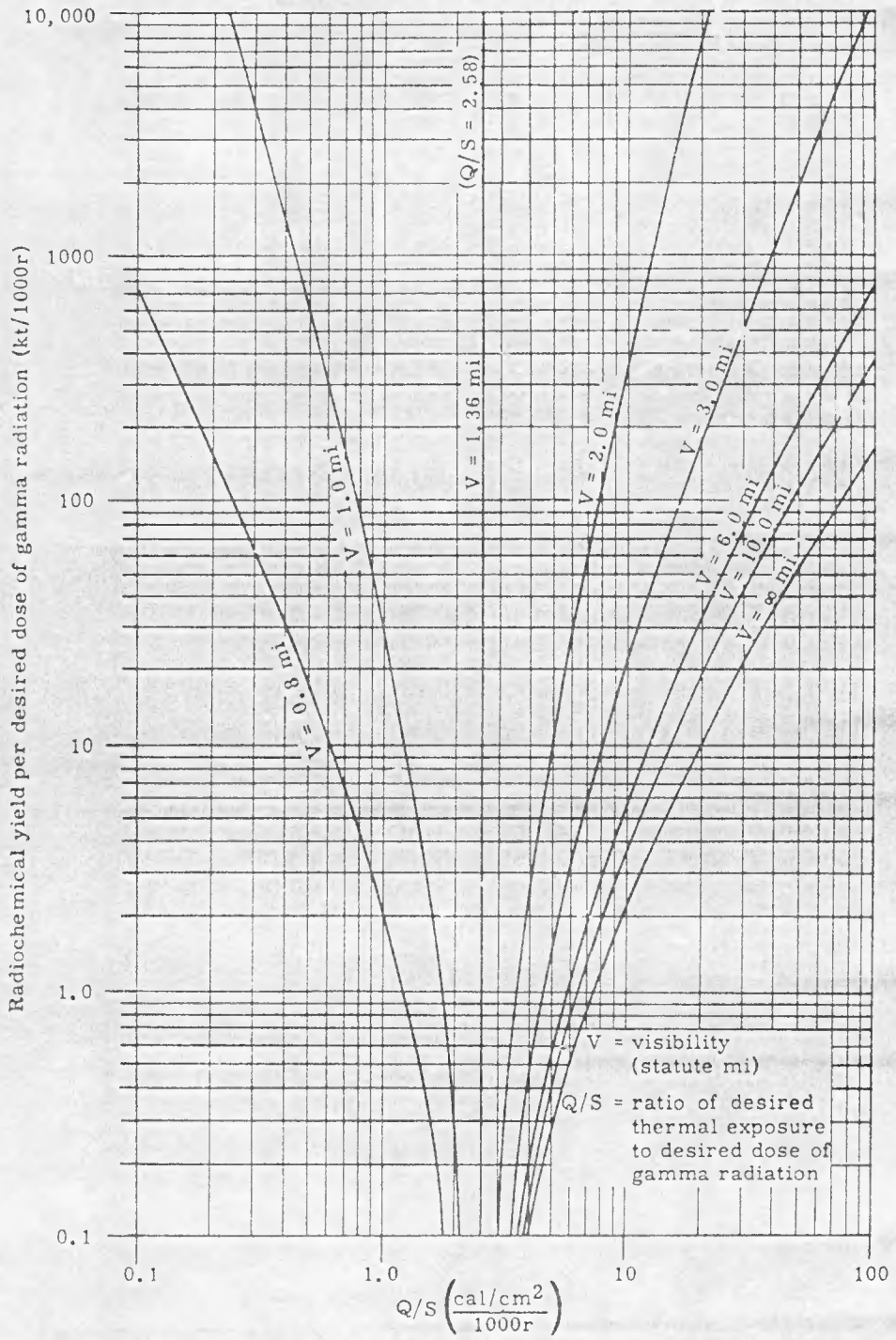

Fig. 6 -- Radiochemical yield (per 1000r of desired gamma radiation) necessary to produce equivalent effects at a given slant range versus ratio of desired thermal-to-gamma criteria—Group II; ambient atmospheric density is 0.6 of the air density at normal temperature and pressure

$Q/S = \frac{12\ cal/cm^2}{1000r}$. This means that for S = 1000 roentgens the thermal exposure level will be 12 cal/cm^2, and the 6-cal/cm^2 level will occur at a greater slant range than the 1000-roentgen level.

Once the biological effectiveness can be determined as a function of a combined thermal exposure and gamma radiation dose it might be of interest to know what gamma radiation level is coincident with the 6 cal/cm^2 of thermal radiation. Although the specification of a value for Q and for Y is not sufficient to establish an abscissa and an ordinate value respectively, the ratio of the latter two values is uniquely determined. In Fig. 4 (c = 1.0), construct a line whose rectangular coordinates have the same ordinate-to-abscissa ratio as Y/S to Q/S or Y to Q—that is, 10 kt to 6 cal/cm^2. This line has unit slope with respect to the logarithmic coordinate values. The abscissa of the intersection of this line with the two-mile visibility curve is $Q/S = \frac{18\ cal/cm^2}{1000r}$; or for a desired Q value of 6 the associated gamma radiation dose is approximately 330 roentgens.

Example 5

Given: The meteorological conditions over the target determine the value of c to be nearest 0.6, and the visibility to be about 1.0 mile. It is desired to have a Q of 20 cal/cm^2 or an S of 5000 roentgens. The available weapon has a yield of 2 kt.

Find: Which form of radiation will determine the height of burst?

Solution: In Fig. 6 (c = 0.6), since S = 5000 roentgens, the ordinate scale must be multiplied by the factor 5 for it to indicate yields in kt. Therefore, the ordinate corresponding to 2 kt is $Y/S = 0.4\ \frac{kt}{1000r}$. Crossover for this yield on the V = 1.0-mile curve indicates Q/S to be $\frac{1.46}{1000r}$ cal/cm^2 or approximately $\frac{7\ cal/cm^2}{5000r}$. Gamma radiation is the preferred energy by a considerable margin. Note that for a 2-kt weapon it would require a 3-mile visibility to give a Q/S equal to about $\frac{4\ cal/cm^2}{1000r}$ or $\frac{20\ cal/cm^2}{5000r}$.

All of the curves in Figs. 4, 5, and 6 approach the vertical line parameterized by the limiting value of V (Equation 7) at an ordinate value of zero. The corresponding abscissa is $Q/S = 2.58\ \frac{cal/cm^2}{1000r}$ (or K = 1). This trend in the curves indicates that ratios of the desired thermal radiation levels to the gamma radiation levels for which crossover can occur become insensitive to visibility and quite limited for weapons having low yield. At high yields the visibility is a significant factor in determining the preferred form of radiation to provide the desired damage. In general, for visibilities such that the crossover curves have positive

slopes, increases in yields above those necessary for crossover will favor thermal radiation. If the curves have negative slopes, the gamma radiation will have a greater effect coverage with increasing yield (above crossover) than will thermal radiation.

Within the conditions imposed for the construction of the crossover curves, these curves can be applied unquestionably only to certain types of targets. These types have the common characteristic that the incapacitation produced is sensitively dependent only upon the slant range separating the target from the burst point. In general, examples of such types would be those targets which are fully exposed to the direct radiation from the fireball and those which are partially but uniformly shielded from the direct radiations.

SUMMARY

Two representations of crossover curves for thermal and gamma radiation have been devised. They relate the yield of a nuclear weapon to the atmospheric visibility and the air density at which specified levels of thermal and gamma radiation criteria occur at the same slant range from the point of detonation. If applied to limited ranges of the variables, these curves are accurate enough for practical purposes and are immediately applicable. These limitations are best given in tabular form in Table II.

TABLE II

Conditions for Immediate Applicability of Crossover Curves

Visibility $\geq$ 0.5 mile

Slant range >> radius of fireball

Height of burst { > radius of fireball and large enough to prevent dust shielding; < 50,000 feet }

Weapon type—standard implosion

Yield < 100 kt

Target fully exposed to radiant energy from burst point

Generally, if situations outside the limits of Table II are considered, supplementary curves will be needed to appropriately adjust the scales and parameters of the crossover curves. This additional procedure may sufficiently complicate the reading of these curves to defeat their purpose. It may then be more desirable to produce another set of crossover curves applicable to the new region of the variables.

In particular, it would be of immediate interest to know with what validity these curves are applicable to contact bursts. Since there have been only two such detonations, the experimental data are insufficient even to predict how significant the changes are in the energy partition between thermal and gamma radiation as compared to this partition for a free-air detonation. Perhaps an analysis of those tower shots in which the fireball radius was greater than the burst height can give a first approximation to a correction that can be applied to the results obtained from the crossover curves included in this report. If such an analysis can be made successfully, it is hoped that a companion report may soon be issued which will widen the scope of applicability of these crossover curves.

APPENDIX A

Thermal Exposure from a Point Source in an Attenuating Medium

Consider the total elemental change in the irradiance, dW_T, along a radial direction from the burst point. The irradiance is defined as the ratio of the radiant flux incident on an element of surface to the area of that element. The irradiance may be considered as a combined function of the source-target configuration, represented by the generalized coordinates, q_1, $q_2 \ldots q_n$, and the attenuation, α, of the radiant intensity by the atmospheric medium, or

$$W_T \equiv W_T (q_1, \ldots q_n, \alpha); \text{ therefore,}$$

$$dW_T = \frac{\partial W_T}{\partial q_1} dq_1 + \ldots \frac{\partial W_T}{\partial q_n} dq_n + \frac{\partial W_T}{\partial \alpha} d\alpha .$$

This change may be considered as occurring between the inner and outer surfaces of a portion of a spherical shell having a thickness, dr, and subtending a solid angle, Ω, at the center (which is coincident with the burst point). The specification of these surfaces and the assumption of radial symmetry in energy emission reduces the number of generalized coordinates to one—namely, r (or q_1), the separation of the exposed surface from the burst point. The irradiance on this portion of the spherical shell, as affected only by the divergence of the radiant flux, is inversely proportional to the area and can be expressed as

$$W_T = \frac{B}{r^2 \Omega},$$

where B is the proportionality constant.

Therefore,

$$\frac{\partial W_T}{\partial q_1} \equiv \frac{\partial W_T}{\partial r} = -\frac{2}{r} W_T .$$

The increment in W_T due solely to an increment in the separation of the energy source and target is

$$\frac{\partial W_T}{\partial q_1} dq_1 \equiv \frac{\partial W_T}{\partial r} dr = -\frac{2}{r} W_T \, dr .$$

Now assume a 'good geometry' in which all the radiant flux scattered from the beam traversing the volume element of the spherical shell is considered to be lost. With this assumption the change of irradiance due to atmospheric attenuation alone may be expressed as proportional to the irradiance, per se, and, dr, the distance traversed; therefore,

$$\frac{\partial W_T}{\partial \alpha} d\alpha = -\sigma W_T \, dr ,$$

where σ is the attenuation coefficient when both scattering and absorption are considered. Combining terms,

$$dW_T = -W_T\left(\frac{2}{r} + \sigma\right) dr ,$$

which upon integration becomes

$$W_T = \frac{A}{r^2} e^{-\sigma r}$$

When $\sigma = 0$,

$$W_T = \frac{A}{r^2} = \frac{E}{4\pi r^2} ;$$

$$\therefore W_T = \frac{E}{4\pi r^2} e^{-\sigma r} ,^*$$

where E is the rate of thermal energy emission from the bomb. In general, σ and E are dependent upon the wavelength of the radiation. A generalized expression for W_T as a function of time reckoned from the instant of detonation is

$$W_T(t) = \int_\lambda \frac{E_\lambda(t)}{4\pi r^2} e^{-\sigma(\lambda) r} d\lambda , \qquad (9)$$

where $E_\lambda(t)$ represents that portion of the bomb's thermal energy emitted per unit time within the wavelength range from λ to $\lambda + d\lambda$, and the integration extends throughout the

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*Though this expression is frequently used in current publications, it is usually presented without derivation. It is hoped that the above derivation will serve to clarify the assumptions and approximations underlying this equation and hence provide a better feeling for its range of applicability.

wavelength range of thermal energy. Since $e^{-\sigma(\lambda) r}$ and $E_\lambda(t)$ are each equal to or greater than zero, Equation 9 may be written as

$$W_T(t) = \frac{e^{-\sigma r}}{4\pi r^2} \int_\lambda E_\lambda(t)\, d\lambda .$$

The value of σ is some value of $\sigma(\lambda)$ within the range of integration. The thermal exposure, Q, defined mathematically as $\int_t W_T(t)\, dt$, becomes

$$Q = \frac{e^{-\sigma r}}{4\pi r^2} \int_t \int_\lambda E_\lambda(t)\, d\lambda\, dt .$$

The dependence of Q upon yield, Y, and burst height, h, may be indicated as

$$Q = \frac{e^{-\sigma r}}{4\pi r^2}\, Yf(h, Y) ,$$

where

$$Yf(h, Y) = \int_t \int_\lambda E_\lambda(t)\, d\lambda\, dt$$

is the amount of the bomb energy released in the form of thermal radiation, and f(h, Y) is the fraction of the radiochemical yield appearing as thermal energy.

APPENDIX B

Absorption of Gamma Radiation from a Point Source in an Attenuating Medium

By a method of reasoning similar to that applied in the determination of the thermal irradiance (Equation 9), the expression for the gamma irradiance, W_γ, at a distance r from a point source may be written as

$$W_\gamma(t) = \int_\lambda \frac{N_\lambda(t)\, E_\lambda}{4\pi r^2}\, e^{-\mu(\lambda)\, r}\, d\lambda\,, \tag{10}$$

where

$N_\lambda(t)$ = number of photons in the wavelength range of λ to $\lambda + d\lambda$ that are emitted per unit time,

E_λ = energy per photon characterised by λ (the average energy is about 3 mev), and

$\mu(\lambda)$ = total linear attenuation coefficient of the atmosphere for photons in the wavelength of λ to $\lambda + d\lambda$.

The integration extends throughout the wavelength range comparable to an energy range of 0.5-5.0 mev. For intermediate gamma-ray energies and scattering atoms having low atomic weight (< 100) such that the Compton effect makes the major contribution to the attenuation, the mass attenuation coefficient (the ratio of $\mu(\lambda)$ to the density of the medium) is a constant. The range of gamma-ray energies emitted in nuclear detonation and the atomic weights of the absorbing gaseous constituents and aerosols comprising a given atmospheric medium fall within the aforementioned limits; therefore,

$$\mu(\lambda) = c\mu_o(\lambda)\,,$$

where c is the ratio of the density of the existing atmospheric medium, ρ, to the air density, ρ_o, under NTP conditions, and $\mu_o(\lambda)$ is the linear absorption coefficient for air at NTP. Equation 10 may now be written as

$$W_\gamma(t) = \int_\lambda \frac{N_\lambda(t)\, E_\lambda}{4\pi r^2}\, e^{-c\mu_o(\lambda)\, r}\, d\lambda = \frac{e^{-c\mu r}}{4\pi r^2} \int_\lambda N_\lambda(t)\, E_\lambda\, d\lambda\,,$$

where μ is some value of $\mu_o(\lambda)$ in the range of the integration. The areal density of the incident gamma ray energy is

$$Q_\gamma = \int_t W_\gamma(t)\, dt = \frac{e^{-c\mu r}}{4\pi r^2} \int_t \int_\lambda N_\lambda(t)\, E_\lambda\, d\lambda\, dt .$$

Again the factor represented by the integration is the amount of energy that is emitted as gamma radiation within the first minute following the detonation; therefore,

$$Q_\gamma = \frac{g(w)}{4\pi r^2}\, Y\, e^{-c\mu r} ,$$

where Y is the radiochemical yield, and g(w), expressed as a function of the weapon type, w, represents the fraction of this yield appearing as gamma radiation.

The rate at which the gamma-ray exposure, Q_γ, decreases with increasing radial distance from the burst point is

$$\frac{dQ_\gamma}{dr} = Q_\gamma \left(\frac{2}{r} + c\mu\right) .$$

The first term represents the decrease in Q_γ due to the radial divergence of the gamma ray flux, and the second term expresses the volume rate, S, of gamma radiation absorption which is

$$S = c\mu\, Q_\gamma = \frac{c\mu}{4\pi r^2}\, Y\, g(w)\, e^{-c\mu r} .$$

APPENDIX C

Dependence of Visibility and Atmospheric Density

The visibility and atmospheric density will be influenced by the presence of hydrometers and suspension of minute, solid particles in the form of smoke, dust, fumes, etc. The total attenuation of visible radiation will be affected by scattering and absorption. For multimolecular particles the scattering coefficient, σ_s, is*

$$\sigma_s = K\left(\frac{2\pi r}{\lambda}\right) \pi r^2 N = K(\alpha)\, \pi r^2 N = K(\alpha)\, \frac{3}{4}\, \frac{M}{\rho' r} ,$$

where

r is the particle radius,

N is the number density of particles in the atmosphere,

ρ' is the particle density, and

M is the mass concentration of aerosol in the atmosphere.

For $\alpha < 0.5$, $K\left(\frac{2\pi r}{\lambda}\right)$ approaches $\frac{8\alpha^4}{27}(n^2 - 1)^2$, where n is the index of refraction of the particle. Therefore, σ_s becomes*

$$\sigma_s = \frac{32\pi^4 (n^2 - 1)^2}{9\, \lambda^4\, \rho'}\, r^3\, M .$$

The absorption coefficient, σ_a, can be expressed as $\sigma_a = K_1 \times M$; therefore, the attenuation, σ, is written as

$$\sigma = \sigma_s + \sigma_a = M\left[\frac{32\pi^4 (n^2 - 1)^2}{9\, \lambda^4\, \rho'}\, r^3 + K_1\right] . \qquad (11)$$

Also, from Equation 2:

$$\sigma = \frac{\beta}{V} = \frac{3.9}{V} , \qquad (12)$$

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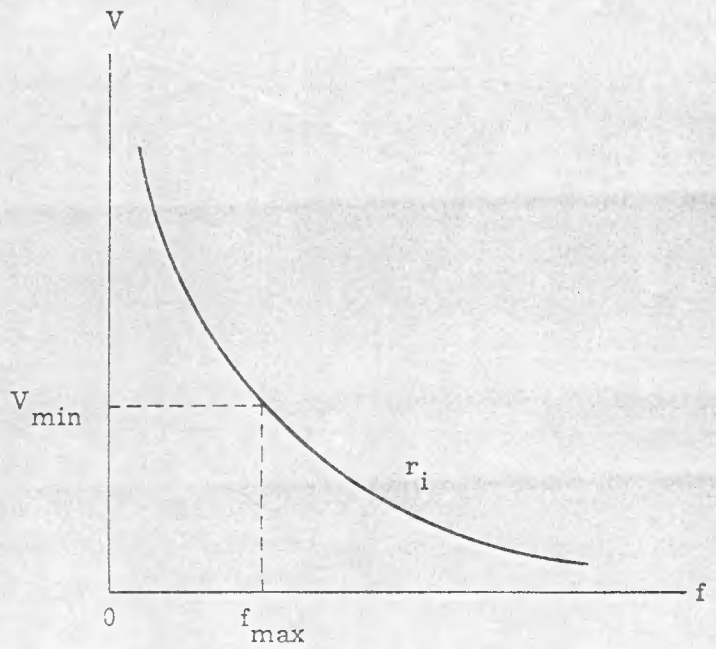
*Ref 10, pp 173-177

where V is the visibility. By eliminating σ from Equations 11 and 12,

$$Vf = \begin{cases} \dfrac{3.9}{\rho\left[\dfrac{3K(\alpha)}{4\,\rho' r} + K_1\right]} = C_1 \text{ for } \alpha > 0.5 \\[2ex] \dfrac{3.9}{\rho\left[\dfrac{32\,\pi^4\,(n^2-1)^2}{9\,\lambda^4\,\rho'}\,r^3 + K_1\right]} = C_2 \text{ for } \alpha < 0.5 \end{cases} \tag{13}$$

Here $f = M/\rho$, which is the ratio of the mass concentration of aerosol in the atmosphere to the density of the atmosphere. Equation 13 expresses the relationship between visibility and the fractional atmospheric density of the aerosol as a rectangular hyperbola (shown below).



As the visibility decreases from infinity to its minimum value (about 0.5 mile), a variation in f from zero to about 0.01 can be tolerated before the effect of atmospheric density upon the visibility need be considered. To determine the maximum effect that the ranging of V will have upon f, one must consider the limiting hyperbola having the largest constant, ie, the largest product of V and f. Therefore, the denominator in Equation 13 should be a minimum. In the expression of C_1 (Equation 13) the function $K(\alpha)$ oscillates about the value 2, rising to a maximum of about 10 for r approximately equal to λ; thus C_1 depends more strongly upon r directly than it does upon r through the function $K(\alpha)$. Since the maximum values of C_1 and C_2 are of interest, zero absorption will be assumed; therefore, $K_1 = 0$. Now C_1 is a

maximum when r is a maximum (about 0.1 cm), and C_2 is a maximum when r is a minimum (about 0.01 micron). These values of r indicate the expected size range of the aerosols.*

Let $K(\alpha) = 2$, $n = 1.3$, $\lambda = 0.5$ micron, $\rho' = 2$ gm/cc, and $\rho = 1.22 \times c$ gm/l where c is the ratio of the ambient atmospheric density to the density of air at NTP. These values show that $C_1 > C_2$ and $C_1 = 0.003$ mile for $c = 1$; therefore, for an assumed minimum visibility of 1/2 mile, $f = 0.006$, and the dependence of the atmospheric density upon visibility may be considered as insignificant.

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*Ref 10, p 160

LIST OF REFERENCES

1. Shelton, F. H., High-Altitude Effects on Blast-Thermal Partition of Energy from Nuclear Explosions, and Associated Scaling Laws, SC-2969(TR), September 15, 1953

2. Middleton, W. E. K., Vision Through the Atmosphere, University of Toronto Press, 1953, pp64-70

3. Blackwell, H. R., "Contrast Thresholds of the Human Eye," Journal of Optical Society of America, 36, No. 11, 1946, pp 624-643

4. Capabilities of Atomic Weapons, AFSWP, October 1, 1952, TM 23-200

5. Storm, E., Gamma Radiation Exposure as a Function of Distance, WT-408, Los Alamos Scientific Laboratory, March 1952, p 34

6. Storm, E., Gamma Radiation Exposure as a Function of Distance, WT-549, Los Alamos Scientific Laboratory, July 1952

7. Larrick, R. G., Fuller, E. J., Smith, L. S., and Boss, R. C., Total Gamma Exposure vs Distance, WT-522, September 1952

8. Perkins, J. G., Pearse, H. E., and Kingsley, H. D., Studies on Flash Burns, UR-217, University of Rochester, December 1952

9. Paxson, E. W., Thermo-Nuclear Attack on an Army Group, RM-869, Rand Corporation, June 16, 1952

10. McCabe, L., Air Pollution, McGraw Hill, New York, 1952

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July 29, 1954

TO: DISTRIBUTION OF SC-3186(TR)

RE: Errata sheet for SC-3186(TR)

On pages 4 and 14 for Fig. 2, please read "...ambient atmospheric density is 0.6 of the air density at normal temperature and pressure."

On pages 4 and 15 for Fig. 3, please read "...ambient atmospheric density is 0.8 of the air density at normal temperature and pressure."

On page 12 under Solution, in the second line please read Fig. 3 for Fig. 2.

On page 17, in the second line please read Fig. 2 for Fig. 3.

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