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APPROXIMATE CALCULATIONS OF RADIATION-INDUCED CURRENTS.(U)
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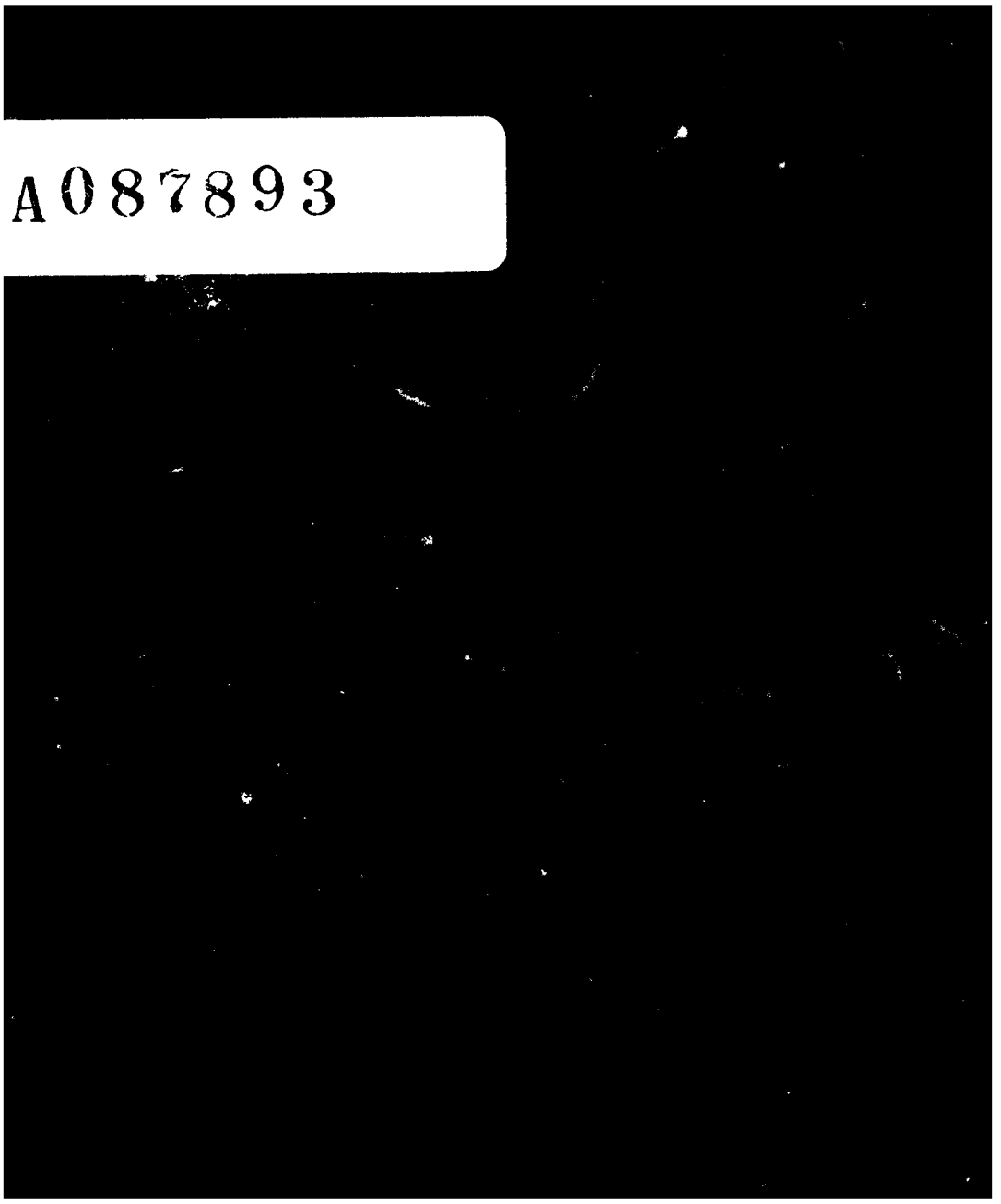
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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

A simple procedure for calculating approximate values of radiation-induced currents is discussed. The procedure is intended for those who require only first-order estimates of such currents or who have neither time nor access to computer facilities for a more precise treatment. An example is given to illustrate the method.

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1. INTRODUCTION

In the development of military systems having radiation-hardness requirements and in assessments of radiation response in existing military equipment, it is frequently necessary to carry out immediate theoretical estimates of radiation-induced currents. Frequently, these analyses must be performed by individuals unfamiliar with the quantitative side of radiation physics. As an aid to these workers, a review of a simple first-order prediction of radiation-induced current is presented, and a sample calculation is included to illustrate the procedure.

The most common radiation environment of concern to system designers includes a fast pulse of photons having energies in the kiloelectron-volt to megaelectron-volt range. Since the procedure described below applies only to monoenergetic photons, it is necessary to divide the photon spectrum into a series of approximately monoenergetic increments. For the portion of the spectrum between 1 and 100 keV, a 10-keV bin width is adequate; above 100 keV, bin widths may be increased to 0.1 MeV or more without introducing serious error in the integral result. Once the current contributions from the various photon increments are calculated, they can be added linearly to arrive at a first-order estimate of total radiation-induced current. The discussion that follows treats a photon pulse that is assumed to be monoenergetic. (See fig. 1 for a pictorial representation of this transport model.)

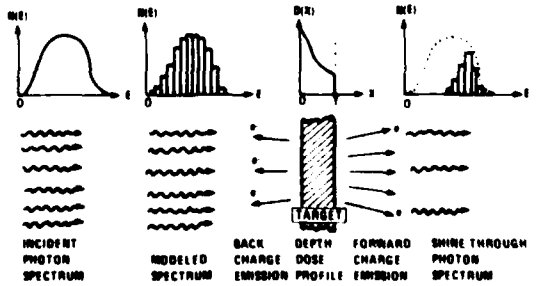

Figure 1. Photon transport through and electron emission from slab target.

2. PROCEDURE

2.1 Calculating Shine-through Fluence from Incident Fluence

To calculate shine-through fluence from incident fluence, let f_0 be the energy fluence of photons incident at right angles to the target. Energy fluence has units of energy per unit beam area.

Then $f(x) = f_0 e^{-\mu x}$ is the fluence of original photons left at a linear depth x in a target material of atomic number Z; and $\mu = \mu(h\nu; Z)$, the attenuation coefficient, is the reciprocal of the depth in the material at which the original fluence is reduced by a factor of 1/e. Equivalently, x may be considered the target mass traversed by the photon beam per unit beam area; then μ is given as the total cross-sectional area presented to the photons per unit mass of target material. The factor linking these two representations is the density of the target material. The shine-through fluence is then $f(T) = f_0 e^{-\mu T}$, where T is the target thickness.

2.2 Calculating Dose from Shine-through Fluence and Vice Versa

The dose at the emitting surface attributed to the shine-through photons $f(T)$ is the energy deposited by those photons per unit mass of material. Since some of the energy removed from the original photon beam by interactions with the target material reappears in the form of lower-energy photons (Compton scatter, fluorescence, etc.), some of which may also escape the target, a different coefficient, the energy absorption coefficient μ', must be used to calculate dose. With μ' denoting the rate at which energy is deposited in the material, one may define dose D at the emitting surface as follows:

Let energy absorbed per unit area of the target in the interval x and $x + \Delta x$ be ΔE. $f(x) - f(x + \Delta x)$, where $f(x + \Delta x)$ is energy fluence at depth $x + \Delta x$ reduced from its value at x only by the factor $e^{-\mu' \Delta x}$. (For small Δx, the secondary photons produced in that interval

are still present in the total photon fluence; that is, their energy is not deposited in Δx.)

Then

$$\Delta E = f(x) - f(x)e^{-\mu'\Delta x}$$

$$\simeq f(x) - f(x)[1 - \mu'\Delta x]$$

$$= f(x)\mu'\Delta x \quad .$$

Dose at depth x can then be defined as the limit

$$D(x) \equiv \lim_{\Delta x \to 0} \frac{\Delta E}{\Delta x} = \mu' f(x) \quad ,$$

and, reciprocally,

$$f(x) = D(x)/\mu' \quad .$$

It must be acknowledged that this is only a first approximation since some contribution to energy deposited in Δx comes from secondary photons produced in the intervals 0 to x and $(x + \Delta x)$ to T. This contribution is neglected here because these secondary photons have lower energies and shorter mean free paths than the primary photons and thus tend to be more localized, although not so much so as are the photoelectric and Compton electrons produced in the photon's interactions with the target. More to the point, a really accurate treatment would require tracking these secondary photons by using Monte Carlo transport techniques. Secondary photon buildup renders this means of calculating dose increasingly in error the deeper one goes into thick targets (targets whose thicknesses are a significant part of the photon's mean free path). For these cases, one may bracket the dose using μ' for the lower limit and μ for the upper limit. The photon energies for which there is a noticeable difference between μ and μ' lie in the range where the Compton interaction dominates the photoelectric effect; in this range, the secondary photons that are produced have a significant fraction of the primary photon's energy and thus are quite likely to escape thin targets.

This digression clarifies alternative means of defining a photon environment. Setting aside for the moment the matter of radiation time histories, one can specify a photon environment uniquely in two equivalent ways; one way is to specify fluence and energy spectrum; the second way is to specify dose *in a given material* and the photon energy spectrum. Of the two, fluence and spectrum are the more fundamental descriptions of the radiation; dose is really a radiation effect (energy deposition) in a specified medium. The first way is more common to the study of the system-generated electromagnetic pulse (SGEMP), for which photoelectric and Compton electrons are the drivers; the second way is used in the study of transient radiation effects in electronics (TREE), which are effects associated with direct deposition of photon energy in electronic components. There is no inconsistency in describing a radiation environment by using a dose unit specified for one material when the radiation is incident on an entirely different material. Specifying the photon spectrum and having available a quantitative description of the various photon interactions with matter allow one to convert from the first dose quantity to a fluence and thence to the dose in the material irradiated.

2.3 Calculating Emitted Charge and Current from Dose

As an example of calculating emitted charge and current from dose, assume that one is given a monochromatic fluence of 1.2-MeV photons and a dose of 1 rad (Si) at the shadowed surface of a 0.28-cm-thick iron plate. What charge is emitted from the plate?

The dose is given in rads (Si). This dose may be converted to fluence by using the relationship derived in section 2.2 and then may be converted to emitted charge by using a graphical representation of a Monte Carlo treatment of electron emission — in this case, the computer code POEM.[1] Figures 2 through 8 show the electron yield dependence on photon energy for a variety of elements. Also shown for comparison

[1] H. J. Chaides and C. H. Wilson, X-Ray Photoemission, Science Applications, Inc., McLean, VA, HDL-CR-75-108-1 (September 1975).

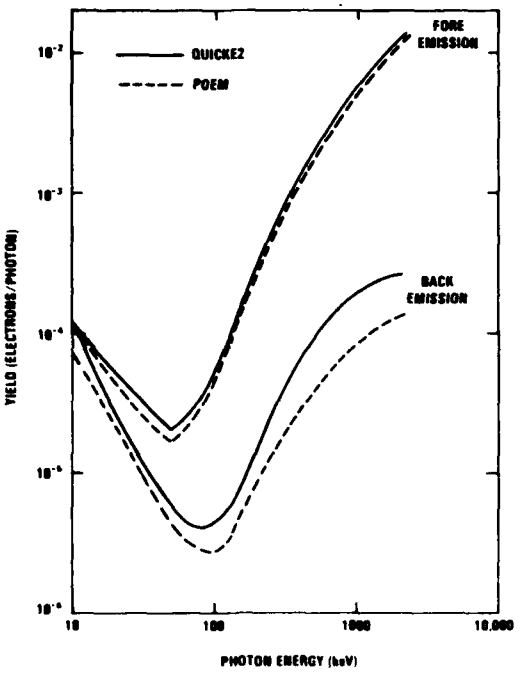

Figure 2. Yield versus photon energy for carbon (from SAI HDL-CR-75-138-1).

are the results from a QUICKE2 analytical transport calculation and a variety of representative electron transport experiments. Figures 9 through 18 show the photon absorption and the attenuation coefficients as functions of photon energy for these same elements, as well as for silicon, iron, and lead. Chadsey and Wilson[1] and Brown[2] treat additional elements not represented here. If one must calculate currents emitted from an element for which no yield and cross-section data are at hand, it is sufficiently accurate to calculate the desired quantities by interpolation. The approach is to identify the two elements represented in this report whose atomic numbers most closely bracket the atomic number of the target element. A linear interpolation, based on atomic number, of cross sections and yields then provides the desired data, usually accurate to within 10 percent.

[1] W. J. Chadsey and C. W. Wilson, X Ray Photoemission, Science Applications, Inc., McLean, VA, HDL-CR-75-138-1 (September 1975).

[2] W. D. Brown, X Ray Attenuation and Absorption Coefficients, The Boeing Aerospace Co., Seattle, WA, D2-125065-1 (September 1966).

Figure 11 shows that the silicon absorption cross section at a photon energy of 1.2 MeV is

$$\mu' = 2.8 \cdot 10^{-2} \text{ cm}^2/\text{g} \quad .$$

The dose in silicon at the back side of the iron plate, 1 rad (Si), is translated to a fluence in the manner described in section 2.2:

$$f(\text{MeV/cm}^2) = D(\text{MeV/g})/\mu'(\text{cm}^2/\text{g}) \quad .$$

Using the value for μ' above and the equivalence

$$1 \text{ rad} = 6.25 \cdot 10^7 \text{ MeV/g}$$

(which applies to all materials), one gets

$$f \simeq 2.3 \cdot 10^9 \text{ MeV/cm}^2 \quad .$$

Conversely, the dose in iron associated with this fluence is (using fig. 13)

$$D = f \cdot \mu'_{Fe} = (2.3 \cdot 10^9 \text{ MeV/cm}^2) \times (2.5 \cdot 10^{-2} \text{ cm}^2/\text{g})$$

$$= 5.7 \cdot 10^7 \text{ MeV/g}$$

$$= 0.9 \text{ rad (Fe)} \quad .$$

Since the energy of each photon is 1.2 MeV, the shine-through energy fluence is equivalent to a photon number fluence of

$$f \simeq 1.9 \cdot 10^9 \text{ photons/cm}^2 \quad .$$

An interpolation of the forward-directed electron yield (Y) between titanium and copper (fig. 4, 5) gives for iron

$$Y \simeq 6.1 \cdot 10^{-1} \text{ electrons/photon} .$$

Incidentally, since the photon energy is in the megaelectron-volt range, this yield is almost all Compton production. (See Evans[3] for a general discussion of interaction mechanisms.) The electron charge emitted per unit area is then

[3] R. D. Evans, The Atomic Nucleus, McGraw-Hill Book Co., New York (1955).

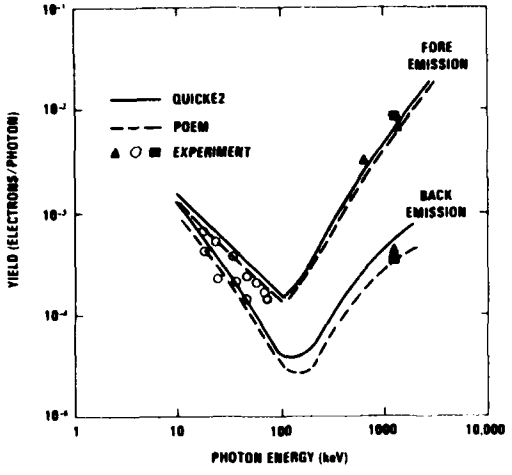

Figure 3. Yield versus photon energy for aluminum (from SAI HDL-CR-75-138-1).

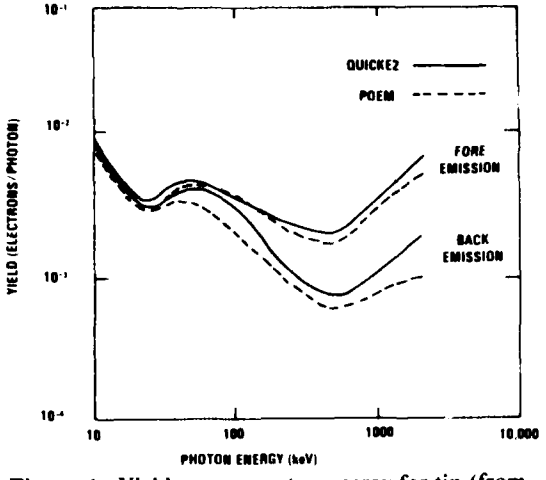

Figure 6. Yield versus photon energy for tin (from SAI HDL-CR-75-138-1).

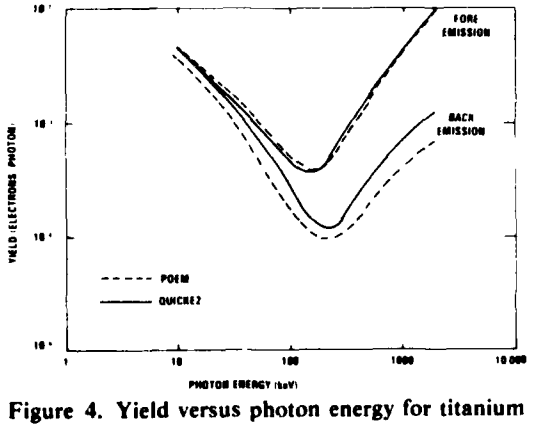

Figure 4. Yield versus photon energy for titanium (from SAI HDL-CR-75-138-1).

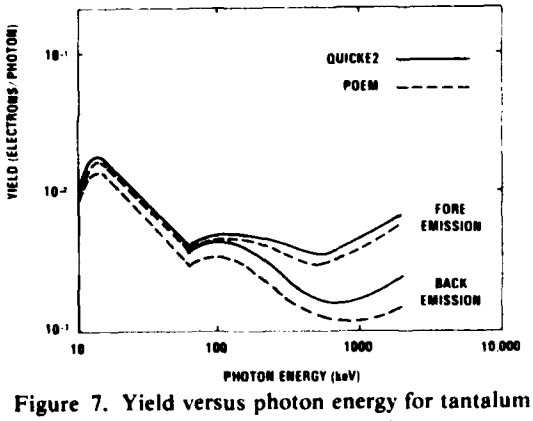

Figure 7. Yield versus photon energy for tantalum (from SAI HDL-CR-75-138-1).

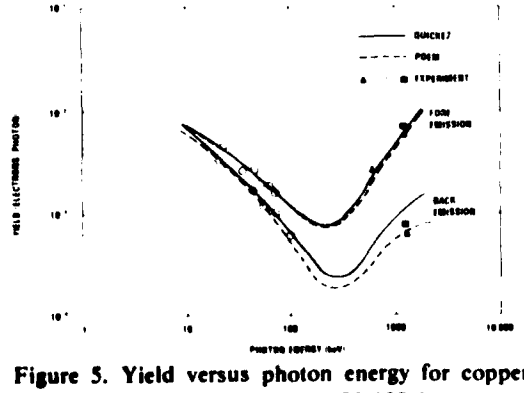

Figure 5. Yield versus photon energy for copper (from SAI HDL-CR-75-138-1).

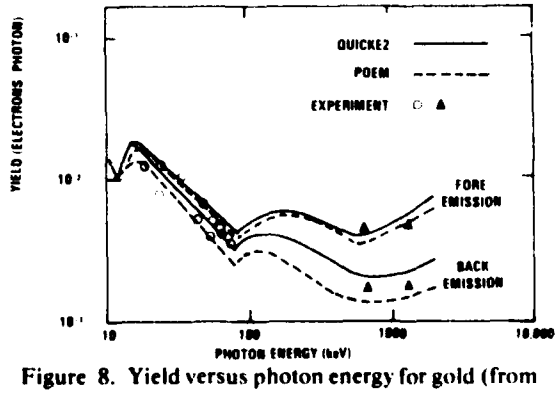

Figure 8. Yield versus photon energy for gold (from SAI HDL-CR-75-138-1).

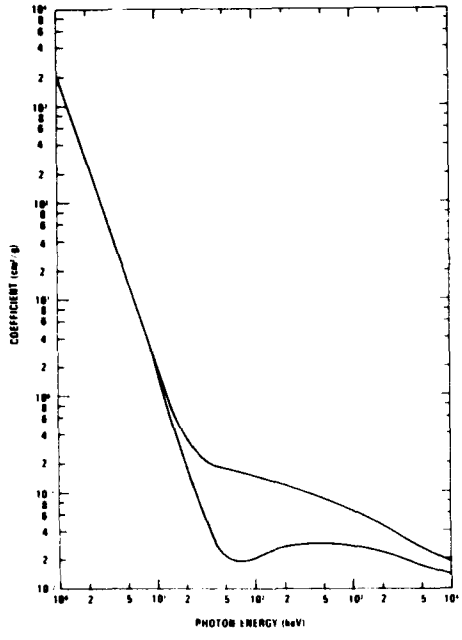

Figure 9. Attenuation and absorption coefficients for carbon, atomic number = 6 (from Boeing D2-125065-1).

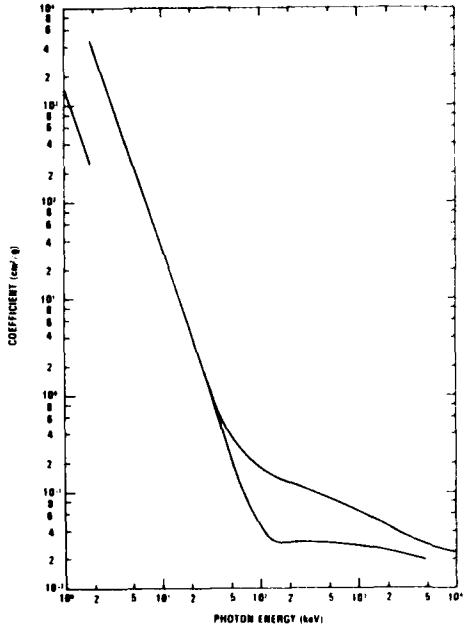

Figure 11. Attenuation and absorption coefficients for silicon, atomic number = 14 (from Boeing D2-125065-1).

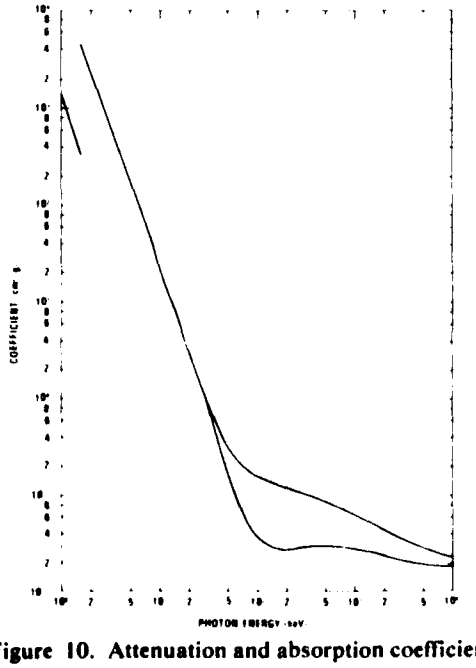

Figure 10. Attenuation and absorption coefficients for aluminum, atomic number = 13 (from Boeing D2-125065-1).

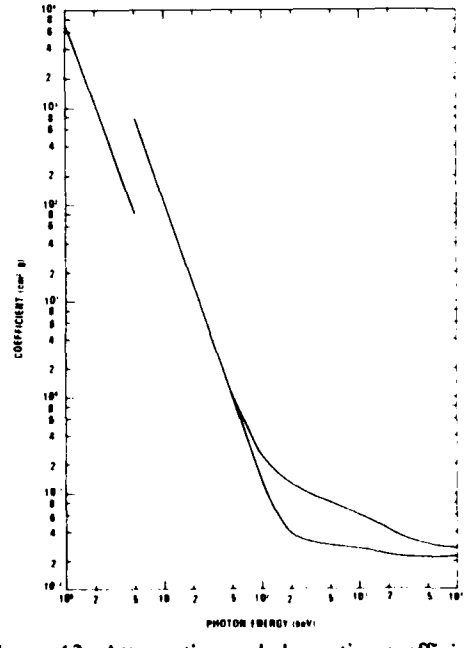

Figure 12. Attenuation and absorption coefficients for titanium, atomic number = 26 (from Boeing D2-125065-1).

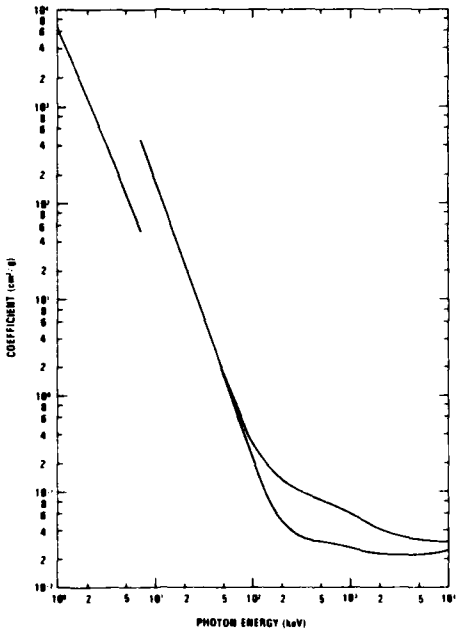

Figure 13. Attenuation and absorption coefficients for iron, atomic number = 26 (from Boeing D2-125065-1).

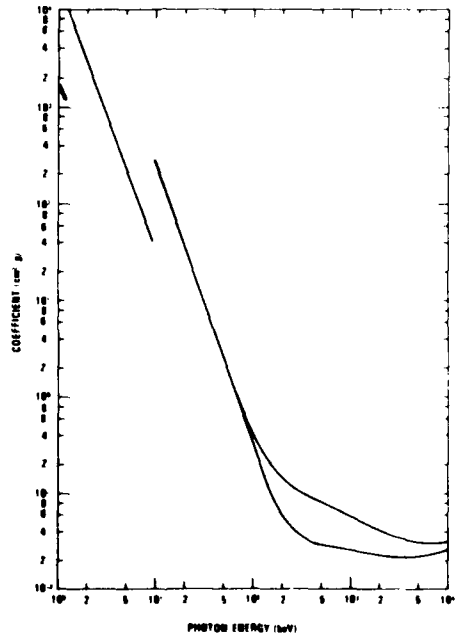

Figure 14. Attenuation and absorption coefficients for copper, atomic number 29 (from Boeing D2-125065-1).

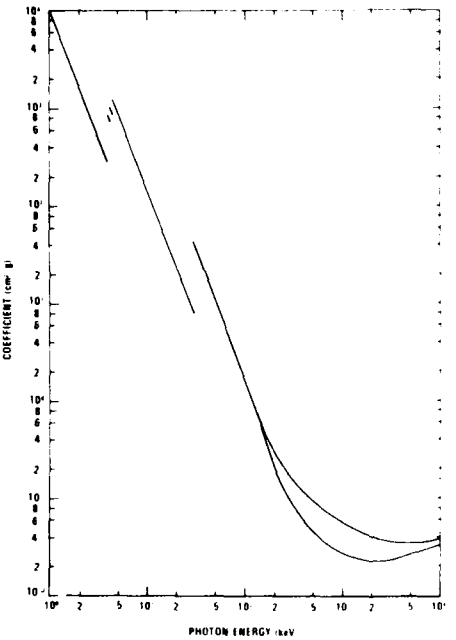

Figure 15. Attenuation and absorption coefficients for tin, atomic number = 50 (from Boeing D2-125065-1).

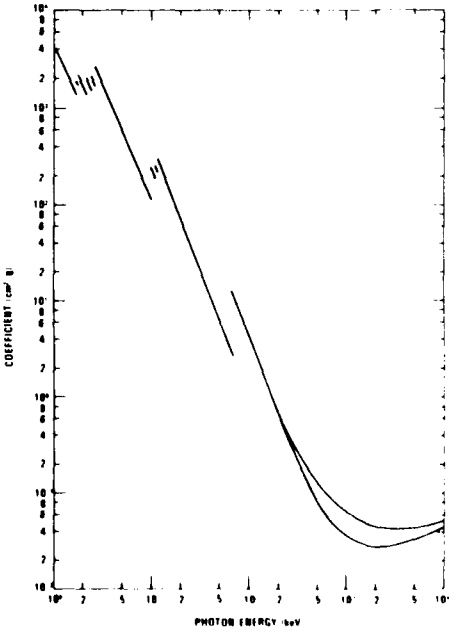

Figure 16. Attenuation and absorption coefficients for tantalum, atomic number 73 (from Boeing D2-125065-1).

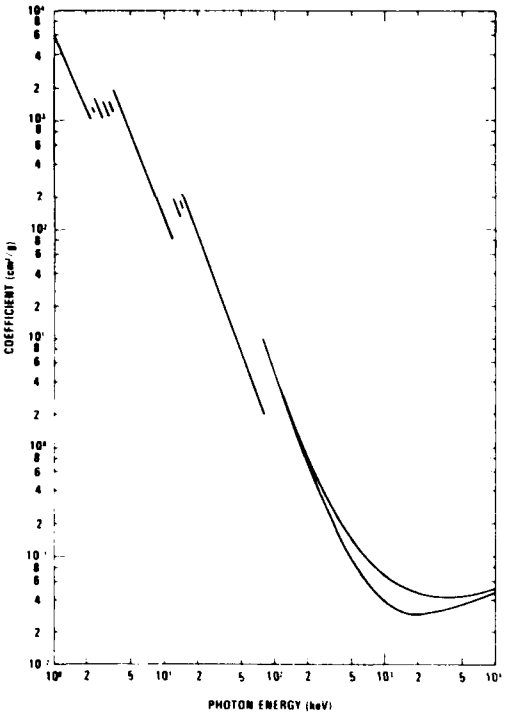

Figure 17. Attenuation and absorption coefficients for gold, atomic number = 79 (from Boeing D2-125065-1).

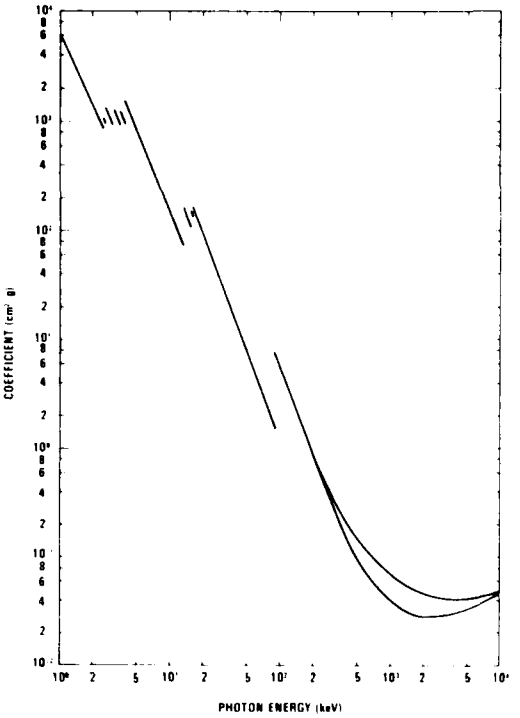

Figure 18. Attenuation and absorption coefficients for lead, atomic number = 82 (from Boeing D2-125065-1).

$$Q = fY \quad 1.2 \cdot 10^{7} \text{ electrons/cm}^2$$

$$= 1.9 \cdot 10^{-12} \text{ coulomb/cm}^2 \quad .$$

One may define an emission factor

$$K = Q/D \quad ,$$

which, for iron and 1.2-MeV gamma rays, is

$$K = 1.9 \cdot 10^{-12} \text{ coulomb/cm}^2/\text{rad (Si)} \quad .$$

The nominal uncertainty in this result is ±20 percent.

Because the photons are monoenergetic, the 1-rad (Si) dose on the back side of the iron plate can be backtracked exponentially to determine the corresponding dose on the front surface:

$$\text{dose (front surface)} \quad \text{dose (back surface)}/e^{-\mu T} \quad ,$$

where now μ is the attenuation constant at $h\upsilon = 1.2$ MeV for iron, $5.7 \cdot 10^{-2}$ cm²/g. The dose on the leading surface, using 7.9 g/cm³ as the density of iron, is

$$1 \text{ rad (Si)}/e^{-\mu T} = \exp\left[(5.7 \cdot 10^{-2} \text{ cm}^2/\text{g})\right.$$

$$\left. \times (0.28 \text{ cm})(7.9 \text{ g/cm}^3)\right] \text{ rad (Si)}$$

$$= 1.1 \text{ rad (Si)} \quad .$$

This dose corresponds to an incident fluence of

$$f_0 \quad 2.3 \cdot 10^{9} \text{ MeV/cm}^2 \cdot e^{-\mu T}$$

$$2.6 \cdot 10^{9} \text{ MeV/cm}^2 \quad .$$

The photon time history is the same time history that the emissions of Compton electrons

and photoelectrons follow; hence, in SGEMP studies, it must be specified before electron current magnitudes can be determined. (Currents are required because magnetic fields and time derivatives of charge density are current-dependent quantities.) The radiation time history and fluence are usually conveyed in terms of the radiation flux, the time derivative of fluence. In this case, the constant K calculated above has the same magnitude, but now is given in amperes per square centimeter per rad (Si) per second. When TREE is the concern, radiation delivery times are frequently so short that damage effects are pulse-time independent; that is, the energy deposition occurs in intervals short compared with energy dissipation times. When this condition applies, it is common to deal in terms of dose, rather than dose rates, and less attention is paid to radiation pulse shapes.

3. COMMENTS

If one is seeking an estimate of net current between two parallel layers of material, the procedure of section 2.3 can be applied to estimate forward emission from the shadow side of the first layer and backward emission from the illuminated side of the second layer. If the distance separating these two surfaces is too small for space-charge limiting to occur, and if ionization of gases in the space between them is either too small or too late to allow a significant conduction current, then an algebraic addition of current from the two surfaces yields a good estimate of the net current between layers.

If the photon beam strikes the target off normal by an amount θ, the emission current density is reduced for two reasons: (1) The electrons ejected by photons in a unit area of the photon beam are spread over a surface area $1/\cos\theta$ larger than the unit area; hence, the emission densities are smaller by a factor of $\cos\theta$. (2) The photon fluence reaching the rear surface of the target is smaller because photons have traversed a longer path length in the target; thus the front-to-rear attenuation factor is $e^{-\mu T/\cos\theta}$ instead of $e^{-\mu T}$.

Finally, the target may be composed of several elements in a mixture or in a compound, or it may be formed from a number of layers, each layer composed of a single element. The transport of photons through both types of target may be treated in the same way: T_i, the total cross-sectional mass density of the ith element seen by the photon beam in its front-to-rear passage, produces a beam attenuation factor of $e^{-\mu_i T_i}$; the attenuation factor for the whole target is simply the product of all the $e^{-\mu_i T_i}$ factors. The electron yield from the rear surface is calculated as follows: For a rear surface composed of a single element having a thickness equal to or greater than an extrapolated electron range in that element, the approach is exactly that used in the example. If the rear surface layer is a mixture or a compound of several elements, the calculation of emission charge and current is more complicated. If electron ranges (in grams per square centimeter) are approximately the same for the various constituent elements, the fractional yield (that is, the yield for the one-element target weighted by the ratio of that element's density in the target to the total target density) may be summed with the fractional yields for the other components of the target to arrive at a net yield.

If the ranges are greatly dissimilar, the complexity of the problem exceeds the scope of this report. For this case, a zero-order estimate may be found by using the yield for the element with the shortest electron range; this element will have (not incidentally) the highest atomic number and the highest yield factor of those elements in the target.

NUMERICAL CONVERSIONS FOR CALCULATING RADIATION-INDUCED CURRENTS

1 eV	is equivalent to	1.6022×10^{-19}	joule
		or 1.6022×10^{-12}	ergs
		or 3.8294×10^{-20}	calorie
1 erg	is equivalent to	1.0000×10^{-7}	joule
1 e (electron charge)	is equivalent to	1.6022×10^{-19}	coulomb
1 ampere	is equivalent to	1.0000	coulomb/s
1 cm	is equivalent to	0.3937	in.
1 cm^2	is equivalent to	0.1550	$in.^2$
1 barn	is equivalent to	1.0000×10^{-24}	cm^2
1 g	is equivalent to	0.5274×10^{-2}	ounce
1 rad (dose)	is equivalent to	1.0000×10^{2}	ergs/g
		or 6.25×10^{7}	MeV/g
1 roentgen (fluence)	is equivalent to	84	ergs/g (air)
		or 1.61×10^{12}	ion pairs/g (air)

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