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HANDBOOK FOR DOSE ENHANCEMENT EFFECTS IN ELECTRONIC DEVICES

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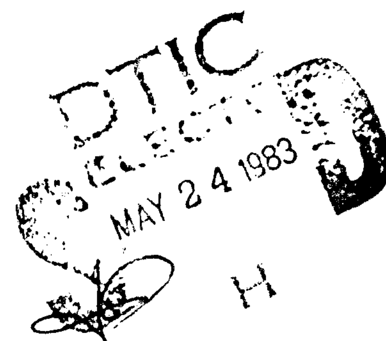

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The handbook provides tabulations of dose enhancement factors for electronic devices in X-ray and gamma environments. The data is applicable to a wide range of semiconductor devices and selected types of capacitors. The radiation environment includes energy spectra for system design and for radiation test facilities.

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TABLE OF CONTENTS

PAGE

1.0 INTRODUCTION 1

2.0 REVIEW OF DOSE ENHANCEMENT EFFECTS 3

2.1 Origin of Dose Enhancement 3

2.2 Dose Enhancement Factor (DEF). 6

2.3 Dose Enhancement Effects in Devices. 6

2.3.1 Total Dose Effects 8

2.3.2 Transient Effects 11

2.3.3 Dose Enhancement Effects in Capacitors. 12

3.0 DOSE ENHANCEMENT FACTORS FOR SYSTEM DESIGN 15

4.0 DOSE ENHANCEMENT FACTORS FOR RADIATION TEST FACILITIES 18

5.0 USING THE DOSE ENHANCEMENT FACTOR 21

6.0 DOSE ENHANCEMENT FACTORS FOR ARBITRARY ENERGY SPECTRA. 25

APPENDIX A: SPECTRA USED FOR HANDBOOK CALCULATIONS. 35

APPENDIX B: LIST OF DEF CALCULATIONS. 41

BIBLIOGRAPHY 45

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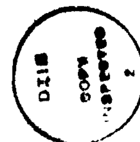

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1.0 INTRODUCTION

The purpose of this handbook is to provide a single reference source for dose enhancement factors in electronic devices of interest to common electronic systems. The handbook contains information applicable to a wide range of semiconductor devices and selected types of capacitors. Radiation environments include X-ray and gamma-ray spectra applicable to system nuclear environments, as well as radiation test facility environments.

Section 2 provides a summary of dose enhancement phenomenology. This includes a description of the origin and the nature of the primary effects. The effects on electronic parts are then summarized to clarify the nature of the response mechanisms and the relevant device parameters which influence the effects.

Section 3 presents the dose enhancement factors (DEFs) for system design applications. This includes worst case DEF values for a range of generic device and package structures in X-ray and gamma environments. Explanations of the basis of the values are provided, as well as sample problems to illustrate the use and the derivation of handbook values.

Section 4 presents the dose enhancement factors for radiation test facilities using the same device categories as in Section 3. This permits an assessment of dose enhancement effects for radiation simulation testing to aid in the interpretation of system related responses. Handbook usage is again illustrated by sample problems.

Section 5 provides graphs which can be used to determine the dose enhancement factors for gold packaged devices for an arbitrary photon energy spectrum. This permits consideration of spectra other than those specifically evaluated in Sections 3 and 4.

The appendices contain data to substantiate the computational basis for the handbook values. Appendix A contains the photon spectra used in the calculations and Appendix B provides a list of dose-depth calculations from which the handbook data is derived.

Finally, a bibliography is included which provides the references used for the handbook and a guide to the published literature in dose enhancement effects.

2.0 REVIEW OF DOSE ENHANCEMENT EFFECTS

2.1 ORIGIN OF DOSE ENHANCEMENT

When a material is irradiated with X-rays or gamma rays energy is absorbed by the material. Dose is defined as the energy per unit mass absorbed by the material. The photons lose energy by interacting with electrons in the material, resulting in a transfer of energy from the photons to the electrons. The energetic electrons then lose their excess energy by collisions with other electrons in the material, resulting in a large number of secondary electrons of various energies. It requires a finite distance for the secondary electrons to lose their excess energy in the material.

Figure 2-1 illustrates the nature of the dose distributions which occur in gold-silicon interfaces irradiated with X-rays or gamma rays. At distances far from the interface (greater than the range of the most penetrating secondary electron), electron equilibrium exists and the dose approaches equilibrium values for each material. Within an electron range of the interface, electron equilibrium does not exist, and the dose differs from the equilibrium bulk values. The dose variation occurs over a transition region determined by the range of the most energetic electrons in each material. Dose enhancement is defined as:

$$\text{Dose Enhancement} = \frac{\text{Local dose in the transition region}}{\text{Equilibrium dose}} \quad (2\text{-}1)$$

X-rays produce much larger dose enhancement effects than gamma rays because X-rays usually have a much lower energy than gamma rays. X-rays interact with matter predominantly by the photoelectric process, in which the X-ray is totally absorbed by an atom and the atom emits an electron from its inner shell.

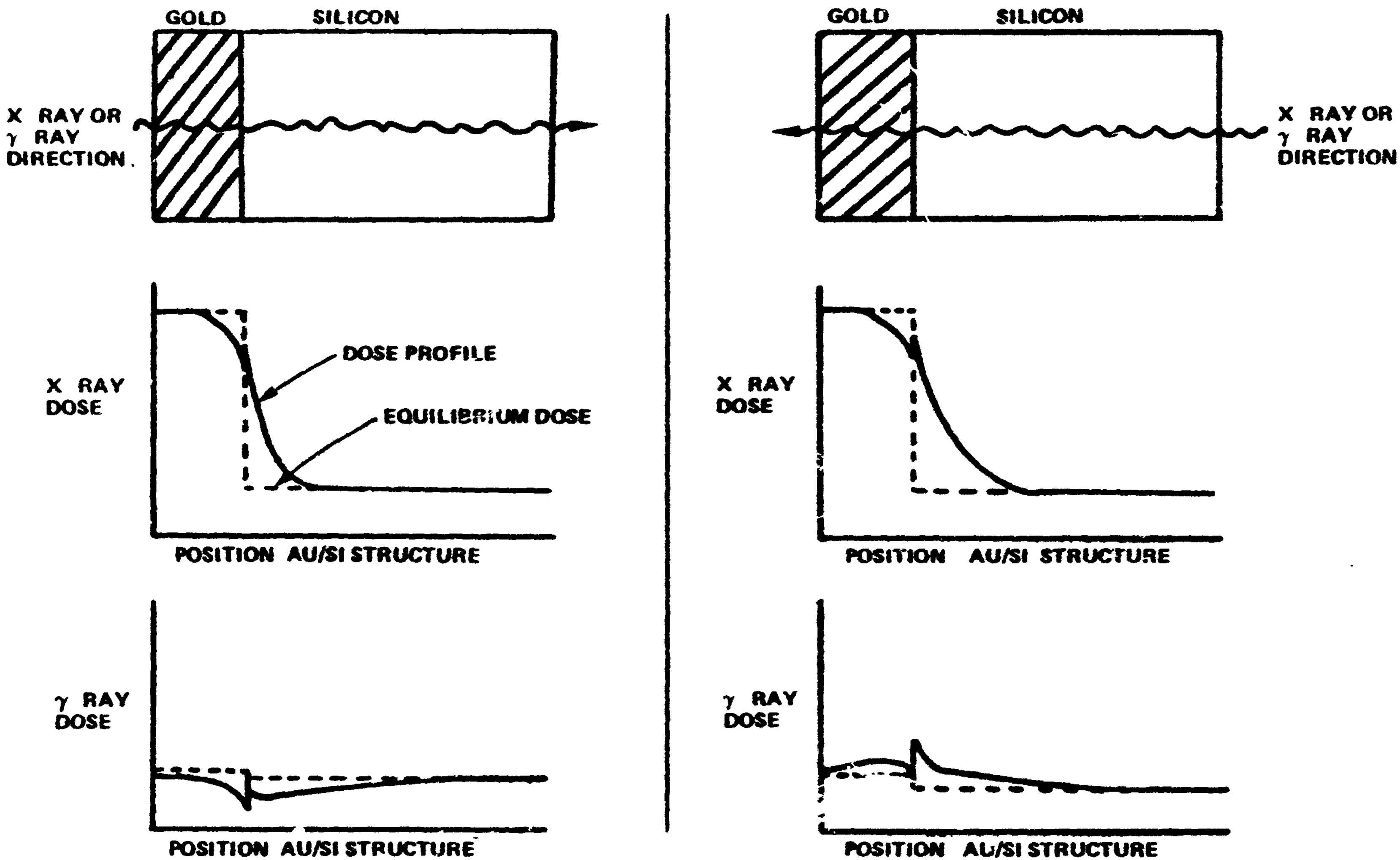


FIGURE 2-1. DOSE DISTRIBUTIONS NEAR GOLD-SILICON INTERFACES DUE TO X-RAYS AND GAMMA-RAYS

This process depends strongly on the atomic number (Z) of the atom, and is largest for high-Z materials. At a gold-silicon interface, there are many more electrons generated in the gold. The electrons penetrate into the silicon and enhance the dose in silicon near the interface (Figure 2-1). There is a discontinuity in dose at the interface due to differences in electron stopping power between the two materials. The dose distribution is approximately the same for X-rays traversing the interface in either direction since the photoelectric effect emits electrons isotropically. In a gold-silicon interface, the maximum dose enhancement is approximately 30, which occurs for X-rays with an energy of about 100 KeV. In gold-polyethelene interfaces, the dose enhancement can be as large as 400 for X-rays.

Dose enhancement effects are much less for gamma rays than for X-rays due to the higher energy of the gamma rays. Gamma rays interact with matter predominantly by the Compton process, in which the photon collides with electrons in the material. The process is largely independent of the atomic number of the material; the gamma rays produce approximately the same number and spectrum of electrons in any material. Hence, dose enhancement arises primarily from electron scattering differences at the interface. This mechanism can produce at most a dose enhancement value of 2.0, which is much less than for X-rays. The electron range (transition region thickness) for gammas is higher than for X-rays because of the higher photon energies, and the dose enhancement is directionally dependent due to the predominance of forward scattered electrons in the Compton process. Since the dose enhancement for X-rays is much larger than for gammas, the emphasis in this handbook is devoted to characterizing X-ray dose enhancement effects.

2.2 DOSE ENHANCEMENT FACTOR (DEF)

In practice, it turns out that we can account for the effects of dose enhancement in electronic devices by using a term called Dose Enhancement Factor, DEF. By multiplying the equilibrium dose times the DEF we obtain the actual dose being received by the sensitive portion of the device in question. The Dose Enhancement Factor is defined as:

$$DEF = \frac{\text{Average dose in sensitive region of device}}{\text{Equilibrium Dose}} \qquad (2\text{-}2)$$

There are two major response mechanisms which must be considered: (1) Total dose damage, and (2) photocurrent response. For total dose damage, the sensitive region is the SiO_2 insulator layer on the top of the silicon chip. For transient effects, the sensitive region is the photocurrent collection volume. These two sensitive regions are illustrated in Figure 2-2. The illustration is for an MOS transistor, although the concept of sensitive regions is similar for bipolar transistors.

2.3 DOSE ENHANCEMENT EFFECTS IN DEVICES

Strong dose enhancement effects occur in semiconductor devices when there are high-Z materials in the device structure. In semiconductor parts, high-Z materials can occur in the chip metallization or in the device package. The active region of a chip is located near the top surface of the chip, and it is the dose in the active region which affects device performance. The chip is thick enough to protect the active region from significant dose enhancement effects from the bottom of the chip; e.g., chips which are mounted using a gold-eutectic bonding do not have significant dose enhancement effects in the top (active) region of the chip. There are then only two critical regions of a device where high-Z materials can be used which will cause significant dose enhancement. These are:

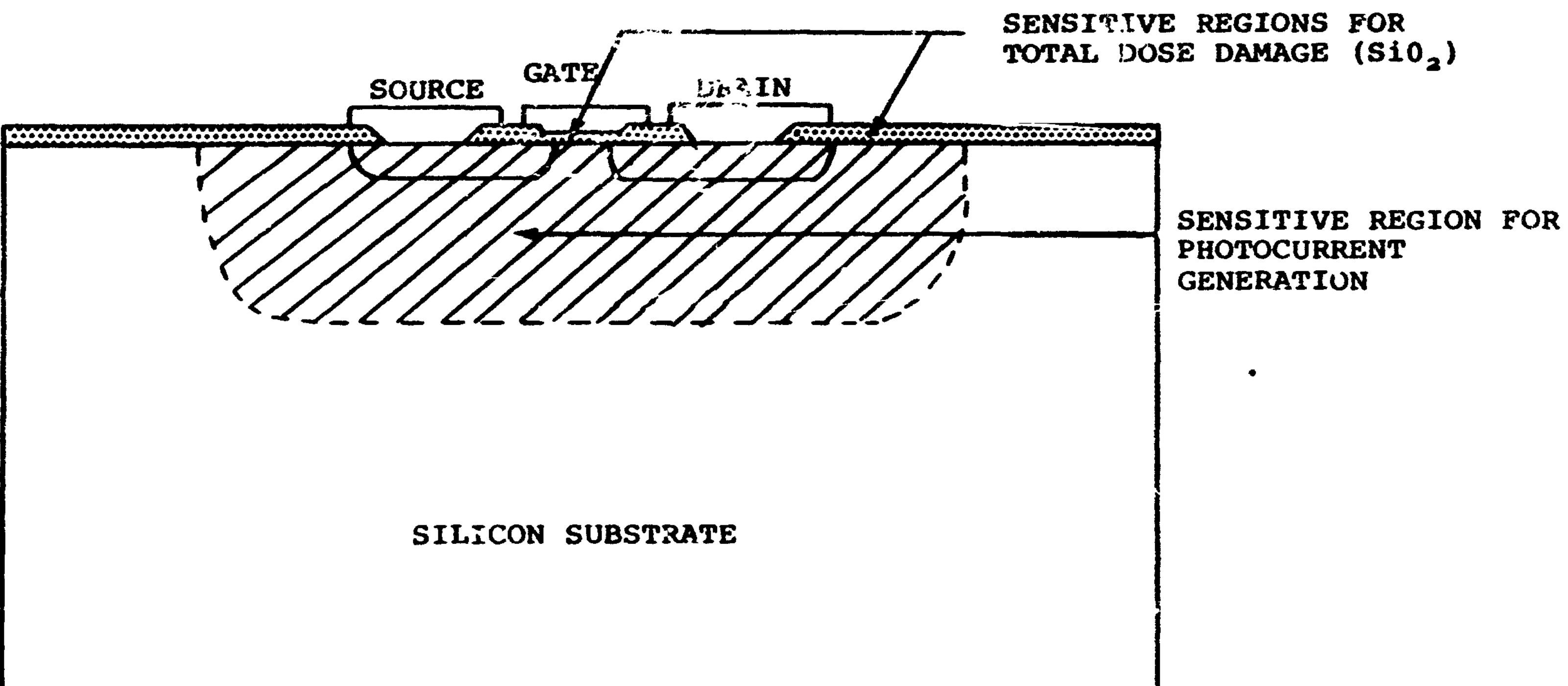


FIGURE 2.2. SENSITIVE RESPONSE REGIONS FOR AN MOS TRANSISTOR

1) The chip metallization and,
2) the inside material of the package lid.

There are three major types of metallization or interconnect systems in common use today which can be categorized as follows for dose enhancement purposes:

1. Aluminum or polysilicon
2. Schottky
3. Gold

Similiarly, there are 3 types of package lids which can be categorized as follows:

1. "Ceramic": This include Alumina, Berillium Oxide, transparent glass, or other lids with atomic number $Z \leq 14$.

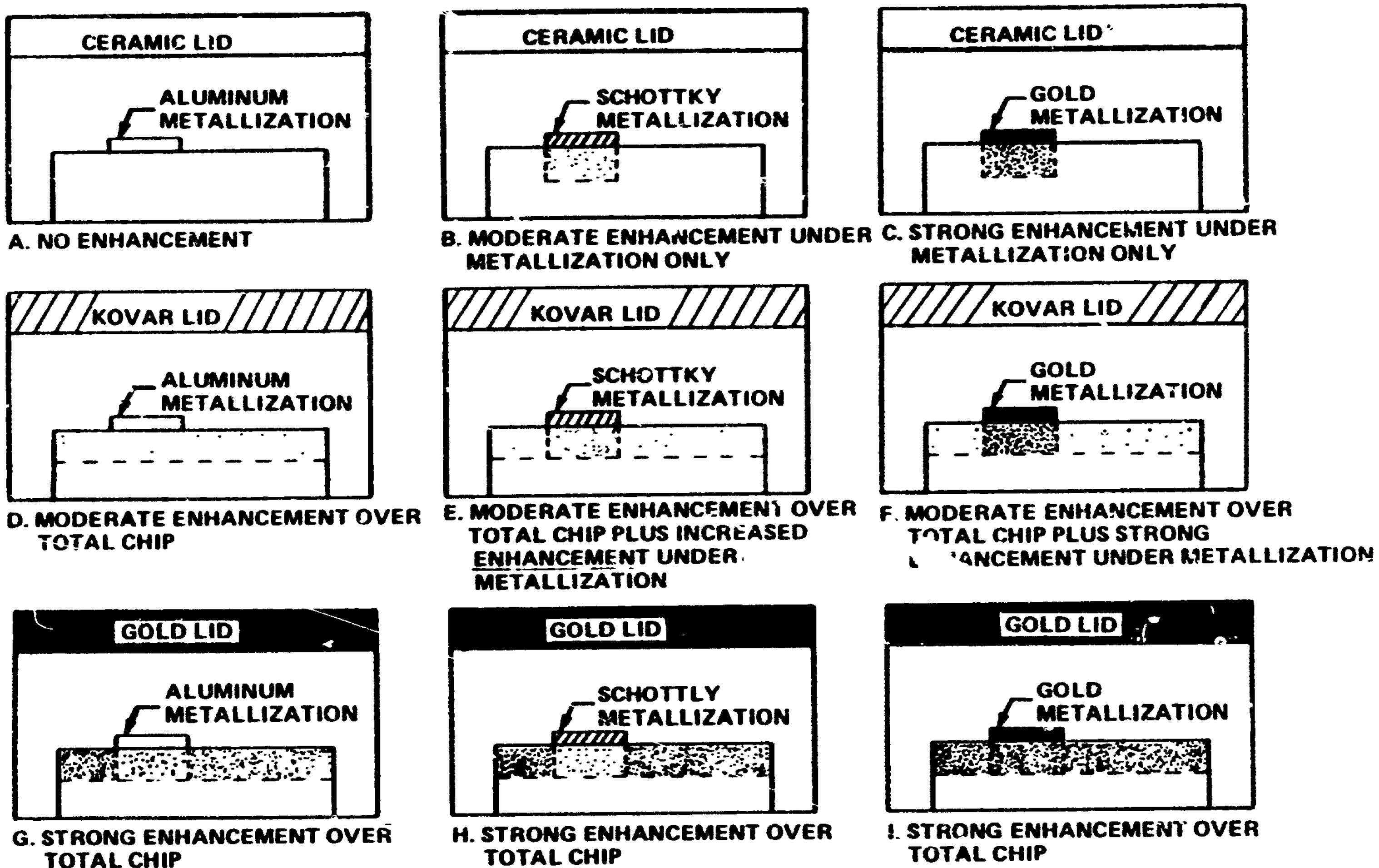
2. "Kovar": This includes Kovar lids, nickel plating, chromium plating or other materials with $Z = 27$ to 32.

3. "Gold": Gold plated lids.

Hence, there are nine configurations of chip metallization and package lid types. These configurations are illustrated in Figure 2-3, showing the resulting regions of enhancement in the chip. In ceramic packages for example, enhancement occurs only directly under a high-Z metallization, whereas for gold plated lids the enhancement is rather uniform over the total chip regardless of the type of metallization.

2.3.1 Total Dose Effects

In MOS technologies, the major effect of total dose is a shift in threshold voltage (V_T) due to charge buildup in the gate oxide and the field oxide. Leakage currents increase due to either inversion underneath the field oxide or due to increased recombination velocity at depleted p-type surfaces. The charge buildup in an oxide depends on the total number of electron-hole pairs generated in the oxide, which is dependent on the



Note: Shaded areas ( ) represent regions and magnitudes of dose enhancement.

FIGURE 2.3. PACKAGE METALLIZATION CONFIGURATIONS

average dose in the oxide. The buildup of interface states is dependent on the transport of holes or other charged particles through the oxide, and it is assumed that their number is also dependent on the average dose in the oxide. For handbook calculations, the DEF value is based on the dose at the top of the oxide (no intervening material between a high-Z lid and the oxide). This provides the highest DEF value, and is worst case for system design purposes.

For bipolar transistors, the parameters affected by total dose are (1) current gain, h_{FE}, (2) emitter base leakage current, IEBO and (3) collector base leakage current, ICBO changes in these parameters are caused by interface states which increase the surface recombination velocity. Leakage currents are also affected by channel formation at the surface, if it occurs. The change in parameters is dictated by the average dose in the oxide. In Schottky or gold metallized devices, where the dose enhancement occurs under the metal, the appropriate dose enhancement factor is a weighted value depending on the parameter and type of transistor. Assuming positive charge buildup in the oxide, and that degradation occurs due to interface states at depleted p-type surfaces, the effective DEF's for Schottky npn transistors are:

$$h_{FE}\text{, IEBO, and ICBO: Effective DEF} = \frac{DEF_M\, A_{B_M} + DEF_{OX}\, A_{B_{OX}}}{A_{B_M} + A_{B_{OX}}} \quad (2\text{-}3)$$

Base region inversion: Effective DEF = DEF_M

Where DEF_M = DEF under metal

DEF_{OX} = DEF for oxide regions not covered by metal

A_{B_M} = Base area covered by metal

$A_{B_{OX}}$ = Base area covered by field oxide

In Schottky integrated circuits, the worst case DEF for the circuit is the highest DEF of each of the individual transistors on the chip. This occurs for the device with the highest fraction of metal coverage over the base region.

For pnp gold metallized transistors, the critical regions are the emitter and collector p-type surfaces and the effective DEF's are:

$$h_{FE} \text{ and IEBO: Effective DEF} = DEF_M \tag{2-4a}$$

$$\text{ICBO: Effective DEF} = \frac{DEF_M\, A_{C_M} + DEF_{OX}\, A_{C_{OX}}}{A_{C_M} + A_{C_{OX}}} \tag{2-4b}$$

$$\text{Collector-region inversion: Effective DEF} = DEF_{OX}. \tag{2-4c}$$

Where A_{C_M} = Collector area covered by metal

$A_{C_{OX}}$ = Collector area covered by oxide only

2.3.2 Transient Effects

The second major category for dose enhancement effects is transient response. Ionizing radiation creates electron-hole pairs in the silicon and the excess carriers are swept across the pn junction creating a primary photocurrent Ipp. The photocurrent collection depth includes the pn junction depletion region plus a diffusion length on each side of the depletion region, unless terminated by the region boundaries. For the tabulated values in this handbook, a representative collection length of 10 microns has been selected. The DEF values for I_{pp} then represent the average dose over a 10 micron depth into the silicon, and the values are considerably less than the maximum DEF at the surface.

In integrated circuits, three response mechanisms can be of concern: Transient upset, latchup, and burnout. Transient

upset occurs when the transient output voltage of a circuit exceeds a tolerance value. The transient output voltage is a function of the circuit design and the geometry of internal elements. Latchup may occur when the h_{FE} product of npn and parasitic pnp transistors exceeds unity. Burnout can occur due to excessive power dissipation at some point in the chip. These mechanisms depend on different critical parameters within the chip, and on different critical response times. Different DEF values could exist for each response mechanism but detailed models and calculational techniques are not available for their computation. However, all of the mechanisms are dependent on the photocurrent drives produced in the bulk silicon region, and the photocurrent DEF values listed in Sections 3 and 4 are representative for all the above dose rate response mechanisms.

In Schottky or gold metallized devices, the dose enhancement factor for transient effects is a function of the metal coverage of individual devices on the chip. The effective DEF is:

$$\text{Effective DEF} = \frac{DEF_M\, A_M + DEF_{OX}\, A_{OX}}{A_M + A_{OX}} \qquad (2\text{-}5)$$

where A_M is the metallized area and A_{OX} is the non-metallized area of an individual device (including emitter, base, and collector regions). For worst case purposes, the weighted DEF should be based on the device on the chip with the highest total metal coverage ratio.

2.3.3 Dose Enhancement Effects in Capacitors

Ionizing radiation produces two major effects on capacitors: (1) Transient conductivity of the dielectric, and (2) a change in the built-in polarization charge in the dielectric. The voltage changes caused by these effects are dependent on the magnitude, spatial variation and time variation of the dose in the

dielectric, and can show complex time dependence during the build-up and decay of excess carriers in the dielectric. To deal with dose enhancement effects, it is assumed that the average dose in the dielectric is the relevant quantity to use for characterization purposes.

Organic capacitors have low-Z dielectric materials, and can exhibit large dose enhancement factors in X-ray environments. Section 5 contains a graph showing the average DEF as a function of depth in the dielectric and as a function of photon energy (Figure 5-3) for a gold polyethylene interface. This curve can be used to obtain the DEF using the calculation procedures given in Section 5. Polyethylene is a very low-Z material (C_2H_4), and it provides a worst case estimate for other materials such as mylar, polycarbonate, or other organic dielectric materials. The enhancement at the boundaries of a polyethylene dielectric can be as high as 400, as shown in the data in Section 5.

Inorganic capacitors, such as ceramic or glass capacitors, generally exhibit less enhancement than organic capacitors, though both categories may contain high-Z elements in the dielectric or electrode materials. For glass dielectrics which have $Z \leq 14$, the worst case dose enhancement is similar to that produced by a gold-silicon interface. Data in Section 5 permits the DEF to be calculated using a similar procedure as that described for gold-polyethylene above. The magnitude of the maximum DEF at the dielectric boundary is 30 for this case.

Some ceramic capacitors contain high-Z elements in the dielectric; e.g., barium titantate (BaTiO). The barium results in a high X-ray absorption in the dielectric material, regardless of the electrode material. The dose enhancement factor for such capacitors is estimated to be less than 1.2.

Tantalum capacitors have a high-Z dielectric (Ta_2O_5) and high-Z electrodes (Ta). The dose enhancement factor is near unity for such capacitors.

3.0 DOSE ENHANCEMENT FACTORS FOR SYSTEM DESIGN

Table 3-1 shows the DEF values for system X-ray and gamma environments. The values in the table are worst case values and can be used for worst case system design applications.

Columns 1 and 2 show the type of chip metallization and the type of package. These two columns characterize the type of high-Z material which can cause dose enhancement. Also noted are the device technologies which incorporate the specified type of chip metallization. Each technology can be packaged in any of the package types shown in the table.

Column 3 identifies the response mechanism. Two categories are used. The notation "surface" means that the DEF values are computed at the top surface of the SiO_2 on a silicon chip. These values are the highest DEF values which will be encountered anywhere in the silicon or SiO_2 regions of the chip, and are applicable for total dose (e.g., surface effects) damage mechanisms. The second category "10µm average" represents the average DEF over a region within 10 microns of the top SiO_2 surface. This value is applicable for photocurrent enhancement. The sensitive regions for these two response mechanisms were illustrated previously in Figure 2.2.

The next 3 columns show the DEF values for a 5 KeV blackbody X-ray spectrum which passes through materials of:

1. 20 mils of Aluminum
2. 200 mils of Aluminum
3. 20 mils of Aluminum plus 20 mils Tantalum

Similar data is shown for a 15 KeV blackbody in the succeeding three columns.

TABLE 3-1 DOSE ENHANCEMENT FACTORS FOR SYSTEM DESIGN APPLICATIONS

TYPE OF CHIP METALLIZATION	TYPE OF PACKAGE (Fig 2-3)	RESPONSE MECHANISM	5 KeV Blackbody			15 KeV Blackbody			GAMMA ENV.
			20 Mil Al	200 Mil Al	20 Mil Al +20 Mil Ta	20 Mil Al	200 Mil Al	20 Mil Al +20 Mil Ta	
ALUMINUM (or Silicon)	CERAMIC (A)	Surface	1.0	1.0	1.0	1.0	1.0	1.0	1.0
• CMOS, NMOS, PMOS, CCD		10μM average	1.0	1.0	1.0	1.0	1.0	1.0	1.0
• TTL: 54, 54L, 54H, DI	KOVAR (D)	Surface	5.2	5.7	3.6	6.3	6.7	4.0	1.4
• I^{2}L, ECL DTL		10μM average	1.7	1.9	1.9	2.9	3.4	2.5	1.4
• Discrete diodes and Transistors	GOLD (G)	Surface	19	18	11	19	19	18	2.0
		10μM average	4.1	3.9	3.5	8.6	8.0	8.9	2.0
SCHOTTKY (Pt,W,Ti,Al)	CERAMIC (B)	Surface	7.9	7.8	5.6	7.8	6.9	4.7	1.5
• TTL: 54LS, 54S, LSI		10μM average	1.9	2.1	2.9	2.8	3.1	3.0	1.5
• Schottky Diodes	KOVAR (E)	Surface	12	12	9	13	12	7.2	1.5
		10μM average	3.0	3.0	3.2	6.0	5.8	3.8	1.5
	GOLD (H)	Surface	19	18	11	19	19	18	2.0
		10μM average	4.1	3.9	3.5	8.6	8.0	8.9	2.0
GOLD	ALL	Surface	19	18	11	19	19	18	2.0
• TTL DI IC's		10μM average	4.1	3.9	3.5	8.6	8 0	8.9	2.0
• RF Devices									

NOTE: DEF values shown above are worst case (highest) values. In some instances, a smaller "Effective DEF" can be used based on device geometry ratios (see text, eq. 2-3, 2-4, 2-5)

The last column shows the worst case DEF for a gamma environment. This value is obtained using a value of 2.0 for a gold interface, with conservative interpolation for lower-Z interfaces. This worst case value is valid only for the case where the gold thickness is 5 microns or more, and where the gamma photons impact the gold after traveling through the silicon first. For gamma photons which traverse the gold first, the DEF is approximately equal to 1.4. For thinner layers of gold, the DEF is roughly linearly reduced with gold thickness below 5 micons. The DEF is also reduced for photons in the reverse direction, and for lower Z materials. In practice, one can use the extremum values for DEF, i.e., DEF = 2.0 and DEF = 1.0 to determine if either extremum produces a problem. If so, then careful determination of the DEF may be necessary for the particular device/irradiation.

One must be careful to be sure that the spectrum in the environments at issue is similar to the spectrum used for these calculations as described in Appendix A. For example, a Cobalt-60 gamma source in a water pool can produce a DEF greater than 10 due to a large flux of scattered photons below 200 KeV. An example is presented in Section 6.

4.0 DOSE ENHANCEMENT FACTORS FOR RADIATION TEST FACILITIES

Table 4-1 contains DEF values for radiation test environments. The table layout is similar to that of Table 3-1 and the description of table entries in Section 3 is applicable here for all except the environments. The radiation environments shown in the table include 3 Flash X-ray environments and a Cobalt-60 environment. The three Flash X-ray environments are categorized into low, medium, and high energy environments. In the DEF calculations, energy spectra for the Blackjack III, Febetron 705, and Hermes facilities were used for the three categories (Appendix A). DEF values for other Flash X-ray facilities can be obtained from the following equation:

$$DEF = f_1 \, DEF_1 + f_2 \, DEF_2 + f_3 \, DEF_3$$

where DEF_1, DEF_2 and DEF_3 are the values shown in the table for low, medium, and high energy environments respectively, and f_1, f_2 and f_3 are interpolation fractions as listed below:

Facility	f_1 Low Energy	f_2 Medium Energy	f_3 High Energy
Casino	1.0	0	0
Blackjack III	1.0	0	0
REBA	0.8	0.2	0
Febetron 705	0	1.0	0
Ion Physics FX25	0	1.0	0
PI 1140	0	0.5	0.5
IP FX75	0	0.4	0.6
TREF	0	0.2	0.8
HERMES II	0	0	1.0
AURORA	0	0	1.0

TABLE 4-1. DOSE ENHANCEMENT FACTORS FOR RADIATION TEST ENVIRONMENTS

TYPE OF CHIP METALLIZATION	TYPE OF PACKAGE	RESPONSE MECHANISM	FLASH X-RAY FACILITIES			COBALT 60 INCIDENCE ANGLE=0°&180°
			LOW E	MED E	HIGH E	
ALUMINUM (or silicon)	CERAMIC	Surface	1.0	1.0	1.0	1.0 - 1.0
• CMOS, NMOS, PMOS, CCD		10μM average	1.0	1.0	1.0	1.0 - 1.0
• TTL: 54, 54L, 54H, DI	KOVAR	Surface	3.9	1.9	1.5	1.2 - 1.6
• I^2L, ECL DTL		10μM average	2.6	1.7	1.4	1.2 - 1.6
• Discrete diodes and Transistors	GOLD	Surface	13	3.4	1.5	1.4 - 2.2
		10μM average	6.9	2.8	1.4	1.4 -2.2
SCHOTTKY (Pt,W,Ti,Al)	CERAMIC	Surface	6.4	1.8	1.4	1.3 - 1.9
• TTL: 54LS, 54S, LSI		10μM average	2.9	1.7	1.3	1.3 - 1.9
• Schottky Diodes	KOVAR	Surface	8.4	2.5	1.4	1.3 - 1.9
		10μM average	4.4	2.1	1.3	1.3 - 1.9
	GOLD	Surface	13	3.4	1.5	1.4 - 2.2
		10μM average	6.9	2.8	1.4	1.4 - 2.2
GOLD	ALL	Surface	13	3.4	1.5	1.4 - 2.2
• TTL DI IC's		10μM average	6.9	2.8	1.4	1.4 - 2.2
• RF Devices						

The DEF entries for the Flash X-ray facilities in the table are for exposure of the device in a reverse direction (e.g., 180°, top surface of the chip pointing away from the source). This exposure direction yields the highest DEF value.

The values for the gold-silicon interface in a Cobalt-60 environment are experimental values taken from Reference 16. This data shows that the DEF at the surface is greater than unity for both directions of gamma irradiation. This occurs because the photon spectrum (Appendix A) includes low energy components in addition to the 1.25 MeV average energy gammas. The values given are maximum (worst case) values based on equilibrium gold thickness. The lowest number listed corresponds to a radiation direction from the gold to the silicon (0°), and the second value corresponds to a radiation direction from the silicon to the gold (180°). In semiconductor devices the gold layer is generally thin compared to the electron range, and the DEFs will be lower than shown in the Table. The Kovar and Schottky values in the table for Cobalt-60 are conservatively interpolated from the gold data.

Recent data in Reference 28 indicates that strong enhancement can occur in photon environments when there is a large amount of low-Z shielding material around the source (eg, water pool sources). The shielding material results in a much softer energy spectrum due to scattered photons[29, 30] and the DEF can exceed 10 for shielding thicknesses of more than 5 mean free paths. An illustrative problem is given in Section 6.

5.0 USING THE DOSE ENHANCEMENT FACTOR

The manner in which DEF values in Section 3 and 4 are to be used is described below:

I. Measure experimental data in a test facility as a function of dose level. Examples of measured quantities on devices are:

TOTAL DOSE TESTING: h_{FE} or ICBO (Discrete Transistors)

: TPHL, TPLH, I_{CC} (Digital IC's)

TRANSIENT EFFECTS : I_{pp} (Discrete Transistors or diodes)

: ΔV_{out}, ΔI_{CC} (Digital IC's)

A. First, measure the equilibrium silicon dose D_{EQ} at each exposure. Dosimetry should be taken using proper techniques as described in References 24, 25, 26 and 27. For dosimeters other than silicon, the silicon dose must be computed from the dosimeter dose.

B. Then, the sensitive region dose D_{SR} is obtained by multiplying the equilibrium silicon dose by the dose enhancement factor from Table 4 for the given device type, response mechanism, and test facility:

$$D_{SR_{TEST}} = D_{EQ_{TEST}} \cdot DEF_{TEST}$$

The measured test data (h_{FE}, ΔV_{out}, etc.) are then known as a function of the sensitive region dose to which the device was exposed during the testing.
As an example, assume a Kovar packaged transistor with aluminum metallization is tested for Ipp at a dose of 1000 Rad(Si) in a Febetron 705 Flash X-ray facility.

The DEF from Table 4-1 (aluminum metallization, Kovar, 10 micron average) is 1.7, and the resulting sensitive region dose is 1000 · 1.7 = 1700 Rad(Si).

II. The performance of the part in a system application is obtained by interpolation of the above test data at the sensitive region dose required by the system. The sensitive region dose in the system is computed by:

$$D_{SR_{SYS}} = D_{EQ_{SYS}} \cdot DEF_{SYS}$$

where, $D_{EQ_{SYS}}$ is the equilibrium silicon dose required to be withstood by the part in the system application, and DEF_{SYS} is the dose enhancement factor from Table 3 for the given device, response mechanism, and environment.

Using the same example again, suppose this device must survive 1000 Rads(Si) of 15 keV blackbody system dose. Suppose that 200 mils Aluminum shields the device. Then from Table 3-1, (aluminum metallization, Kovar, 10μm average) the appropriate DEF is 3.4. Therefore, the sensitive region must survive a dose of 3.4 x 1000 or 3400 Rads(Si). Since we earlier tested the sensitive region only to 1700 Rads(Si), we need to retest. The new test should be done to

$$(1000 \text{ Rads(Si)}) \times \frac{3.4 \text{ DEF sys}}{1.7 \text{ DEF test}} = 2000 \text{ Rads(Si)}.$$

III. The following examples further illustrate the usage of the DEF tables.

EXAMPLE 1: Device Performance in a System Environment

Given: Cobalt-60 data on a transistor in a gold plated TO-5 package exposed at 0° beam orientation shows the following h_{FE} degradation

Dose (Rad(Si))	h_{FE}
0	100
10,000	90
20,000	80
30,000	70

Find: The h_{FE} value for a system gamma dose requirement of 10,000 Rad(Si), high energy gamma irradiation.

Solution: DEF_{TEST} = 1.4 (from Table 4-1, gold-package surface region.)

DEF_{SYS} = 2.0 (from Table 3-1, gold-package surface region.)

The system dose requirement of 10,000 Rads(Si) will be encountered at a Cobalt -60 test level of 10,000 • (2.0/ 1.4) = 14,300 Rad(Si). Interpolating from the above test data, the desired h_{FE} for system application is 85.7.

EXAMPLE 2: TESTING LEVEL TO SIMULATE SYSTEM ENVIRONMENT

Given: (1) Schottky TTL integrated circuit in a ceramic package.

(2) System X-ray dose requirement = 10,000 rad(Si) (15 KeV Blackbody, 200 mils Aluminum shielding.)

Find: The dose to be used in a Hermes Facility for burnout survival testing to match the same active region prompt dose seen in the system.

Solution: DEF_{TEST} = 1.3 (Table 4-1, Schottky, Ceramic, 10μm average).

DEF_{SYS} = 3.1 (Table 3-1, Schottky, Ceramic, 10μm average).

In the worst case, assume high metallization coverage (geometry factor = 1.) Then the desired test level is $10{,}000 \cdot \frac{3.1}{1.3} = 23{,}850$ Rad(Si)

If a 50% metal coverage had been assumed, the desired test level would be

$$10{,}000 \cdot \frac{(.5(3.1) + .5(1.0))}{(.5(1.3) + .5(1.0))} = 17{,}800 \text{ Rad(Si)}$$

In general it is necessary to convert both test doses and system doses into an equilibrium silicon dose in order to correct for the dose enhancement effects. Equilibrium doses are not dependent on the radiation energy spectrum in the same way the sensitive region doses are dependent on the energy spectrum. It is because the tests differ substantially from the system spectra that we need to use the DEF.

These DEF values are approximate and tend to be worst case values. Gold metallizations are sometimes thin enough that the full DEF is not created under the higher energy spectra. One must be careful not to use these data where high accuracy is required for several reasons. However, these data serve as a warning that substantial errors are likely if the DEF is not considered by survivability engineers. Expensive techniques are available to more accurately assess the problem when individual cases warrant it.

6.0 DOSE ENHANCEMENT FACTORS FOR ARBITRARY ENERGY SPECTRA

The information in this section can be used to calculate worst case DEF values for energy spectra which are not contained in the previous two sections. Figure 6-1 shows the dose enhancement in silicon at distances of 1,2,5, 10 and 30 microns from a gold interface as a function of photon energy, assuming equilibrium thicknesses for each material. Figure 6-2 shows similar information except that the depth lines in the figure represent the average dose over the region from the interface to the depth point shown. The computation of DEF over an energy spectrum for either Figure 6-1 or 6-2 is accomplished by calculating the average DEF:

$$\text{Average DEF} = \frac{\sum_E DEF(E) \cdot D(E) \cdot \Delta E}{\sum_E D(E) \cdot \Delta E} \qquad 6\text{-}1$$

where D(E) is the equilibrium dose arising from photons of energy E in ΔE:

$$D(E) = 1.6 \times 10^{-8} \frac{\mu a}{\rho} E\phi(E) \text{ (Rads)}$$

$\frac{\mu a}{\rho}$ = mass absorption coefficient (cm^2/gm). (Ref. 8-12) Values are shown in Figure 6-3 (from Ref. 8)

$\phi(E)$ = photon fluence (photons/cm^2)

E = photo[illegible] energy (MeV)

The product E $\phi(E)$ is t[illegible] photon energy fluence (MeV/cm^2).

The data in Figures 6-1 through 6-3 can also be used to account for low-Z material differences a[illegible] the chip surface. For example, if a gold lid device is separated from the surface of

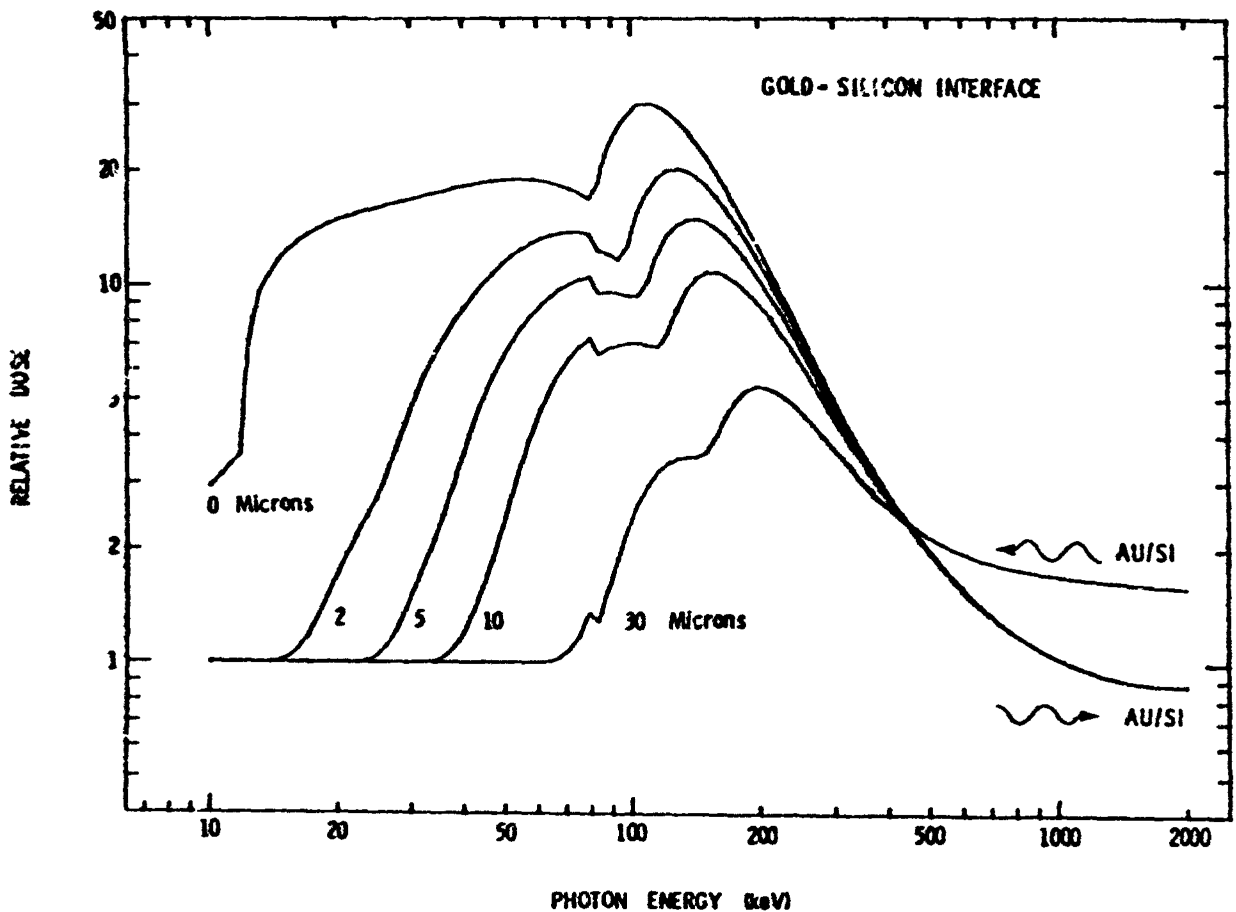


FIGURE 6-1. DOSE ENHANCEMENT FACTOR IN SILICON AT SEVERAL DISTANCES FROM A GOLD INTERFACE. ABOVE 500 KeV THERE IS A DEPENDENCE ON PHOTON DIRECTION AS SHOWN BY THE ARROWS.

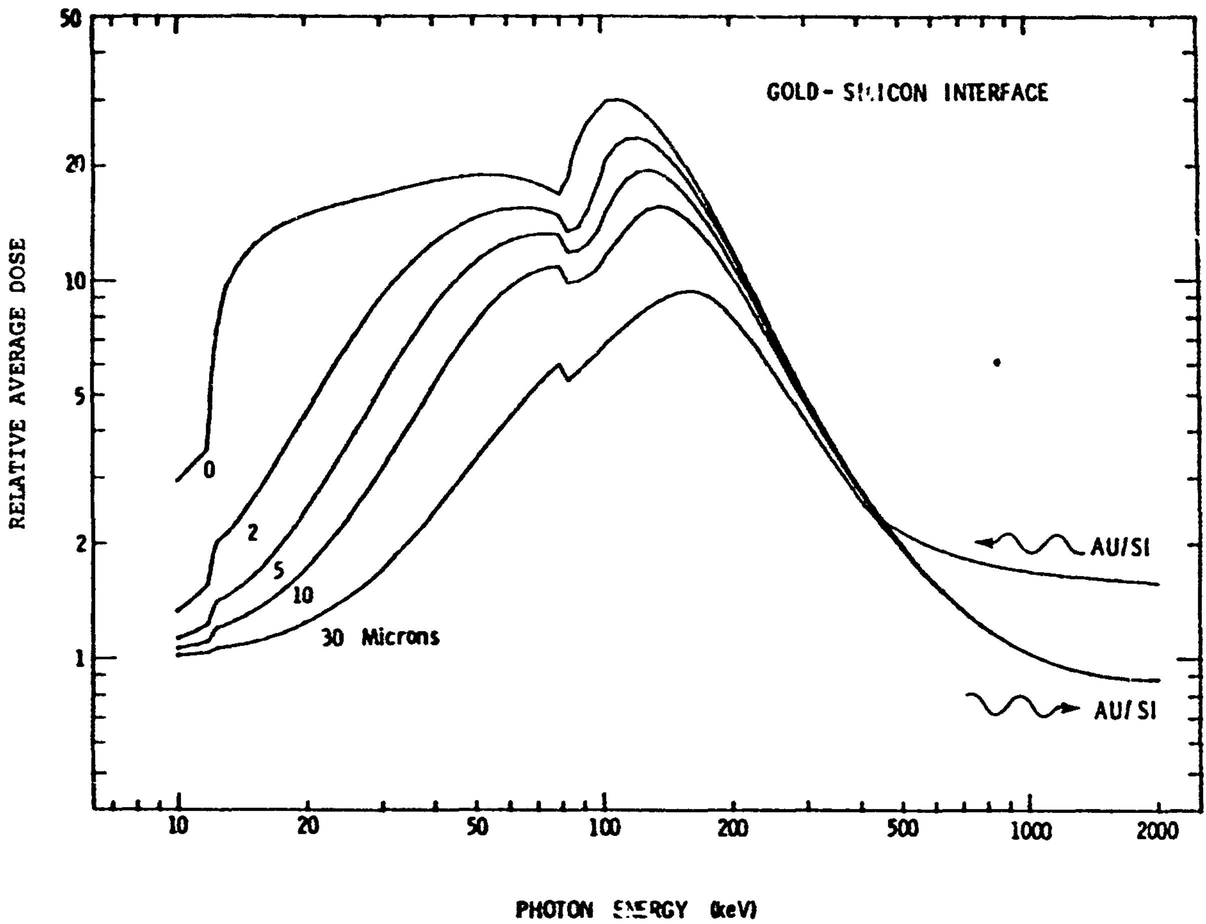


FIGURE 6-2. AVERAGE DOSE ENHANCEMENT FACTOR IN DIFFERENT SILICON THICKNESS REGIONS ADJACENT TO A GOLD-SILICON INTERFACE. ABOVE 500 KeV THERE IS A DEPENDENCE ON PHOTON DIRECTION AS SHOWN BY THE ARROWS.

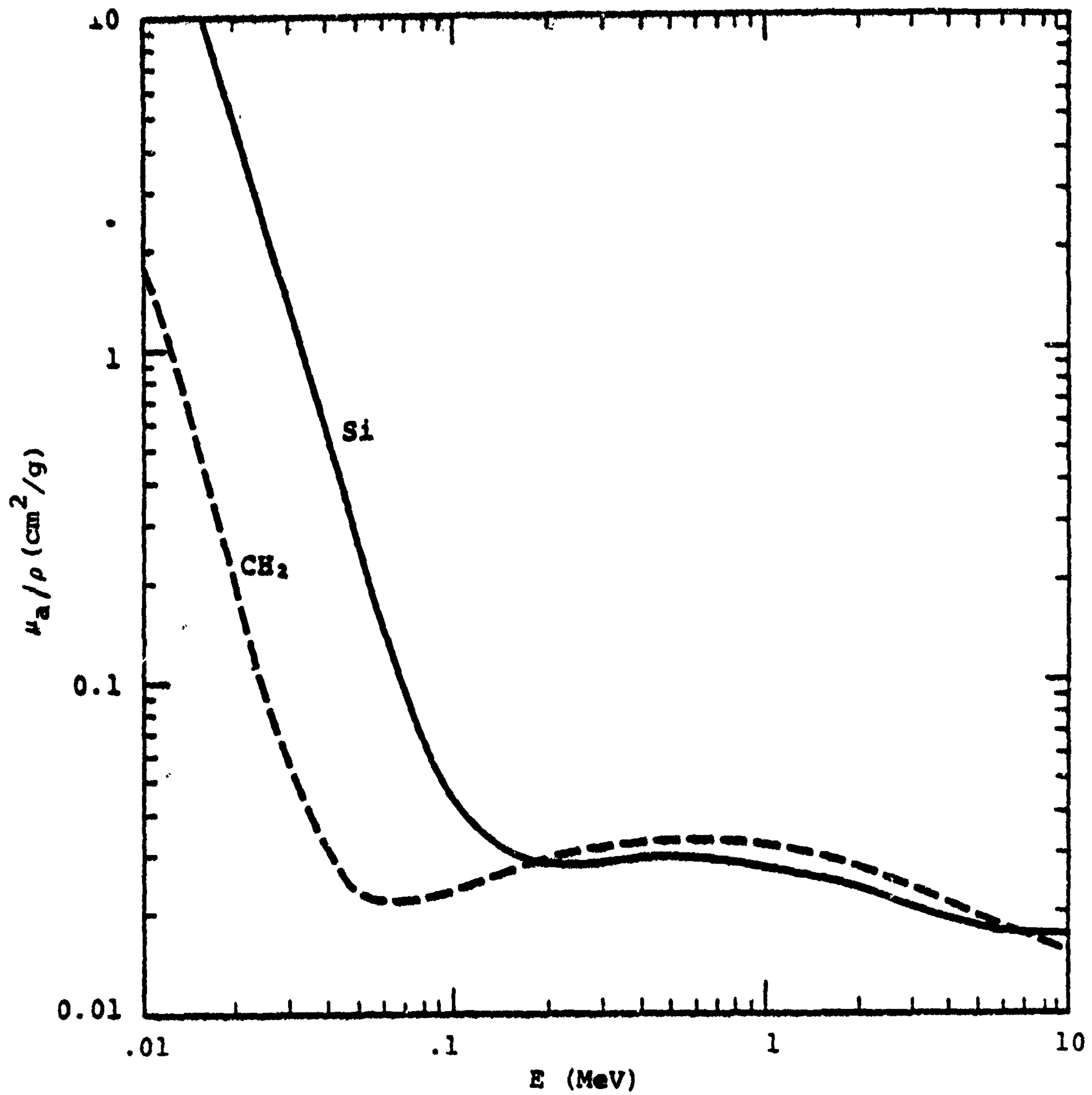


FIGURE 6-3. Equilibrium Dose Per Unit Photon Energy Fluence (Mass Energy Transfer Coefficient) – Silicon and Polyethylene

the silicon chip by 50 mils of encapsulated nitrogen gas and 0.6 micron of SiO_2, the equivalent silicon thickness on a gram/cm^2 basis is:

Material	Thickness (cm)	Density (gm/cm^3)	Equivalent Si Thickness* (cm)
Nitrogen gas	0.125	.00125	6.7×10^{-5}
SiO_2	6×10^{-5}	2.27	6×10^{-5}

This represents a total of 1.27 microns equivalent silicon thickness before the actual silicon surface is reached. When using Figures 6-1 and 6-2, the effect is accounted for by using a different starting depth for the silicon surface. This approximation is valid for intervening materials of $Z \leq 18$ and for photon energies > 10 KeV.

Figure 6-4 shows the dose enhancement in polyethelene due to a gold interface. The parameter plotted is the average dose enhancement in the region between the electrode interfaces and the depth noted in the figure. Equation 6-1 can be used to evaluate the DEF for an arbitrary energy spectrum. In evaluating the DEF for capacitors, contributions from both electrode interfaces must be added together.

* Density of silicon is 2.33 gm/cm^3

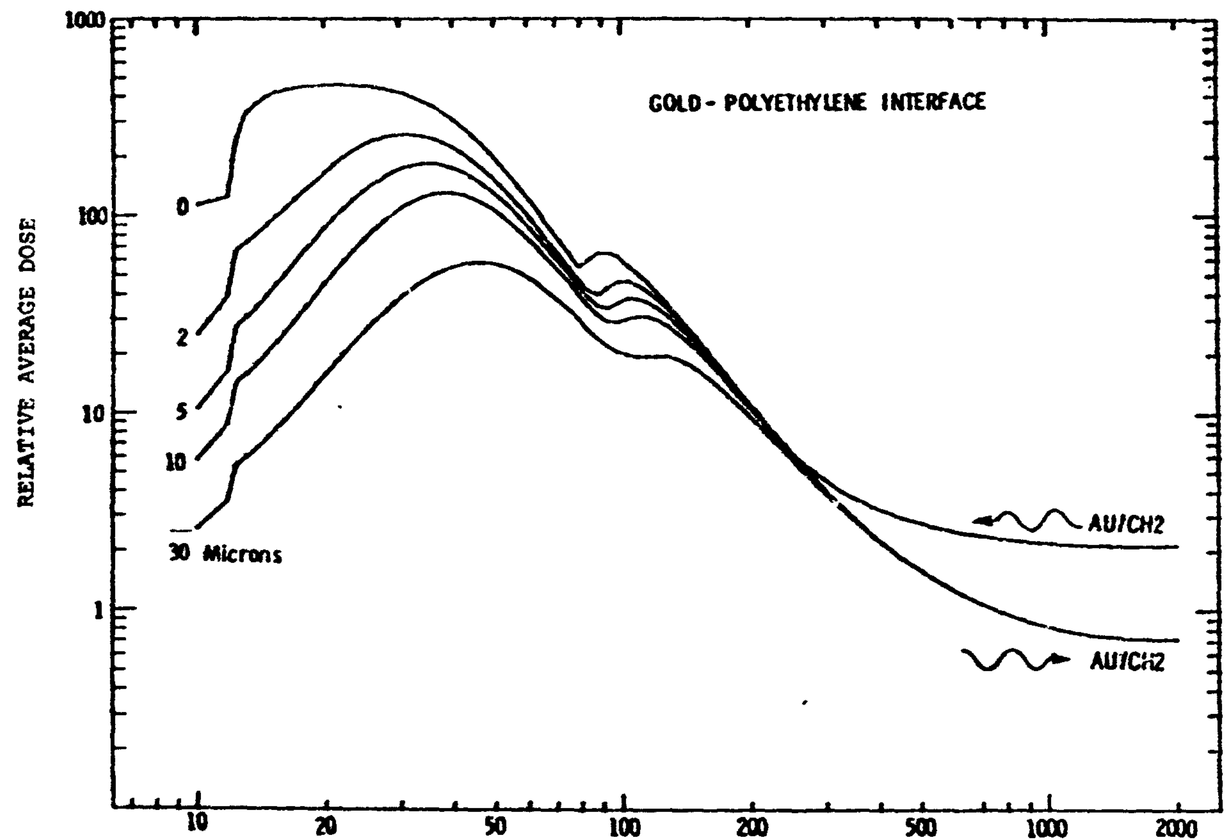


FIGURE 6-4. AVERAGE DOSE ENHANCEMENT FACTOR IN DIFFERENT POLYETHYLENE REGIONS ADJACENT TO A GOLD-POLYETHYLENE INTERFACE. ABOVE 500 KeV THERE IS A DEPENDENCE ON PHOTON DIRECTION AS SHOWN BY THE ARROWS.

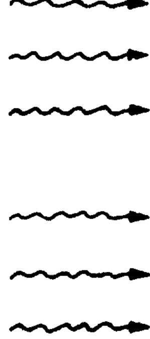
SAMPLE DEF CALCULATION

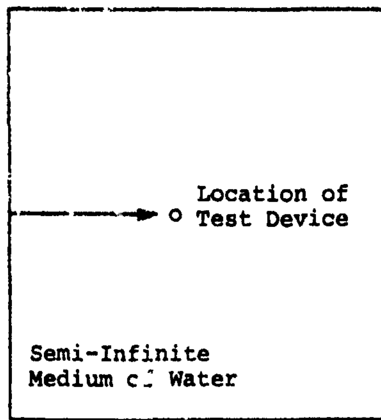
The DEF is calculated below for a one-dimensional gamma source in a semi-infinite water medium. The configuration is illustrated in Figure 6-5 along with the photon energy spectrum from Reference 30 for an assumed gamma ray energy of 1.0 MeV. It can be seen that the spectrum is strongly peaked at 70 KeV, and the scattered portion of the spectrum is approximately the same shape for depths of 4 mean free paths or greater. Table 6-1 shows the DEF calculation. The first column shows the energy intervals assumed for the calculation, and the second column shows the average energy in each interval. Column 3 shows the mass absorption coefficient for the average energy, as obtained from Figure 6-3. Column 4 shows the energy spectrum from Figure 6-5 for $\mu_o r = 4$. The values shown in the figure are in units MeV/MeV (energy flux per unit energy interval) per unscattered primary photon. Column 5 shows the equilibrium dose contribution computed as the product of Columns 3 and 4 and energy bin width ΔE. The total of this column provides the equilibrium dose over all energy intervals. Column 6 shows the DEF value obtained from Figure 6-1 for the enhancement at the surface of a silicon-gold interface irradiated at a direction of 180° (silicon to gold). DEF values are not readily available for the nearly isotropic scattered photons and some error is caused by this 180° assumption.

The product of the DEF times the incremental dose in an energy interval yields the enhanced dose in the energy interval, and the total of the column provides the enhanced dose over the energy spectrum. The ratio of the enhanced dose to the equilibrium dose yields the DEF value, computed in the table as a value of 11. Hence it can be seen that high DEFs can be obtained from 1 MeV gammas in a low-Z shielding environment. With minimum low-Z shielding, the DEF ranges from 1.4 - 2.2, as shown in Table 4-1. It is apparent that considerable variation can occur in the DEF value, and accurate values will require detailed considerations whenever high energy X-rays or gamma sources are used with surrounding materials

of atomic number less than 30, or whenever X-ray sources below 200 MeV are used (because small amounts of packaging material will have a pronounced effect on the X-ray energy spectrum right at the sensitive interface).

Data on scattered spectra are very scarce and without it we cannot make reasonable estimates of the DEF. In addition, data below 100 KeV in low Z elements may be critical but is usually not available. At such low energies the gold metallization can severely perturb the X-ray intensity and this effect has not yet been quantified for inclusion in the handbook. Further work needs to be done on this problem area.





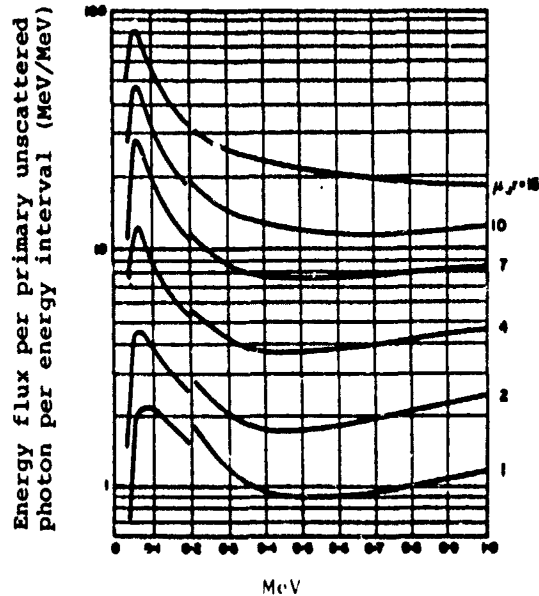


FIGURE 6-5. ENERGY SPECTRUM FOR EXAMPLE GAMMA CALCULATION

The scattered photon energy flux spectrum at penetration depth $\mu_o r$ which accompanies one unscattered photon. μ_o is the attenuation coefficient for the MeV photon.

TABLE 6-1. DEF CALCULATION FOR WATER-SHIELDED 1MeV GAMMA SOURCE IRRADIATING A GOLD-SILICON DEVICE

① ENERGY INTERVAL ΔE (MeV)	② AVERAGE ENERGY (MeV)	③ $\frac{\mu_a}{\rho}$ SILICON (cm^2/g)	④ J SPECTRUM (MeV/MeV)	⑤ ΔD SILICON EQUILIBRIUM DOSE CONTRIBUTION	⑥ DEF (Si/Au INTERFACE :180°)	⑦ ΔD · DEF ENHANCED DOSE CONTRIBUTION
$(E_1 - E_2)$	$\frac{E_1 + E_2}{2}$	Fig. 6-3	Fig. 4-1	③·④·ΔE	Fig. 6-1	⑤·⑥
.04 - .06	.05	.27	10	.0540	18	.972 (1)
.06 - .08	.07	.09	12	.0216	17	.367 (1)
.08 - .10	.09	.05	10	.0100	25	.250 (1)
.10 - .20	.15	.032	7	.0224	25	.560 (1)
.2 - .3	.25	.027	5	.0135	8	.108
.3 - .4	.35	.028	3.9	.0109	3.5	.038
.4 - .5	.45	.029	3.6	.0104	2.4	.025
.5 - .6	.55	.029	3.8	.0110	2.1	.023
.6 - .7	.65	.028	3.9	.0109	1.9	.021
.7 - .8	.75	.028	4.1	.0115	1.8	.021
.8 - .9	.85	.026	4.3	.0120	1.8	.021
.9 - 1.0	.95	.027	4.6	.0124	1.7	.021
(1.0 primary)	(1.0)	(.027)	(1.0)	(.027)	(1.7)	(.046)
				Total = .2276		Total = 2.473

$$DEF = \frac{2.473}{.2276} = 11$$

NOTES: (1) Most of the dose comes from energies less than 0.2 MeV, where spectrum uncertainties are unfortunately the most severe.

(2) Column 5: Dose = $\sum_{E} \frac{\mu_a}{\rho} J \, \Delta E$

(3) Column 4: J is defined in Figure 6-5, $\mu_0 r = 4$ spectrum.

(4) Column 6: DEF is calculated for normal incidence photons.

APPENDIX A

SPECTRA USED FOR HANDBOOK CALCULATIONS

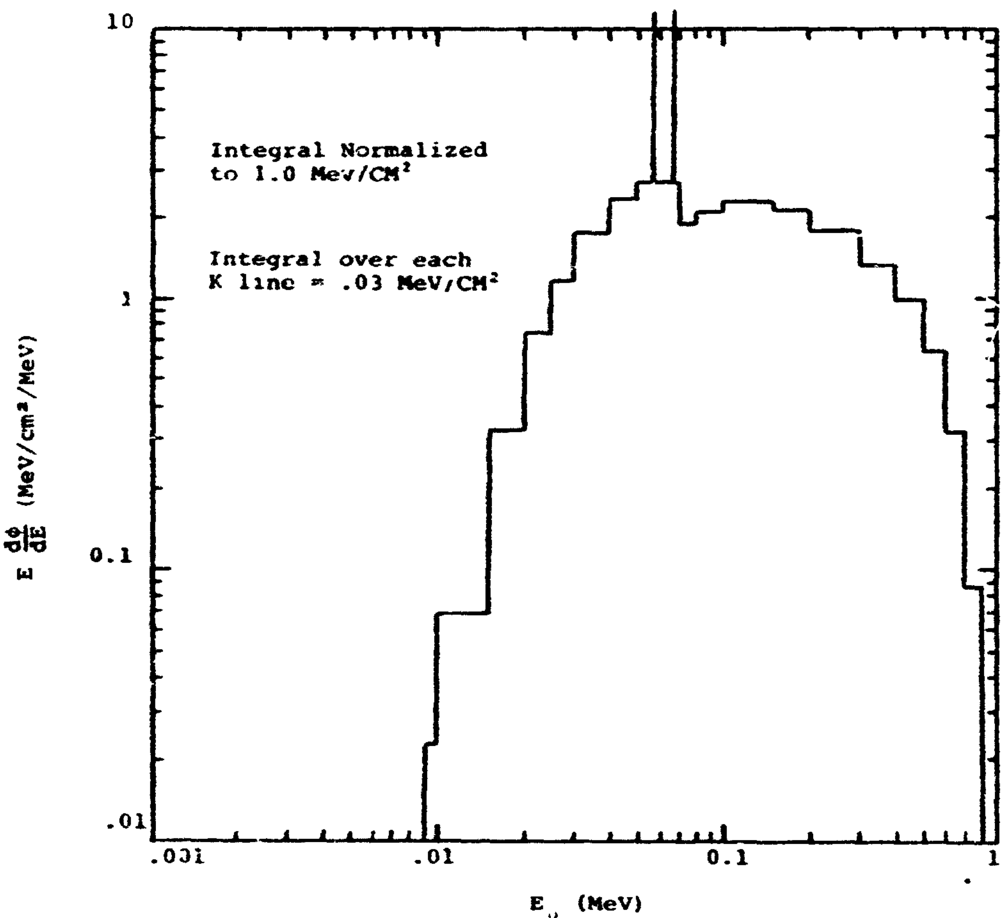


FIGURE A1: BLACKJACK III ENERGY SPECTRUM

Reference: Maxwell Laboratories, San Diego, CA.

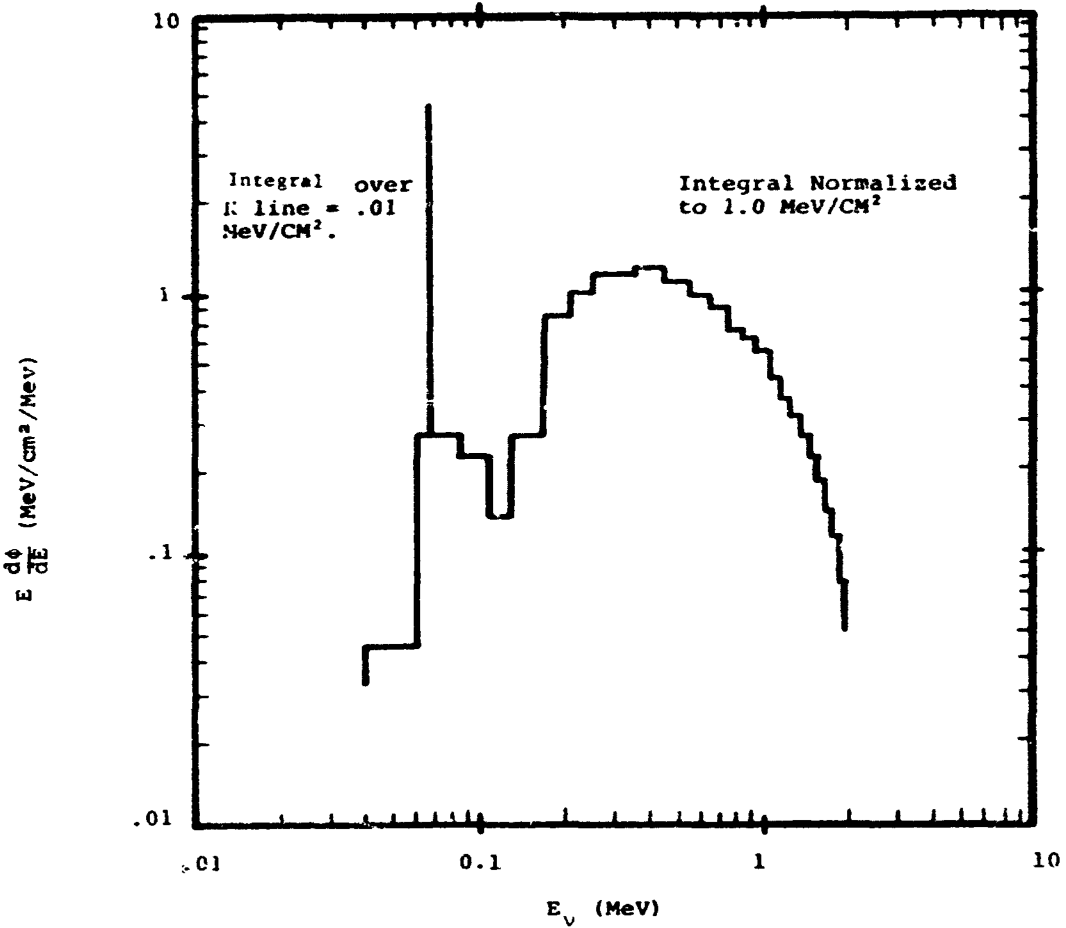


FIGURE A2. FEBETRON 705 ENERGY SPECTRUM

Reference: TREE Simulation Facilities, DNA-2432H, Oct. 1973.

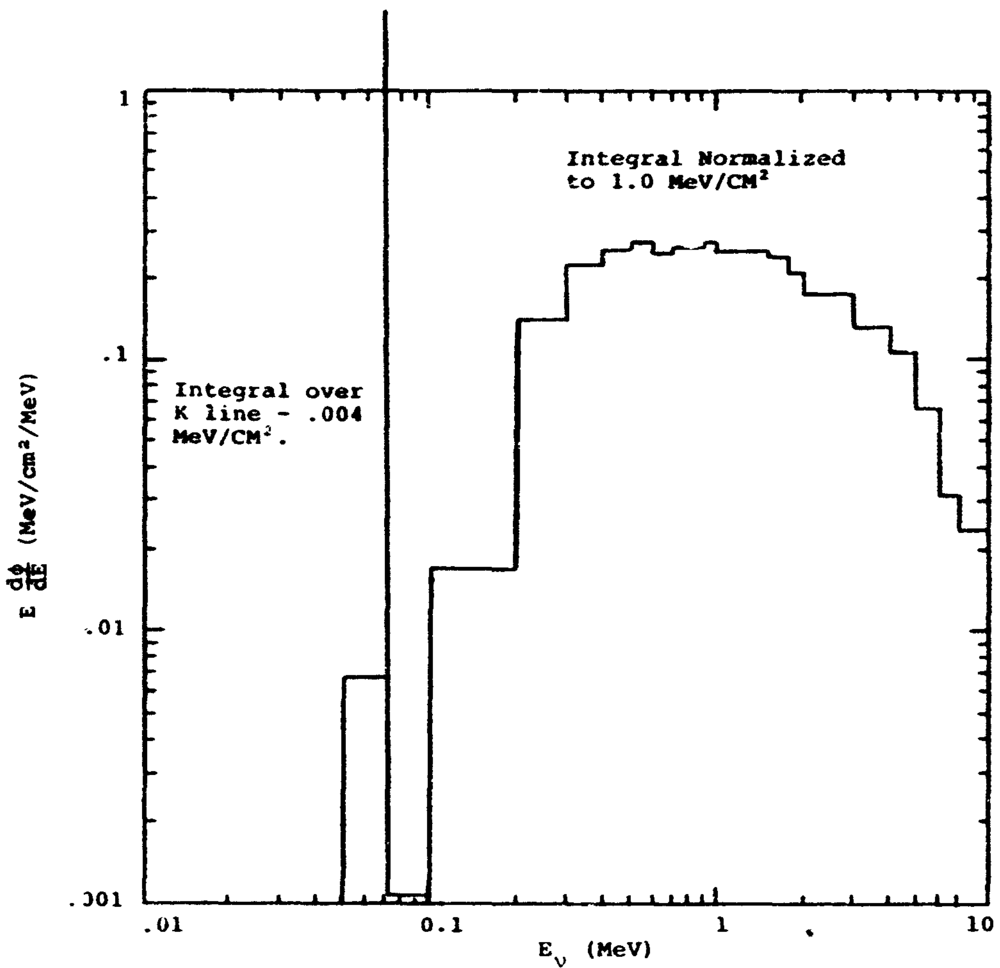


FIGURE A3. HERMES II ENERGY SPECTRUM

Reference: TREE Simulation Facilities, DNA-2432H, Oct. 1973.

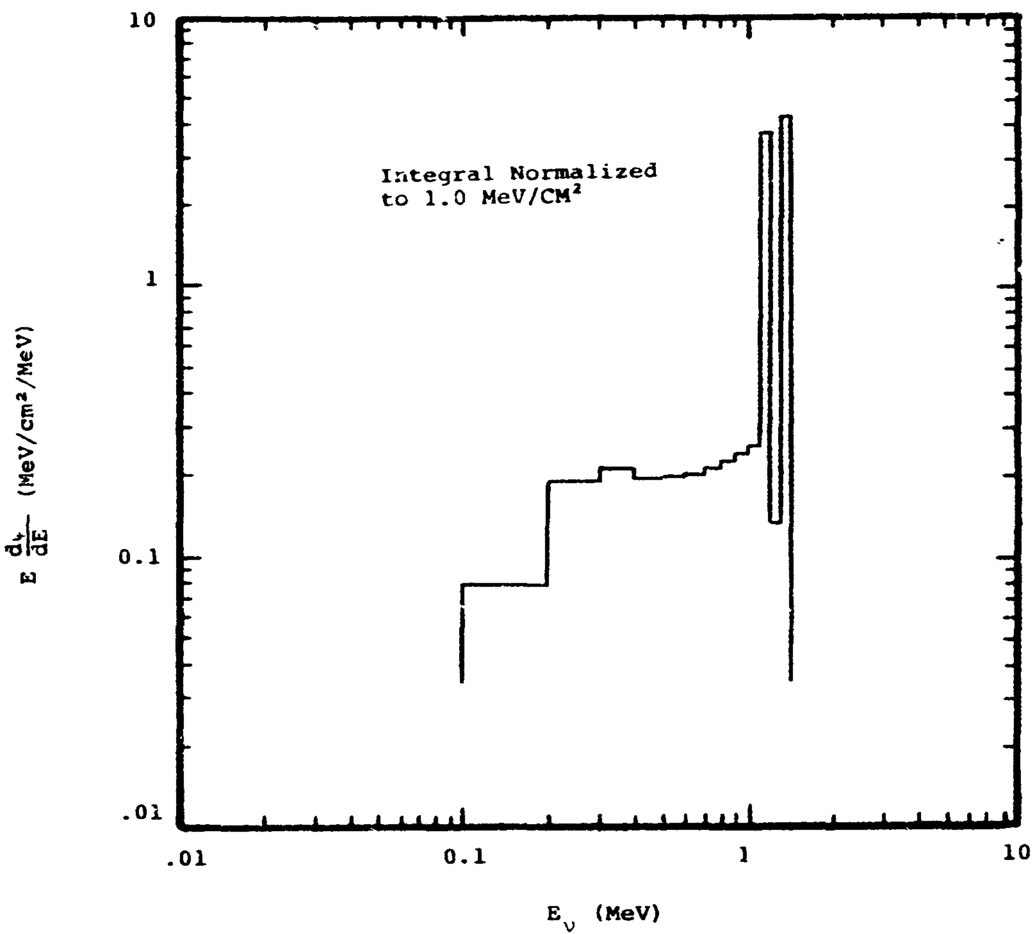


FIGURE A4. COBALT-60 ENERGY SPECTRUM

Reference: A. R. Frederickson, "Gamma Energy Spectra for the RADC/ES Cobalt-60 Sources", RADC-TR-79-68, April, 1979.

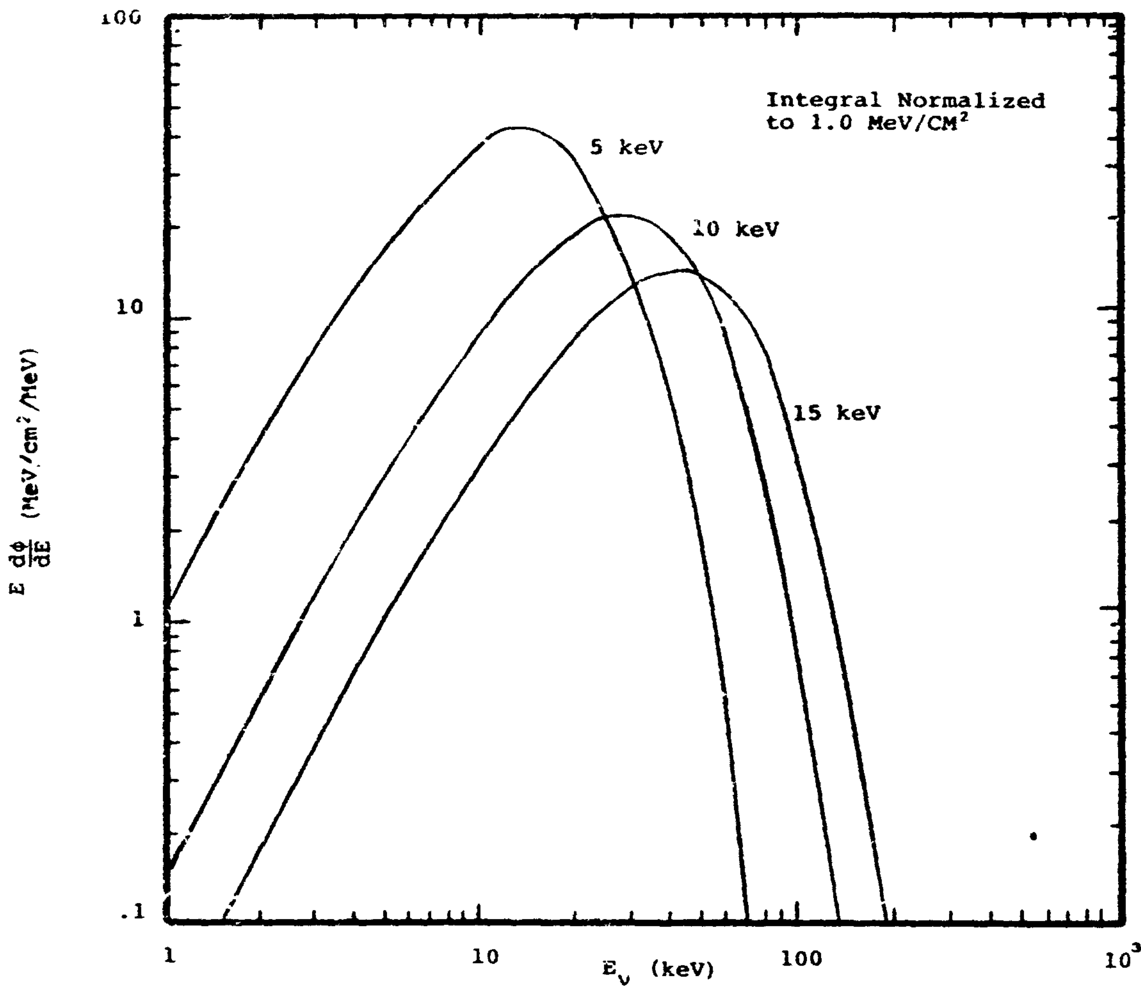


FIGURE A5. BLACKBODY X-RAY SPECTRA

Reference. Any modern physics textbook, eg. R. B. Leighton, Principles of Modern Physics McGraw Hill

APPENDIX B: LIST OF THE DEF CALCULATIONS

This appendix contains depth versus dose profiles for the device configuration and environment shown in Tables 3-1 and 4-1. The values at X = 0 are the surface values shown in the tables. In some instances, the average dose over the region between zero and 10 microns was computed by the equation

$$\bar{D} = \frac{D(0\mu m) - D(10\mu m)}{\ln \frac{D(0\mu m)}{D(10\mu m)}}$$

These DEF calculations are for an assumed spectrum right at the sensitive region. All of the calculations in this handbook are based on this assumption. The reader will have to estimate the spectral changes and their impact caused by the photon attenuation and scattering for a particular geometry. For many cases, especially for nominal thin gold films and kovar cans, such effects are small when incident photons are above 100 KeV.

DEPTH (MICRONS)	15 KEV BLACKBODY X-RAY ENVIRONMENT								
	KOVAR LID			GOLD LID OR GOLD METALIZATION			SCHOTTKY METALIZATION		
	20 MILS Al	200 MILS Al	20 MILS Al 20 MILS Ta	20 MILS Al	200 MILS Al	20 MILS Al 20 MILS Ta	20 MILS Al	200 MILS Al	20 MILS Al 20 MILS Ta
0	6.3	6.7	3.7	18.8	18.8	18.5	7.8	6.9	4.7
4	2.8	2.9	2.9	5.6	6.6	9.1	1.7	2.8	3.0
8	1.7	2.0	1.9	3.0	3.7	4.6	1.2	1.6	2.2
12	1.3	1.6	1.6	2.0	2.1	2.9	1.1	1.2	1.6
16	1.2	1.4	1.3	1.4	1.6	2.1	1.1	1.1	1.3
20	1.1	1.2	1.2	1.3	1.3	1.7	1.0	1.1	1.2
24	1.1	1.1	1.1	1.1	1.2	1.5	1.0	1.0	1.1
28	1.0	1.1	1.1	1.1	1.1	1.4	1.0	1.0	1.1
32	1.0	1.0	1.1	1.0	1.1	1.3	1.0	1.0	1.1
36	1.0	1.0	1.1	1.0	1.0	1.2	1.0	1.0	1.0
40	1.0	1.0	1.0	1.0	1.0	1.2	1.0	1.0	1.0
44	1.0	1.0	1.0	1.0	1.0	1.1	1.0	1.0	1.0
48	1.0	1.0	1.1	1.0	1.0	1.1	1.0	1.0	1.0
52	1.0	1.0	1.1	1.0	1.0	1.1	1.0	1.0	1.0
56	1.0	1.0	1.0	1.0	1.0	1.1	1.0	1.0	1.0
60	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0

DEPTH (MICRONS)	5 KEV BLACKBODY X-RAY ENVIRONMENT									
	KOVAR LID			GOLD LID OR GOLD METALIZATION			SCHOTTKY METALIZATION			
	20 MILS Al	200 MILS Al	20 MILS Al 20 MILS Ta	20 MILS Al	200 MILS Al	20 MILS Al 20 MILS Ta	DEPTH: MICRONS	20 MILS Al	200 MILS Al	20 MILS Al 20 MILS Ta
0	5.2	5.7	3.6	18.8	18.0	11.1	0	7.9	7.8	5.6
0.6	3.6	4.4	3.4	9.6	9.9	8.1	4	1.1	1.5	3.0
1.2	2.9	4.0	3.1	6.7	7.9	6.8	8	1.0	1.0	1.9
1.8	2.3	3.1	3.3	4.7	6.0	6.6	12	1.0	1.0	1.2
2.4	2.0	2.3	2.6	3.4	4.9	5.8	16	1.0	1.0	1.0
3.0	1.9	2.0	2.4	2.7	3.6	5.5				
3.6	1.5	1.8	2.3	2.2	2.7	4.9				
4.2	1.3	1.6	2.1	2.0	2.5	4.2				
4.8	1.2	1.4	2.0	1.5	2.5	3.6				
5.4	1.2	1.3	1.9	1.4	1.9	3.4				
6.0	1.2	1.2	1.7	1.3	1.5	2.8				
6.6	1.1	1.2	1.6	1.2	1.4	2.9				
7.2	1.1	1.1	1.5	1.4	1.3	2.2				
7.8	1.0	1.1	1.4	1.1	1.2	2.1				
8.4	1.0	1.1	1.3	1.1	1.1	1.9				
9.0	1.0	1.1	1.3	1.1	1.1	1.7				
9.6	1.0	1.0	1.2	1.0	1.1	1.8				
10.2	1.0	1.0	1.1	1.1	1.0	1.4				
10.8	1.0	1.0	1.2	1.0	1.0	1.2				
11.4	1.0	1.0	1.1	1.0	1.0	1.1				
12.0	1.0	1.0	1.1	1.0	1.0	1.1				
12.6	1.0	1.0	1.1	1.0	1.0	1.1				
13.2	1.0	1.0	1.0	1.0	1.0	1.1				

DEPTH (MICRONS)	RADIATION TEST FACILITIES								
	BLACKJACK FACILITY			FEBETRON 705 FACILITY			HERMES II FACILITY		
	KOVAR	GOLD	SCHOTTKY	KOVAR	GOLD	SCHOTTKY	KOVAR	GOLD	SCHOTTKY
0	3.9	12.8	6.4	1.9	3.4	1.8	1.5	1.6	1.4
4	2.5	5.2	2.0	1.8	2.7	1.6	1.3	1.4	1.3
8	2.0	3.9	1.4	1.7	2.4	1.7	1.3	1.4	1.3
12	1.6	2.6	1.3	1.7	2.3	1.6	1.4	1.4	1.3
16	1.6	2.3	1.2	1.7	2.4	1.6	1.4	1.4	1.3
20	1.4	2.1	1.1	1.6	2.0	1.6	1.4	1.4	1.3
24	1.4	1.8	1.1	1.5	2.0	1.6	1.4	1.4	1.3
28	1.3	1.9	1.1	1.6	1.9	1.5	1.3	1.4	1.3
32	1.4	1.6	1.1	1.6	1.8	1.5	1.3	1.4	1.3
36	1.2	1.4	1.0	1.5	2.0	1.5	1.3	1.4	1.3
40	1.2	1.4	1.0	1.6	1.7	1.5	1.3	1.4	1.3
44	1.2	1.3	1.0	1.5	1.8	1.5	1.3	1.4	1.3
48	1.2	1.3	1.0	1.5	1.7	1.4	1.3	1.4	1.3
52	1.1	1.2	1.0	1.5	1.7	1.4	1.3	1.4	1.3
56	1.1	1.3	1.0	1.5	1.7	1.4	1.3	1.3	1.3
60	1.1	1.1	1.0	1.5	1.6	1.4	1.3	1.3	1.3
64	1.1	1.2	1.0	1.4	1.6	1.4	1.3	1.3	1.3
68	1.1	1.2	1.0	1.5	1.6	1.4	1.3	1.3	1.2
72	1.1	1.2	1.0	1.4	1.6	1.4	1.3	1.3	1.2
76	1.1	1.2	1.0	1.4	1.5	1.3	1.3	1.3	1.2
80	1.1	1.1	1.0	1.4	1.5	1.3	1.3	1.3	1.3
84	1.1	1.2	1.0	1.4	1.5	1.3	1.3	1.3	1.2
88	1.1	1.1	1.0	1.3	1.4	1.3	1.3	1.3	1.2
92	1.1	1.1	1.0	1.4	1.5	1.3	1.3	1.3	1.2
96	1.1	1.1	1.0	1.3	1.5	1.3	1.3	1.3	1.2
100	1.1	1.1	1.0	1.3	1.4	1.3	1.3	1.3	1.2

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