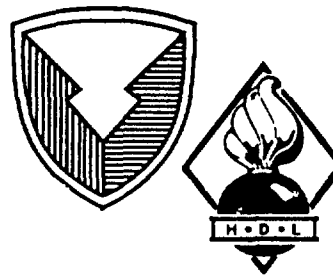AD-A234 507

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March 1991

An Electron-Beam Dose Deposition Experiment: TIGER 1-D Simulation Code Versus Thermoluminescent Dosimetry

by Steven R. Murrill
Charles W. Tipton
Charles T. Self

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13. ABSTRACT *(Maximum 200 words)*

The dose absorbed in an integrated circuit (IC) die exposed to a pulse of low-energy electrons is a strong function of both electron energy and surrounding packaging materials. This report describes an experiment designed to measure how well the Integrated TIGER Series one-dimensional (1-D) electron transport simulation program predicts dose correction factors for a state-of-the-art IC package and package/printed circuit board (PCB) combination. These derived factors are compared with data obtained experimentally using thermoluminescent dosimeters (TLD's) and the Harry Diamond Laboratories FX-45 flash x-ray machine (operated in electron-beam (e-beam) mode). The results of this experiment show that the TIGER 1-D simulation code can be used to accurately predict FX-45 e-beam dose deposition correction factors for reasonably complex IC packaging configurations.

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1. Introduction

In response to recent progress in Strategic Defense Initiative (SDI) and Defense Nuclear Agency (DNA) hardened integrated-circuit (IC) technology programs, Harry Diamond Laboratories (HDL) has developed a high-intensity ($\sim 1 \times 10^{11}$ to 1×10^{13} rads(Si)/s), narrow-pulse (~ 20 ns) dose-rate upset/survivability test facility.[1] The facility uses an Ion Physics FX-45 flash x-ray machine operated in the electron-beam (e-beam) mode and produces electrons with a mean energy of ~ 2 MeV. In this and other relatively low-energy e-beam environments, the prompt dose absorbed by an IC die can be significantly decreased or increased by packaging materials (see fig. 1). Since it is not always possible to remove the lid or other intervening package material(s), and because IC packages can vary widely in construction, one must generally obtain a *dose correction factor* for each device under test

Figure 1. Effect of packaging materials on dose deposited into 15 mils of Si (from TIGER 1-D simulations).
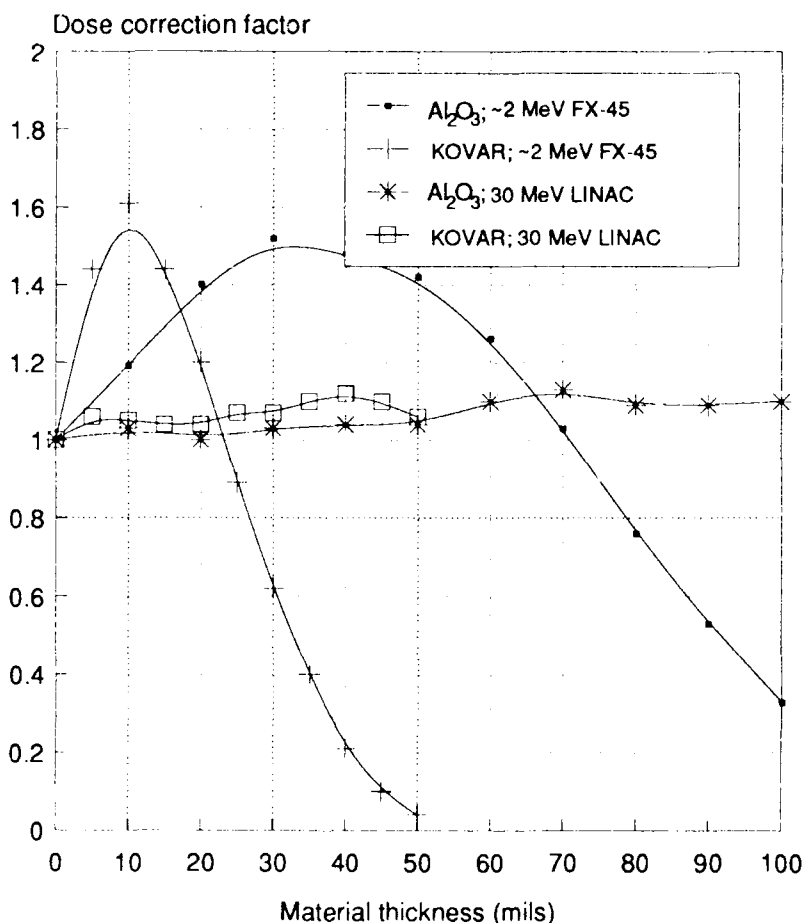
[1] S. Murrill, H. Eisen, and J. Azarewicz, A High Intensity Electron-Beam Facility for Dose-Rate Upset and Survivability Testing, presented at the 1989 Simulation Fidelity Workshop and to be published in the Journal of Radiation Effects.

(DUT) packaging configuration. Correction factors allow the experimenter to use external dosimetry to accurately determine the dose delivered to the die. One widely used tool for calculating such correction factors is the TIGER one-dimensional (1-D) coupled electron/photon Monte-Carlo transport simulation code.[*] The Integrated TIGER Series (ITS) is an integrated collection of eight transport codes, some of which are 1-D, some 2½-D, some 3-D. The 1-D member of the ITS is the code TIGER.

The purpose of this experiment was to verify that the TIGER 1-D code (version 2.1) could accurately predict dose correction factors for both a moderately complex, multilayer IC package and an IC package/printed circuit board (PCB) combination, relative to data obtained experimentally using thermoluminescent dosimeters (TLD's).

The results of this experiment show that the TIGER 1-D simulation code can be used to accurately predict FX-45 e-beam dose deposition correction factors for reasonably complex IC packaging configurations.

2. Methodology

2.1   Materials

The materials and tools used to perform this experiment were as follows:

- a Honeywell (HWL) radiation-hardened (rad-hard) 36-pin surface-mount IC package,

- the HWL IC package mounted on a 62-mil-thick epoxy-glass PCB,

- version 2.1 of the TIGER 1-D simulation code,

- Teledyne Isotopes Mn-doped calcium fluoride (CaF_2:Mn) TLD's (P/N SD-CaF_2:Mn-0.4),

- a Harshaw/Filtrol TLD reader (model No. 2000D), and

- the HDL High Intensity Flash X-Ray (HIFX) test facility (e-beam mode).

[*]*Distributed by Oak Ridge National Laboratory.*

2.2 Procedures

This experiment consisted of two, essentially independent, procedures:

- determination of dose correction factors through simulations (correction factor simulations) and

- determination of dose correction factors from measurements (correction factor measurements).

DEFINITION: In this experiment, a dose correction factor is defined as the ratio of the average dose absorbed in some thickness of material when it is shielded from a pulse of incident electrons by some other object or objects, to the average dose absorbed in that same thickness of material when it is exposed directly to an identical pulse of electrons.

2.2.1 Correction Factor Simulations

All simulated correction factors were determined through the use of the TIGER 1-D electron transport code. TIGER is a powerful and user-friendly software package that permits state-of-the-art Monte Carlo solution of linear time-integrated coupled electron/photon radiation transport problems. The code is based primarily on the ETRAN model, which combines microscopic photon transport with a macroscopic random walk for electron transport.[2] The two basic steps required for solving radiation transport problems using TIGER are to (1) generate cross sections by running the cross-section code and (2) run the Monte Carlo code. To generate the cross sections, the user must provide a list of the materials involved along with their compositions and densities. Running the Monte Carlo code requires both an ordered list of the materials and their thicknesses along with a spectral description of the incident radiation. In this procedure, we combined these two steps through the use of batch processing files.

In order to properly match the simulation conditions to the experimental measurement conditions, particular attention had to be given to experimental dosimetry. The Harshaw TLD reader that was used in this experiment measures the dose absorbed in the thermoluminescent component (Mn-doped CaF_2) of TLD's. For this reason, all correction factors that were derived from TIGER 1-D simulations are based on the absorbed dose in the CaF_2 component of the TLD's. The Teledyne TLD's consist of 5 percent (by weight) CaF_2:Mn and 95

[2] J. A. Halbleib and T. A. Mehlhorn, ITS: The Integrated TIGER Series of Coupled Electron/Photon Monte Carlo Transport Codes—Report No. SAND84-0573, Sandia National Laboratories, Albuquerque, New Mexico (1984).

percent Teflon (C_2F_4).[3] The CaF_2 is homogeneously distributed within the Teflon base. Because the TIGER 1-D code is designed to work with well-defined layers of materials,[2] simulated TLD's were modeled as a layer of pure CaF_2 sandwiched between two equal thicknesses of C_2F_4. (This is a reasonable approximation from the standpoint of symmetry.) The thicknesses for the three layers of the TLD model were calculated from the measured thickness of an actual TLD and the relative mass/densities of the TLD components. These calculations are detailed in appendix A. Figure 2 shows the three material sets that were used in the TIGER simulations to calculate dose correction factors for the HWL IC package and IC package/PCB combination. Note that all thicknesses given for the HWL IC package materials represent nominal manufacturing values.* Figure 3 gives the "binned" spectral distribution of the FX-45 e-beam (charging voltage of ~4.1 MV) that was used in all TIGER 1-D simulation runs.

A listing of all pertinent TIGER 1-D code input parameters used in each simulation run is given in appendix B.

FX-45 e-beam

Set #1 (TLD)

C_2F_4	CaF_2	C_2F_4
7.24 mils	0.52 mils	7.24 mils

Set #2 (HWL package + TLD)

Al_2O_3	W	Al_2O_3	W	Ni	Au	C_2F_4	CaF_2	C_2F_4
50 mils	1 mils	20 mils	1 mils	0.08–0.35 mils	0.08–0.23 mils	7.24 mils	0.52 mils	7.24 mils

Set #3 (PCB + package + TLD)

PCB	Al_2O_3	W	Al_2O_3	W	Ni	Au	C_2F_4	CaF_2	C_2F_4
62 mils	50 mils	1 mils	20 mils	1 mils	0.08–0.35 mils	0.08–0.23 mils	7.24 mils	0.52 mils	7.24 mils

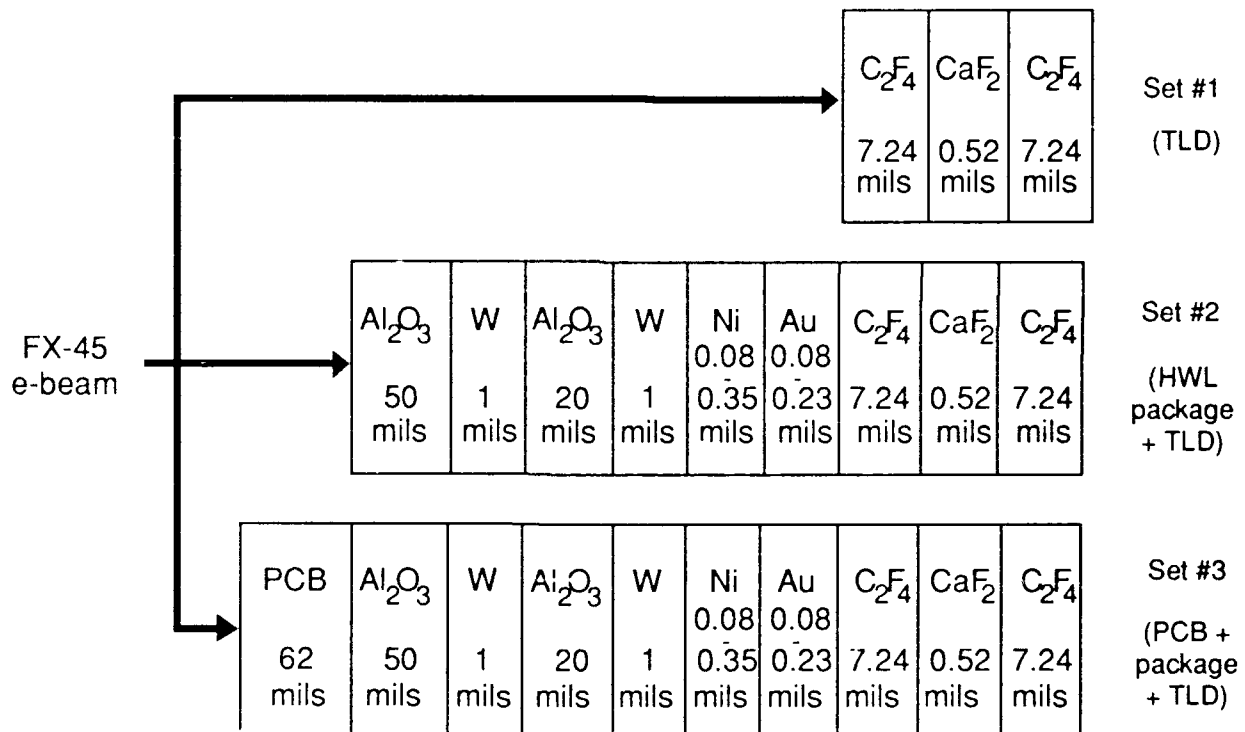Figure 2. TIGER code simulation materials.

[2] J. A. Halbleib and T. A. Mehlhorn, ITS: The Integrated TIGER Series of Coupled Electron/Photon Monte Carlo Transport Codes—Report No. SAND84-0573, Sandia National Laboratories, Albuquerque, New Mexico (1984).
[3] Teledyne Isotopes, Brochure, Teledyne Isotopes (New Jersey).
*Private communication with Mike Heinks, Honeywell Solid State Electronics Division (SSED).

Figure 3. "Binned" FX-45
e-beam spectrum
(charging voltage
~4.1 MV).

Number/energy (normalized)

Energy (MeV)
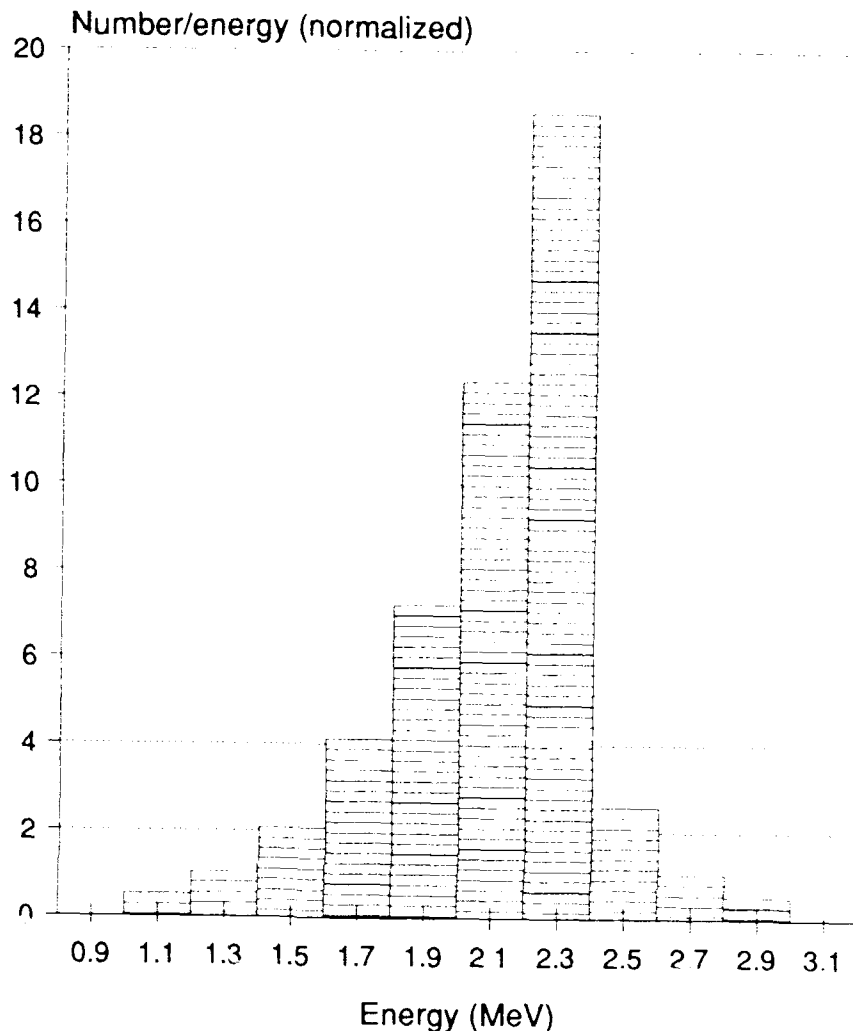
Dose correction factors for the HWL IC package alone were calculated by dividing the TIGER-code-generated dose/incident fluence in the CaF_2 layer of the second material set (fig. 2) by the dose/incident fluence of the CaF_2 layer of the first material set, for each of two conditions: the Ni and Au layers at minimum thicknesses, and the Ni and Au layers at maximum thicknesses. These two conditions were selected in order to determine the worst-case simulated dose correction factor range. Dose correction factors for the IC package/PCB combination were similarly calculated, using the third and first material sets (fig. 2).

2.2.2   Correction Factor Measurements

All experimentally determined dose correction factors were obtained by irradiating TLD's at the HDL HIFX test facility.

To experimentally determine dose correction factor(s) in a manner consistent with both the *definition* and the simulation procedure(s), the following conditions needed to be met:

(1) TLD's must be irradiated in *pairs* so that

- one TLD is shielded from the e-beam by the HWL IC package or IC package/PCB combination, and

- one TLD is not shielded, and

(2) TLD's should be irradiated in a manner that allows for the measurement of absorbed dose (CaF_2)/incident fluence for each TLD in a pair.

The testing facility has several pertinent limitations:

- the e-beam fluence varies from shot to shot,

- the e-beam fluence cannot be directly measured, and

- the test chamber has an ~600-mil-diameter exposure aperture.

Figures 4 and 5 illustrate the procedure used for this experiment, which accommodates the above needs and limitations. Note that, in this setup (fig. 5), each TLD pair is "effectively" irradiated using a single pulse of electrons. This is accomplished by replacing one TLD (of each pair) with two subminiature type-E (Chromel-Constantan) thermocouples which have been calibrated to dose (CaF_2) using Teledyne Isotopes Sd-CaF_2:Mn-0.4 TLD's and the Harshaw TLD reader (see fig. 5 and 6). Figure 7 shows both the measured and calculated thermocouple response/dose (CaF_2) relationships.

All experimentally determined dose correction factors were calculated by dividing the absorbed dose (CaF_2) from each TLD (fig. 5) by the average of the associated dose (CaF_2) thermocouple readings.

Although the physical presence of the two thermocouples represents a slight deviation from the simulation conditions (review fig. 2), two factors combine to significantly reduce any associated error:

- the cross-sectional area of the two thermocouples is small (~9 percent of the cross-sectional area of a TLD), and

- because the thermocouples were also necessarily present during the thermocouple/dose (CaF_2) calibration, the shielding effects tend to cancel in the calculation of dose correction factors.

Figure 4. HIFX e-beam test chamber.

Flash x-ray beam port
Adapter plate
Aperture plate
Aperture
Ti window
Evacuated drift tube
Collimator window
Pb shield
Thermocouple
DUT
DUT mounting board
Outer chamber for line drivers, etc.
Thermocouple
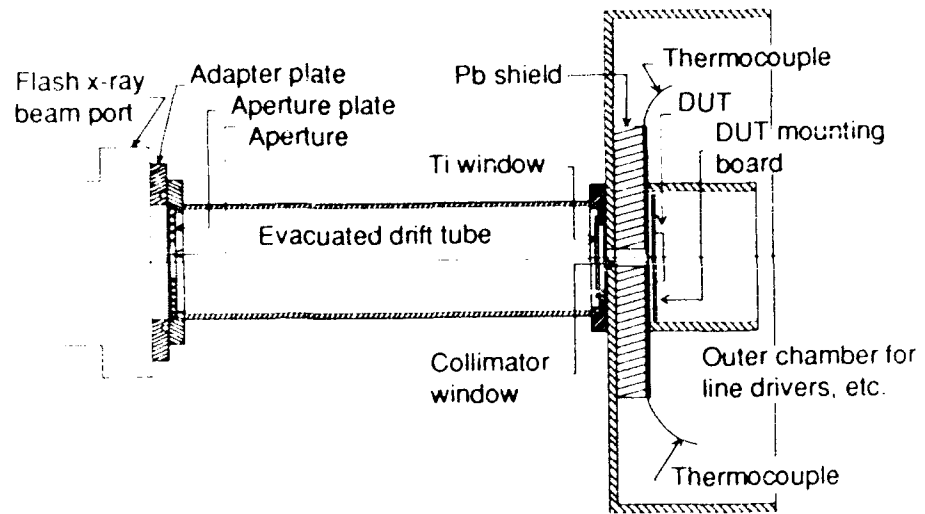
Figure 5. Experimental arrangement.

Pb shield
Al
Al
+ V1 −
Type E thermocouple
PCB
HWL package
FX-45
E beam
TLD
Al
Pb shield
Al
Type E thermocouple
+ V2 −
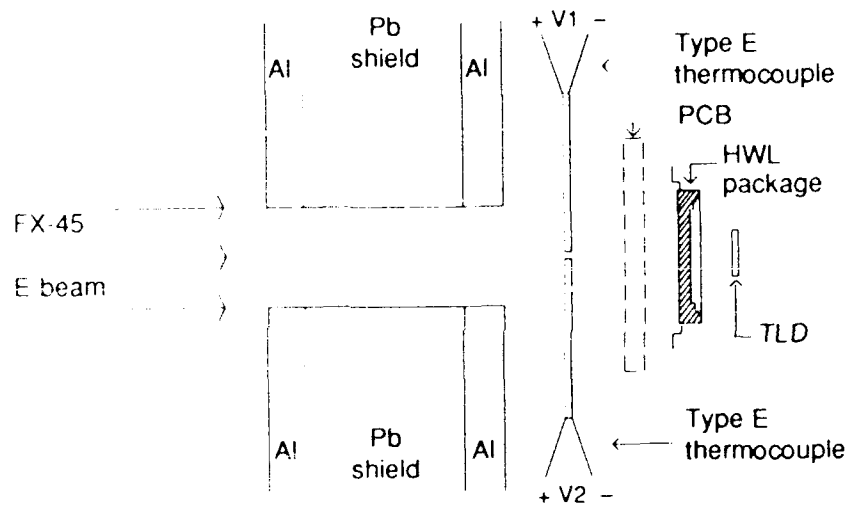
Figure 6. Thermocouple calibration arrangement.

Pb shield
Al
Al
+ V1 −
Type E thermocouple
FX-45
E beam
TLD
Al
Pb shield
Al
Type E thermocouple
+ V2 −
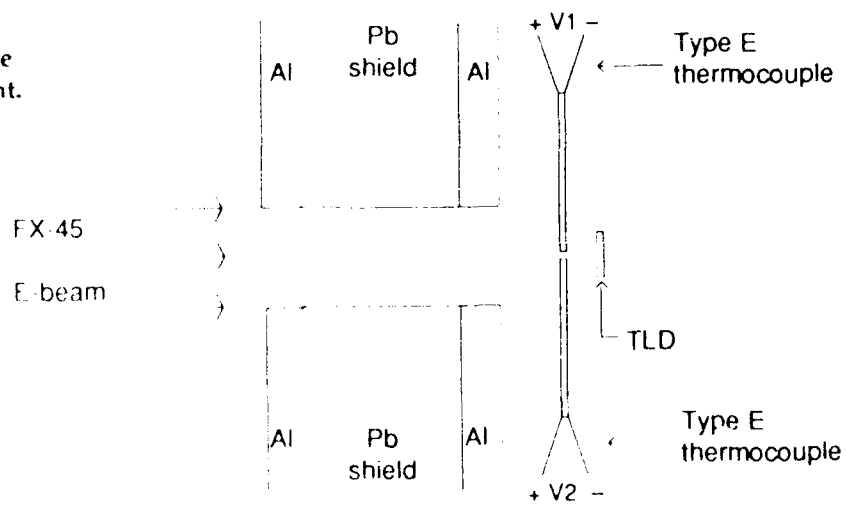
Figure 7. HDL FX-45 thermocouple dosimetry calibration.

TC1 data   TC2 data   --- TC1 fit

TC2 fit   TC response (calc)
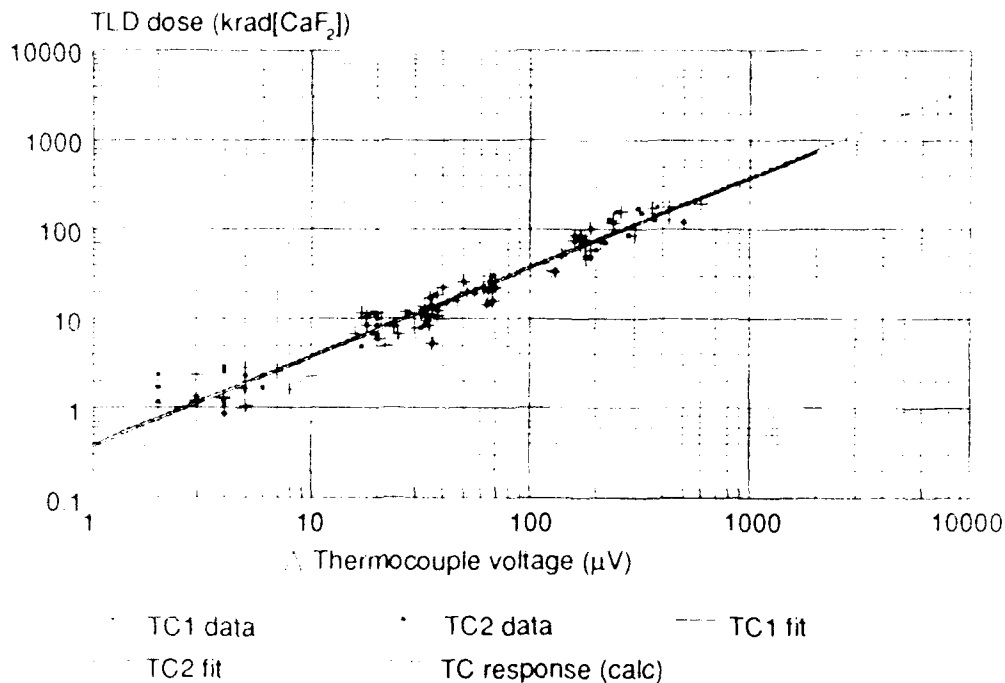
Dose (krad[CaF$_2$]) = 0.359 $\cdot$ Δ μV (TC1)   Dose (krad[CaF$_2$]) = 0.387 $\cdot$ Δ μV (TC2)

Dose (krad[CaF$_2$]) = 0.396 $\cdot$ Δ μV (calc: TIGER 1–D sim)

Note that the Harshaw TLD reader is calibrated to provide measurements of equilibrium dose in silicon (Si) from the absorbed dose in the CaF$_2$ component of a TLD.[4] The absorbed TLD dose (CaF$_2$) is related to the Harshaw dose (Si) reading by the following equations:[4]

$$\text{Dose (Al)} = \frac{(\mu_{en}/\rho)_{Al}^{^{60}Co}}{(\mu_{en}/\rho)_{Si}^{^{60}Co}} \times \text{dose (Si)} = 0.967 \text{ dose (Si)} , \qquad (1)$$

$$\text{Dose (CaF}_2) = \frac{(S)_{CaF_2}^{300\,keV}}{(S)_{Al}^{300\,keV}} \times \text{dose (Al)} = 1.013 \text{ dose (Al)} , \qquad (2)$$

where μ_{en}/ρ is the mass energy absorption coefficient of the material of interest, and S is the electron mass stopping power ($S = (dE/dx)/\rho$).

Substituting equation (1) into equation (2) yields

$$\text{Dose (CaF}_2) = 1.013 \times 0.967 \text{ dose (Si)} = 0.979 \text{ dose (Si)} . \qquad (3)$$

[4] Klaus Kerris, The AURORA Dosimetry System, Harry Diamond Laboratories, HDL TR-1754 (1976), pp 36–39.

3. Results

Table 1 shows the calculated dose correction factors for the HWL rad-hard 36-pin surface-mount IC package and IC package/PCB combination. Note that these correction factors are based on the average absorbed dose in the CaF_2 component of the TLD model (see fig. 2).

Table 2 shows the experimentally determined dose correction factors for the HWL IC package and IC package/PCB combination. These correction factors are based on the average absorbed dose in the CaF_2 component of actual TLD's.

Figure 8 shows the correlation between the dose correction factors that were derived from the TIGER 1-D simulations and those that were determined experimentally. Note that the two simulation ranges given for each of the two material arrangements reflect the minimum and maximum thicknesses of the Ni and Au layers in the HWL IC package (see fig. 2).

Table 1. TIGER 1-D simulation results

Simulation conditions[a]			
Shielding	Ni, Au layer thicknesses	Dose correction factor	Error[b]
None	—	1	—
IC package	Min	0.501	2
IC package	Max	0.432	3
IC package/PCB combination	Min	0.0728	4
IC package/PCB combination	Max	0.0623	5

[a]See figure 2.
[b]Percentage estimate of 1σ statistical uncertainty.
Note: IC packages are manufactured by Honeywell.

Table 2. TIGER 1-D experimental results

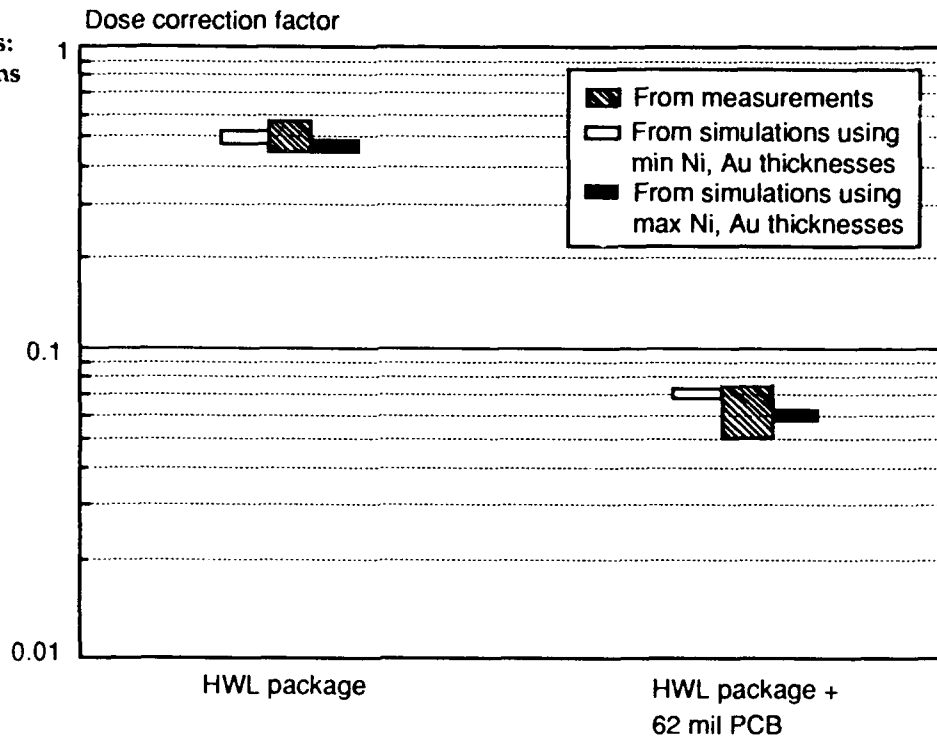| Experimental arrangement[a]	Dose correction factor[b]	Error[c]
No IC package or PCB	1	—
IC package	0.52	0.067
IC package/PCB combination	0.065	0.013

[a]See figure 5.
[b]Represents the mean of 10 irradiations/arrangement.
[c]Represents one standard deviation of uncertainty.
Note: IC packages are manufactured by Honeywell.

Figure 8. One-sigma dose correction factors: TIGER 1-D simulations versus experimental measurements.

Dose correction factor

Legend:
- From measurements
- From simulations using min Ni, Au thicknesses
- From simulations using max Ni, Au thicknesses

HWL package

HWL package + 62 mil PCB

4. Discussion and Conclusion

The dose correction factors obtained from the TIGER 1-D simulations agree, within one standard deviation, with those obtained experimentally for each of the two packaging configurations used in this experiment. Given that the simulations were done using the minimum and maximum thicknesses for the Ni and Au material layers of the HWL IC package, and that there may have been some differences in thickness between other layers of the simulation model and the actual HWL IC package, the agreement is quite good.

The packaging configurations chosen for this experiment were selected for two reasons: (1) they represented realistic test configurations, both in materials and exposure orientation, and (2) they approximated worst-case situations from the standpoint of the number, type, and thicknesses of intervening materials that would be expected in typical HDL FX-45 e-beam test setups. The underlying assumption was, and is, that the greater the number of materials (layers), and/or the greater their thicknesses, the more difficult it would be to accurately determine dose correction factors using the TIGER simulation code.

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It should be noted that, in this experiment, dose correction factors are based on the absorbed dose in the CaF_2 component of TLD's. In order to determine (simulate) dose correction factors which are based on, and can be used to determine, the dose deposited into some region (thickness) of a packaged IC die (usually Si) relative to external dosimetry, the terminal TLD (model) materials (see fig. 2) would have to be replaced by a representative thickness of the material of interest. Such a change in material arrangement is not expected to alter the accuracy of the associated TIGER 1-D simulation.

The complexity of the test configuration used in this experiment, taken along with the closeness of the experimental conditions to typical test configurations and the excellent results of this experiment, leads us to conclude that the TIGER 1-D simulation code can be used to accurately predict FX-45 e-beam dose deposition correction factors for reasonably complex IC packaging configurations.

5. Acknowledgements

Appendix A.—Three-Layer TLD Model

The Teledyne Isotopes thermoluminescent dosimeters (TLD's) used in this experiment are essentially composed of 5 percent CaF_2 and 95 percent Teflon (C_2F_4)[1] (by weight). The TLD's are shaped as slightly concave discs with the following dimensions:

- diameter = ~236 mils,

- thickness = ~15 mils.

The CaF_2 is homogeneously distributed within the Teflon base.

A simple, symmetric, three-layer model of the Teledyne Isotopes TLD can be derived as follows:

- assume that the TLD is shaped as a perfect disc (cylinder),

- let the center layer of the model be composed of pure CaF_2,

- let the two outer layers be composed of equal thicknesses of C_2F_4, and

- calculate the thicknesses of the three layers from the relative mass/densities of the two components.

To calculate the layer thicknesses, assume the following:

Density (ρ) of CaF_2 = 3.18 g/cm³ (Weast[2]) , (A-1)

Density (ρ) of C_2F_4 = 2.20 g/cm³ (Weast[3]) , and (A-2)

Thickness (T) of the TLD = 15 mils (measured) . (A-3)

The ratio of the masses of the two TLD components is

$$\frac{mass_{CaF_2}}{mass_{C_2F_4}} = \frac{5\%}{95\%} = 0.0526 .$$ (A-4)

Given that

$$mass\ (m) = density\ (\rho) \times volume\ (V) ,$$ (A-5)

and

volume (V) of a cylinder = thickness (T) × cross-sectional area (A) , (A-6)

[1]Teledyne Isotopes, Brochure, Teledyne Isotopes (New Jersey).
[2]R. Weast, CRC Handbook of Chemistry and Physics, CRC Press, FL (1989), p B-80.
[3]R. Weast, CRC Handbook of Chemistry and Physics, The Chemical Rubber Co., Ohio (1971), p C-769.

Appendix A

substituting equations (5) and (6) into equation (4) yields

$$\frac{\rho_{CaF_2} \times T_{CaF_2} \times A_{CaF_2}}{\rho_{C_2F_4} \times T_{C_2F_4} \times A_{C_2F_4}} = 0.0526 \ . \tag{A-7}$$

Rearranging terms and noting that $A_{CaF_2} = A_{C_2F_4}$ yields

$$\frac{T_{CaF_2}}{T_{C_2F_4}} = \frac{\rho_{C_2F_4}}{\rho_{CaF_2}} \times 0.0526 \ . \tag{A-8}$$

Substituting equations (1) and (2) into equation (8) yields

$$\frac{T_{CaF_2}}{T_{C_2F_4}} = \frac{2.20}{3.18} \times 0.0526 = 0.0364 \ . \tag{A-9}$$

Since there are only two *component* thicknesses in this model,

$$T_{CaF_2} + T_{C_2F_4} \ \text{must equal the total thickness of the TLD} = 15 \ \text{mils} \ . \tag{A-10}$$

Substituting equation (9) into equation (10) yields

$$T_{C_2F_4} = \frac{15 \ \text{mils}}{1 + 0.0364} = 14.473 \ \text{mils} \ . \tag{A-11}$$

From equation (10),

$$T_{CaF_2} = 15 - T_{C_2F_4} = 0.527 \ \text{mils} \ . \tag{A-12}$$

Because the model calls for two equal layers of C_2F_4,

$$\text{each } C_2F_4 \text{ layer} = \frac{14.473 \ \text{mils}}{2} = 7.237 \ \text{mils} \ . \tag{A-13}$$

Figure A-1 shows the complete TLD model.

Figure A-1. TIGER 1-D TLD model.

C_2F_4	CaF_2	C_2F_4
7.24 mils	0.52 mils	7.24 mils

Appendix B.—TIGER 1-D Input Specifications

The following listing shows all the pertinent TIGER 1-D simulation code input parameters used to calculate FX-45 e-beam dose correction factors for the Honeywell radiation-hardened 36-pin surface mount integrated-circuit (IC) package and printed circuit board/ IC package combination.

```
********   SOURCE   ********
ELECTRONS
SPECTRUM 11
1.0         0.98968     0.96906     0.91752     0.54639
0.29897     0.15464     0.07217     0.03093     0.01031
0.0
3.0    2.8     2.6    2.4     2.2    2.0
1.8    1.6     1.4    1.2     1.0

CUTOFFS   0.05   0.01




——— CROSS-SECTIONS ———
ENERGY   3.0
MATERIAL C      0.382    H 0.039    O 0.346    SI 0.233    DENSITY 1.8
MATERIAL AL     0.529    O 0.471    DENSITY 3.69
MATERIAL AL
MATERIAL SI
MATERIAL NI
MATERIAL W
MATERIAL AU
MATERIAL SI     0.467    O 0.533    DENSITY 2.32
MATERIAL C      0.24     F 0.76     DENSITY 2.20
MATERIAL CA     0.51     F 0.49     DENSITY 3.18
*——————————————*




********   OTHER OPTIONS   ********
HISTORIES 100000
*——————————————*




——  TRANSPORT, SPECTRUM NO. 1 (ELECTRONS) NEW TLD ——
********   GEOMETRY   ********
GEOMETRY 3
*  MAT  NZONE   THIK        ECUT      PTCZ
   9      1     0.0184
   10     1     0.00134
   9      1     0.0184
```

Appendix B

— TRANSPORT, SPECTRUM NO. 1 (ELEC-
TRONS) THIN AU/NI AND NO PCB —
********* GEOMETRY *********
GEOMETRY 9

* MAT	NZONE	THIK	ECUT	PTCZ
2	1	0.127		
6	1	0.00254		
2	1	0.0508		
6	1	0.00254		
5	1	0.0002032		
7	1	0.0002032		
9	1	0.0184		
10	1	0.00134		
9	1	0.0184		

— TRANSPORT, SPECTRUM NO. 1 (ELEC-
TRONS) THICK AU/NI AND NO PCB —
********* GEOMETRY *********
GEOMETRY 9

* MAT	NZONE	THIK	ECUT	PTCZ
2	1	0.127		
6	1	0.00254		
2	1	0.0508		
6	1	0.00254		
5	1	0.000889		
7	1	0.000584		
9	1	0.0184		
10	1	0.00134		
9	1	0.0184		

— TRANSPORT, SPECTRUM NO. 1 (ELECTRONS)
THIN AU/NI AND PCB —
********* GEOMETRY *********
GEOMETRY 10

* MAT	NZONE	THIK	ECUT	PTCZ
1	1	0.15748		
2	1	0.127		
6	1	0.00254		
2	1	0.0508		
6	1	0.00254		
5	1	0.0002032		
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