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AE9/AP9 Electron Displacement Damage Kernels

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Abstract

We have developed two AE9/AP9 kernels that convert incident electron fluence into conservative estimates of the displacement damage produced in Si and GaAs electronics inside spherical Al shielding. We use the multilayered shielding simulation software (MULASSIS) tool to perform many test particle simulations of electrons interacting with Al shielding and entering Si or GaAs targets. We use "NIEL scaling" to characterize displacement damage in terms of an equivalent 1-MeV neutron fluence, where NIEL is the nonionizing energy loss rate per distance traveled by an incident energetic particle. Our estimate is conservative because, for a given deposited displacement damage dose value, an electron is less effective than a proton or neutron at damaging most common electronics. The specific differences between electron and proton/neutron effects are technology- and part-dependent, so no generic kernel for electron displacement damage is possible without making this conservative assumption. The kernels themselves are Extensible Markup Language (XML) files that capture the transform matrix, the energy and shielding grids, and relevant metadata. Future versions of AE9/AP9 will be able to use such kernels to compute displacement damage for individual mission scenarios, and will thereby be able to use the existing AE9/AP9 statistical machinery to compute confidence levels for displacement damage.

Acknowledgments

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1. Introduction

In *O'Brien and Kwan* [2013], we developed the concept of an AE9/AP9 kernel, which is an Extensible Markup Language (XML) file containing a transform matrix that describes the linear transform from a spectrum of fluence versus energy to a radiation effect, such as displacement damage versus depth. The XML file conforms to a standard described in *O'Brien and Whelan* [2015]. The XML file also contains metadata that describes the energy and depth grids, units, and other potentially useful information. However, the main purpose of the kernel file is to provide the transform matrix. For *electrons* we cannot make a generic kernel for two reasons: (1) the electron damage depends significantly on the technology, parts, and performance parameters of interest; and (2) converting from electron fluence to equivalent neutron fluence is *nonlinear* when these details are taken into account. However, treating the electron displacement damage as equivalent to neutron displacement damage for the same deposited nonionizing dose is conservative. Thus, in the present work, we can use NIEL scaling to perform a linear calculation that yields a conservative estimate of the displacement damage produced in devices by electrons. (NIEL scaling is described in the Appendix and in *Srour and Palko*, [2013], and references therein.)

In this report, we describe the rationale for using NIEL scaling to obtain a conservative estimate of electron displacement damage, then we describe our runs of the multilayered shielding simulation software (MULASSIS, *Lei et al.*, [2002]) tool used to estimate the electrons-to-damage transform for Si and GaAs targets behind spherical Al shields. Next, we describe the assembly of the kernel, and finally we verify the kernel for a reference electron spectrum.

2. Electron Displacement Damage via NIEL Scaling

For proton displacement damage, a good first-order approximation allows one to collapse the proton energy spectrum into an equivalent fluence of 1-MeV neutrons via NIEL scaling. In the interest of clarity, we define displacement damage dose (D_d) as the energy deposited through non-ionizing mechanisms per unit mass; it is given in units of energy per mass, such as MeV/g. We define NIEL as the non-ionizing energy loss *rate* from the particle to the material *per unit distance traveled*. That distance is often converted to column density, using the mass density of the target material, giving NIEL in units of MeV/(g/cm^2). Using these definitions, the displacement damage dose D_d at a given shielding thickness T can be computed as:

$$D_d(T) = \int_0^\infty j'_p(E;T) S_p(E) dE, \tag{1}$$

where $j'_p(E;T)$ is the differential proton spectrum versus energy E emerging from shielding thickness T, and $S_p(E)$ is the proton NIEL in the target material (Si or GaAs) for protons with energy E. The equivalent 1-MeV neutron fluence $j_n(T)$ is then:

$$j_n(T) = \frac{D_d(T)}{S_n(E=1\text{ MeV})}, \tag{2}$$

where $S_n(E)$ is the neutron NIEL in the target material. It is this equation that gives “NIEL scaling” its name.

To compute the equivalent neutron fluence at shielding depth T for electrons incident on Al shielding, we must consider two challenges unique to electrons: (1) electrons scatter more than protons as they pass through matter and so a full-physics code is required to compute the spectrum emerging from the shielding instead of a simple range-energy calculation, and (2) electron displacement damage effects on solid-state devices can depend strongly on the technology, part, or parameter of interest, making it essentially impossible to make a generic first-order estimate of the equivalent neutron fluence for a given incident electron spectrum. We will address the scattering problem through the use of a full-physics code, MULASSIS, described in the next section. In this section, we address the problem of electron displacement damage.

Essentially, our argument is that the NIEL-scaling approach can be used for electrons because electrons are much less effective than protons and neutrons in degrading solid-state devices for some properties, but are comparable in their effectiveness for other properties. (See Appendix for details.) The calculated displacement damage dose for electrons is:

$$D_d(T) = \int_0^\infty j'_e(E;T) S_e(E) dE, \tag{3}$$

where $j'_e(E;T)$ is the differential *electron* spectrum emerging from shielding, and $S_e(E)$ is the *electron* NIEL in the target material (Si or GaAs). Then, the equivalent fluence of 1-MeV neutrons is computed according to Eq. (2), assuming, conservatively, that a given D_d from neutrons has at least as much of an effect on a device as the same D_d from electrons.

3. The MULASSIS Runs

To compute the electron displacement damage dose in Si and GaAs, we use MULASSIS, which is itself a wrapper for Geant4 [*Agostinelli et al.*, 2003]. Geant4 manages the physics of individual electrons traversing the aluminum shielding and arriving at the Si or GaAs target. MULASSIS handles the launching of particles and generates the non-ionizing dose (D_d) at the surface of the target volume. In MULASSIS, D_d is computed from the fluence of particles entering the Si target and their NIEL at the point of entry. Therefore, it neglects physical interactions inside the target. MULASSIS provides options for defining shielding material and geometry, target material, and the input species and spectrum. In our case, the input species is electrons and the spectrum is monoenergetic. By compiling runs for many monoenergetic spectra of different energies through different thicknesses of shielding, we can build up the Green's function, which is the displacement damage dose as a function of depth for a Dirac delta function in energy (i.e., a monoenergetic electron isotropic "beam"). The kernel is, in turn, a discretized version of the Green's function.

We ran MULASSIS as described in *Kwan and O'Brien* [2013] for Si and GaAs targets for the following electron energies: 0.04, 0.07, 0.1, 0.25, 0.5, 0.75, 1.0, 1.5, 2, 2.5, 3, 3.5, 4, 4.5, 5, 5.5, 6, 6.5, 7, 8.5, and 10 MeV. This list is based on the energy channels used by AE9.

For each of the selected electron energies, we ran MULASSIS for spherical aluminum shielding of 1 to 10,000 mils in thickness, logarithmically spaced with 10 depths per decade, as in: 1, 1.26, 1.58, …10,000 mils.

The spherical target volume had a radius equal to 10% of the shielding thickness. This approach produces geometric similarity between runs, even though at thicker shielding it produces target sizes considerably larger than those found in common practice. This approach necessarily assumes that details of the target geometry are of little consequence, an assumption built into the MULASSIS approach of tabulating D_d from fluence and NIEL across the target surface.

We ran 10 million electrons for each combination of energy and shielding thickness.

The input file for MULASSIS for the Si target has the following format. (For the GaAs target, "G4_Si" is replaced by "G4_GALLIUM_ARSENIDE" and "JPL_NRL_NASA_2003_Si" is replaced by "JPL_NRL_NASA_2003_GaAs".)

```
/geometry/layer/delete 0
/geometry/material/addNIST G4_Al
/geometry/material/addNIST G4_Si
/geometry/layer/shape sphere
/geometry/layer/add 0 G4_Al 1 $THICKNESS_AL mil
/geometry/layer/add 1 G4_Si 3 $RADIUS_SI mil
```

```
/analysis/file $OUTPUT_FILE_NAME
/analysis/normalise 0.250E+00 cm2
/analysis/niel/add 1
/analysis/niel/functionByLayer 1 JPL_NRL_NASA_2003_Si
/analysis/niel/add 2
/analysis/niel/functionByLayer 2 JPL_NRL_NASA_2003_Si
/analysis/niel/unit MeV/g
/geometry/update
/phys/cuts/global/default 1.000E+00 um
/phys/scenario em
$GPS
/gps/ang/type cos
/gps/ang/mintheta 0.000E+00 deg
/gps/ang/maxtheta 9.000E+01 deg
/event/printModulo 10000000
/run/cputime 1.410E+06
/run/beamOn 10000000
```

$THICKNESS_AL is the thickness of the spherical aluminum shielding. $RADIUS_SI is the radius of the target volume. $OUTPUT_FILE_NAME is the name for the two output files (.rpt and .csv). $GPS is the trapped electron energy in the following format:

```
/gps/particle e-
/gps/energy 4.000000e-02 MeV
```

The MULASSIS runs used about 120 hours of computing time dispersed over the corporate computing cluster. To convert from electron damage to equivalent 1-MeV neutron fluence, we used NIEL values of 2.04×10^{-3} MeV/(g/cm^2) for 1-MeV neutrons in Si, and 5.83×10^{-4} MeV/(g/cm^2) in GaAs.

Figures 1 and 2 show the effect of shielding on displacement damage for the various monoenergetic electron bombardments. Depending on the energy, the displacement damage levels off beyond 100–1000 mils, suggesting that additional shielding adds little benefit (the non-monotonic fluctuations are statistical artifacts of running a finite number of particles).

Looking at the MULASSIS output in a different way, we can see how the Green's function varies with energy and depth. Figure 3 shows that for shielding depths up to about 700 mils, there is a steep turn on of the main damage response to electrons as energy increases. However, at thicker depths, all that is evident below 10 MeV is a roughly power-law subthreshold response, possibly related to bremsstrahlung. The GaAs Green's functions (not shown) are qualitatively similar.

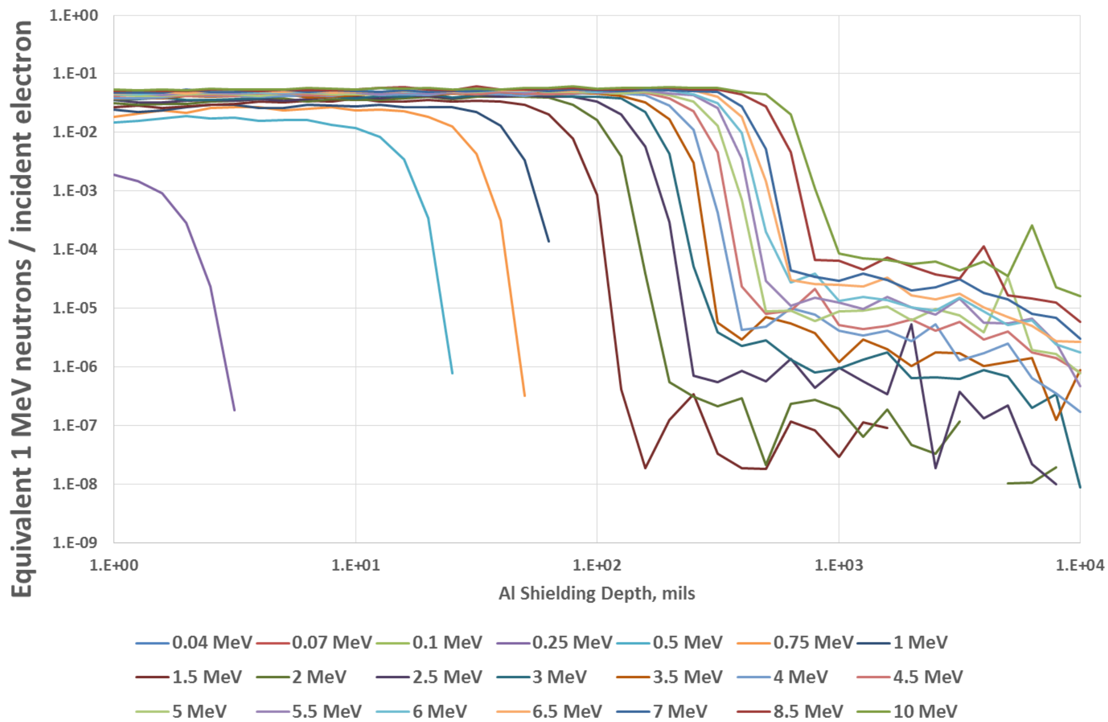

Figure 1. Equivalent 1-MeV neutrons for electrons of various energies incident on spherical Al shields around a silicon target.

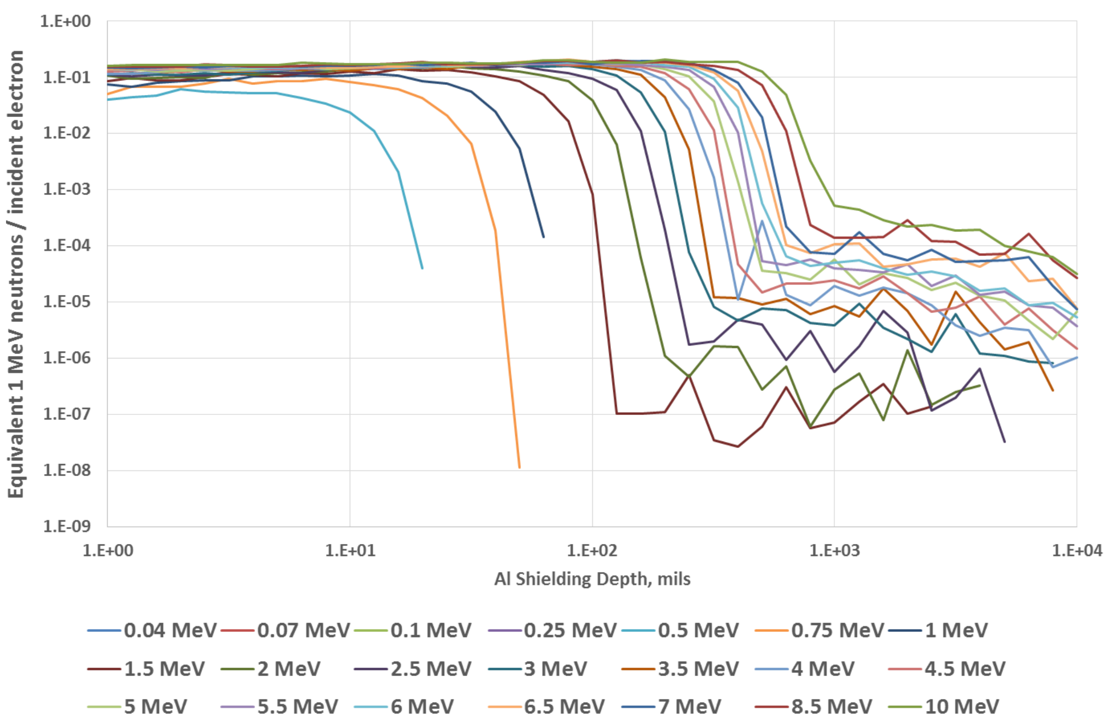

Figure 2. Equivalent 1-MeV neutrons for electrons of various energies incident on spherical Al shields around a gallium arsenide target

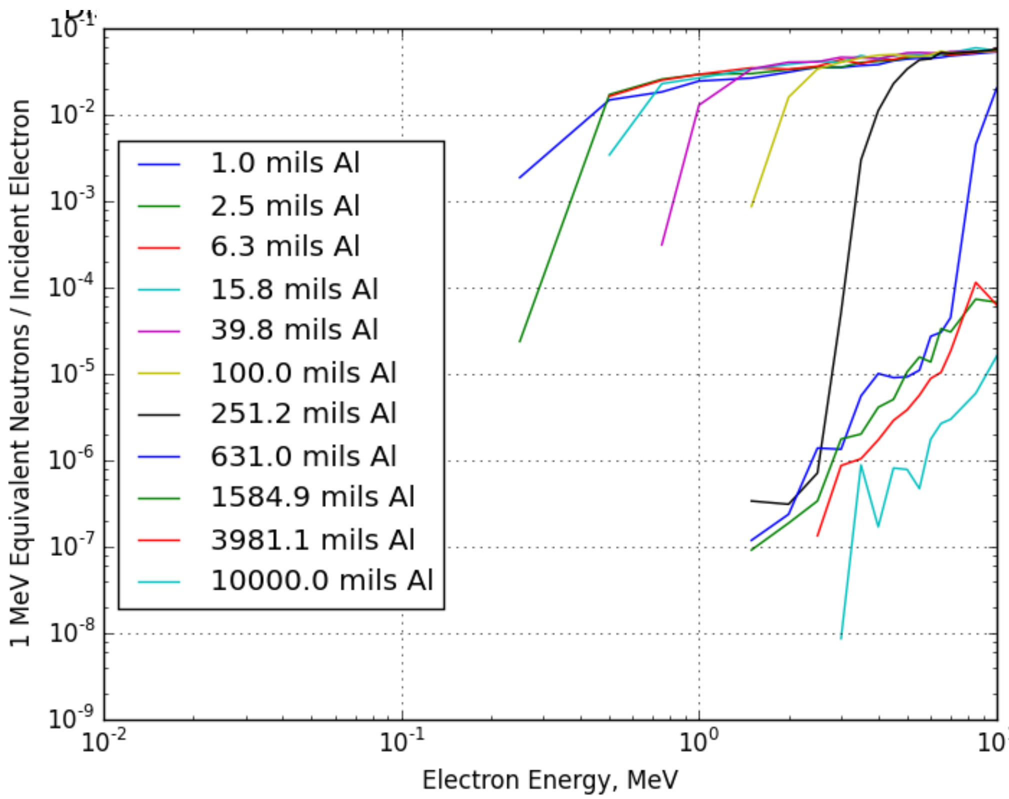

Figure 3. Displacement damage due to monoenergetic electrons through Al spheres incident on Si.

4. Assembling the Kernel

Mathematically, the kernel supplies information needed to perform the following integral:

$$j_n(T) = \int_0^\infty j_e(E)K(E,T)dE, \quad (4)$$

where $j_n(T)$ is the equivalent 1-MeV neutron fluence as a function of depth T, and $K(E,T)$ is the Green's function, i.e., the neutron fluence when $j_e(E)$ is a Dirac delta function $\delta(E - E')$. The kernel accounts for three different factors: the degradation of the electron spectrum as it passes through the aluminum shielding, the displacement damage the resulting electrons do in Si or GaAs, and the conversion of that damage to equivalent neutron fluence via NIEL scaling. All of these factors are accounted for by MULASSIS, except the last one, which is done in a post-processing script.

To assemble the kernel, we read in the post-processed MULASSIS outputs to build up the K matrix:

$$K(E_k, T_i) = j_n(T_i)\{\delta(E - E_k)\}, \quad (5)$$

where the right-hand side is the post-processed MULASSIS output equivalent fluence of 1-MeV neutrons for depth T_i and monenergetic electron energy E_k.

The AE9/AP9 kernel then approximates the equivalent neutron fluence integral as a sum:

$$j_n(T_i) = \int_0^\infty j_e(E)K(E,T_i)dE \approx \sum_k j_e(E_k)K(E_k,T_i)\Delta E_k. \quad (6)$$

The kernel standard [*O'Brien and Whelan*, 2015] allows the transform matrix stored in XML to include the ΔE_k factor in the matrix or to have ΔE_k computed at runtime. In this case, we elect to have ΔE_k computed at runtime. Therefore, we set the XML kernel file's ApplyDeltaE parameter to "true," thus causing the AE9/AP9 application to apply the ΔE_k factor at runtime.

The kernel's energy and depth grids are taken directly from the MULASSIS runs as described in Section 0. The depth grid is supplied in units of mils Al, which the AE9/AP9 application can convert to other shielding units. The AE9/AP9 application can also convert from Al to other shielding materials by assuming equivalent effects for equivalent mass density. However, this equivalence assumption is less accurate for electrons than for protons passing through different shielding materials.

5. Verification

To demonstrate the electron displacement damage kernel, we compute the displacement damage versus depth for the electron fluence spectrum shown in Figure A2 in the appendix, which is the fluence for ten years in the orbit of a GPS satellite. That spectrum is an integral spectrum, so we have to numerically differentiate it. We do this by first computing the numerical derivative of the log fluence with log energy, and then converting that analytically into the derivative of fluence versus energy via the chain rule. The differential fluence is the negative of the derivative of the integral fluence with respect to energy.

We also set up MULASSIS to run the same electron spectrum, first with 10^6 and then with 10^7 particles at each depth with energies sampled from the entire spectrum. We reran at the 10^7 particle count to determine whether the shorter simulation was systematically missing some damage. Figure 4 shows the results of the calculations. The MULASSIS run with 10^6 electrons exhibits some statistical fluctuations at all energies and is typically lower than the kernel. At 10^7 electrons, the statistical fluctuations are largely gone, but MULASSIS is still slightly below the kernel. It is plausible that even

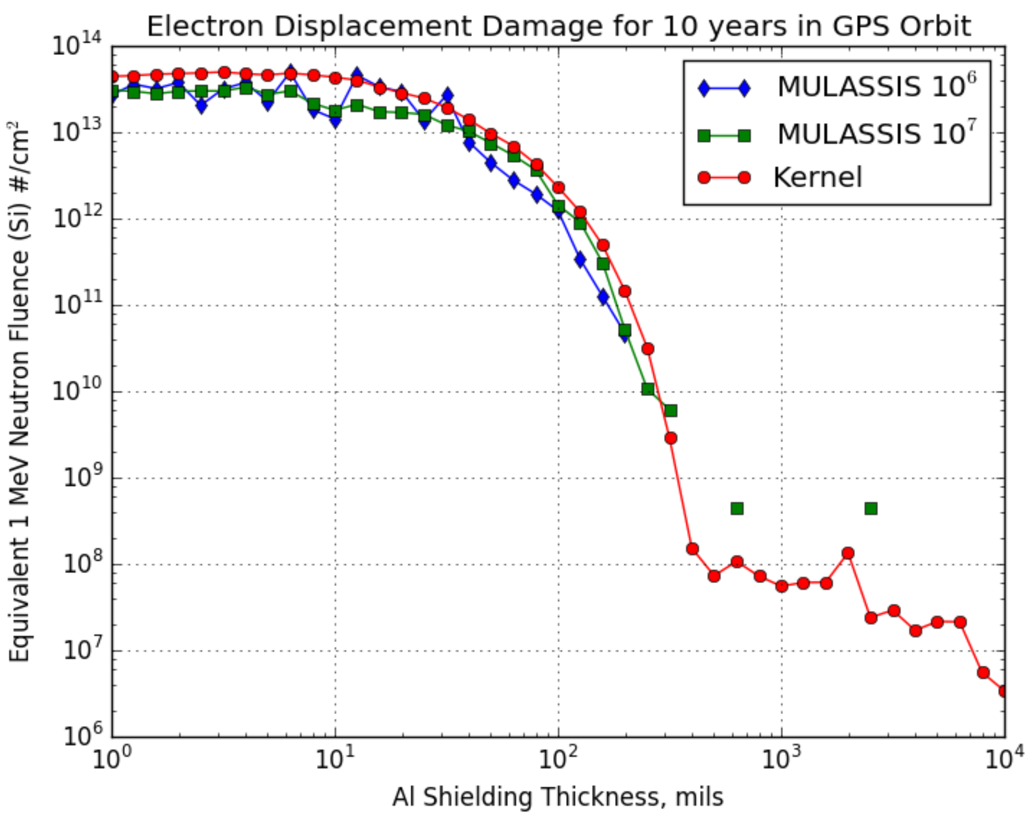

Figure 4. MULASSIS and Kernel calculations of displacement damage vs depth in Al for Si targets, for 10 years in GPS orbit as in Figure A2.

longer MULASSIS runs would further improve the agreement. However, as our goal is a conservative estimate, we are satisfied with the kernel performance. We note that the kernel can resolve damage at thicker depths (>300 mils) better than the individual MULASSIS runs because the kernel was built with 10 million electrons at each energy, whereas the MULASSIS runs with the GPS spectrum had 10 million electrons total over all energies. Figure 5 shows qualitatively similar behavior for a GaAs target.

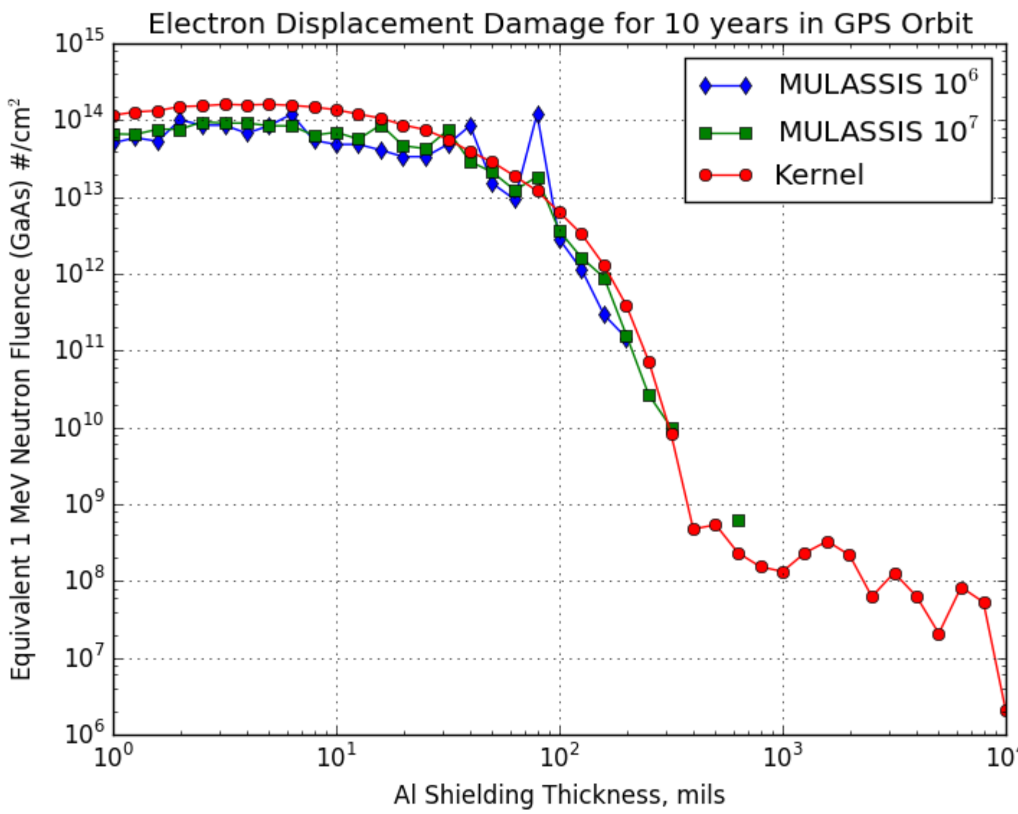

Figure 5. MULASSIS and Kernel calculations of displacement damage vs depth in Al for GaAs targets, for 10 years in GPS orbit as in Figure A2.

6. Summary

This report describes a conservative approach to estimating the displacement damage caused by electrons incident through spherical aluminum shields on silicon and gallium arsenide targets. We capture the approach in AE9/AP9 kernels, which are XML files that future AE9/AP9 applications will read in at runtime and use to convert from an electron spectrum to an equivalent fluence of 1-MeV neutrons. For a specific Al shielding thickness, the resulting equivalent neutron fluence incident directly on the device would produce at least as much degradation from displacement damage effects as would the supplied electron spectrum of interest incident on the shielding.

Computationally, our approach builds on the MULASSIS tool, which is itself a wrapper for the Geant4 radiation transport code. MULASSIS processes the incident electron spectrum through the shielding and then tabulates the displacement damage dose at the surface of the target volume. We then convert this dose to an equivalent 1-MeV neutron fluence by assuming, conservatively, that NIEL scaling applies directly for electrons in the same manner as it does for equating the effects of neutrons and protons on devices. That is, the conversion assumes that a given amount of displacement damage dose from electrons causes the same degradation in the device as the same amount of displacement damage dose from protons or neutrons. The Appendix describes the rationale for this approximation, and why it is conservative. We perform this MULASSIS calculation for several monoenergetic electron spectra and a range of shielding depths. From these results, we create the Green's function, or impulse response function, which we can convolve with an incident electron spectrum to obtain the equivalent 1-MeV neutron fluence versus shielding depth.

Although solid spherical shielding geometry is uncommon in space applications, it, too, is a conservative approximation for more realistic geometries (slabs, rectilinear boxes). Thus, the kernel can be used to estimate the approximate upper limit on shielding needed to reduce the electron displacement damage to an acceptable level for the parts and technologies in use.

7. References

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Appendix—Conservative Approach to Determining Equivalent Displacement Damage Fluence for Trapped Electrons in Earth Orbit

This appendix describes a conservative approach to determining the contribution of energetic trapped electrons to the equivalent displacement damage fluence experienced by electronics in space.

The three key contributors to displacement damage produced in electronics in space are trapped protons, solar protons, and trapped electrons. (Manmade radiation environments can also contribute to displacement damage production but, for simplicity, are not considered here.) For displacement damage, it is common practice to express that space radiation environment for radiation requirements specifications in terms of an equivalent fluence of 1-MeV neutrons versus Al shielding thickness. That is, for a given shielding thickness the specified fluence of 1-MeV neutrons would produce the same degradation as the individual contributors in space (i.e., trapped electrons and protons and solar protons). The unshielded trapped electron and proton environments for a given Earth orbit can be determined using AE9 and AP9, respectively [*Ginet et al.,* 2013]. The unshielded solar proton environment can be determined using ESP/PSYCHIC [*Xapsos et al.*, 2000]. Those unshielded environments must then be transported through various thicknesses of Al shielding (typically for solid spherical shielding) using an appropriate transport code.

Trapped and solar protons are considered first. After transport through a specific shielding thickness, the result can be expressed as a differential spectrum of proton fluence versus proton energy, assuming for simplicity that the trapped and solar contributions are combined into a single spectrum. The displacement damage (or nonionizing) dose D_d is then given by the integral in Eq. (1). (It is also assumed that an incident proton passes through the target device without losing a significant fraction of its energy so that a constant NIEL value can be employed in dose calculations for each incoming particle.) The resulting D_d gives a total displacement damage dose for trapped and solar protons for a specific shielding thickness. Repeating that process for many shielding thicknesses then yields a nonionizing dose versus shielding thickness curve, $D_d(T)$, for an orbit of interest. Using Eq. (2), that curve can be converted to an equivalent fluence of 1-MeV neutrons by NIEL scaling [discussed in *Srour and Palko*, 2013, and references therein]. NIEL scaling works well for the case of comparing neutron- and proton-induced displacement damage effects in Si and GaAs devices. That is, arbitrary spectra of neutrons and protons will produce the same deposited displacement damage dose will, to first order, also produce the same device degradation.

As discussed in *Srour and Palko* [2013, and references therein], in general, the effectiveness of energetic electrons in damaging the properties of Si and GaAs devices differs from the degradation produced by incident protons and neutrons. This situation is further complicated by the fact that the relative effectiveness of electrons varies for different electrical properties. As an extreme example, the increase in thermally generated dark current produced in a Si device by a unit fluence of incident 1-MeV neutrons is about a factor of 50 greater than that produced by a unit fluence of 1-MeV electrons. As another example, protons and neutrons are more effective than electrons in degrading minority-carrier lifetime, which is directly applicable to radiation-induced gain degradation in bipolar transistors. That statement especially applies to devices operated at relatively low injection levels. At relatively high injection levels, however, defects produced by energetic electrons can be comparable to protons and neutrons in terms of their effectiveness in degrading carrier lifetime (and bipolar transistor gain). As a further example, irradiation of Si material and devices to relatively high particle fluences can result in carrier concentration changes. As discussed in *Srour and Palko*, there is no indication that protons and neutrons are more effective than electrons in producing such changes.

The above key examples for Si devices indicate that energetic electrons are much less effective than protons and neutrons in degrading solid-state devices for some properties (i.e., thermally generated dark current and carrier lifetime at low injection levels) but are comparable in their effectiveness for other properties (i.e., carrier lifetime at high injection levels and carrier concentration). These observations suggest a simplified, conservative approach to estimating the contribution of trapped electrons in space to displacement damage in terms of determining an equivalent fluence of 1-MeV neutrons. The approach suggested here is to treat the displacement damage dose deposited by trapped electrons as being equal in its effectiveness to the dose deposited by protons or neutrons. In this approach, the electron D_d is determined and handled in the same manner as described earlier for protons, i.e., using Eq. (3) to compute D_d and Eq. (2) to convert to equivalent 1-MeV neutrons. That is, the electron D_d can be added directly to the proton D_d at that thickness with no effectiveness factor being applied in the electron case. Then Eq. (2) can be used to obtain the equivalent overall neutron fluence $j_n(T)$ (i.e., including protons and electrons). Such an approach will, in general, be conservative in some cases and realistic in others, depending on the specific device property and operating conditions being considered.

A practical example is now provided to examine, at least qualitatively, the impact of using this conservative approach to determining the electron contribution to an equivalent neutron fluence. A GPS orbit (20,200 km altitude, 55^{o} inclination) over a 10-year mission is used to illustrate some key points. Radiation environment information presented here was determined at the SPENVIS website (*www.spenvis.oma.be)* using AE8max [*Vette*, 1991], AP8min [*Sawyer and Vette*, 1976], and the JPL 1991 [*Feynman et al.*, 1993] solar proton model with a 90% confidence level. The trapped and solar proton environments for that GPS mission are shown in Figure A1 in terms of integral proton fluence versus proton energy. For proton energies greater than about 2 MeV, solar protons dominate. Figure A2 presents the trapped electron environment for the GPS mission. Figure A3 shows proton NIEL [*Jun et al., 2003*] and proton range *(www.srim.org)* in Si versus proton energy. Figures A4 and A5 present electron NIEL in Si [*Jun et al., 2009*] and electron range in Al [*Berger et al., 1984*] versus electron energy, respectively.

In this example Figure A2 indicates that there are negligible trapped electrons present with energy greater than about 5 MeV. At that energy, the electron range in Al shielding is about 450 mils (from Figure A5), which might suggest that such electrons potentially could produce significant displacement damage in reasonably well-shielded devices. However, electron fluences for energies near 5 MeV are very low. The displacement damage dose deposited by higher-energy electrons generally will be much less than that deposited by solar protons at comparable shielding thicknesses.

For relatively thin shielding (e.g., 100 mils Al and below), D_d due to electrons can be significant. However, most electronics used on space systems have significantly more shielding (e.g., 200 to 400 mils Al). The point is that, at least qualitatively, the conservative assumption of treating the electron

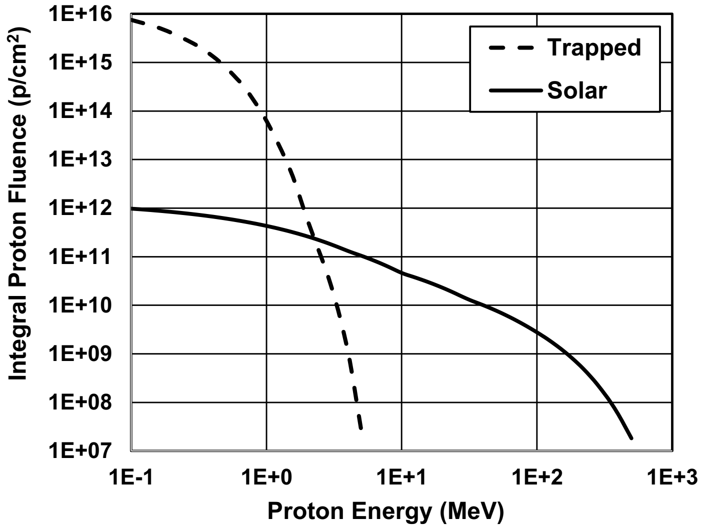

Figure A1. Integral trapped and solar proton fluences versus proton energy for 10 years in GPS orbit (computed with SPENVIS website, *www.spenvis.oma.be*, see text for details).

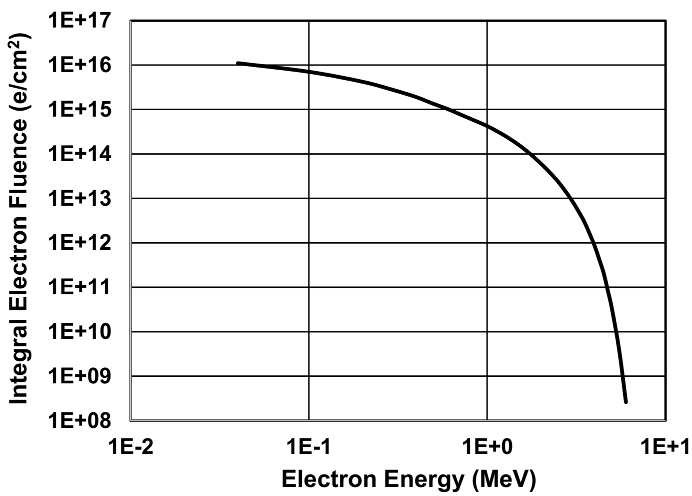

Figure A2. Integral trapped electron fluence versus electron energy for 10 years in GPS orbit (computed with SPENVIS website, *www.spenvis.oma.be*, see text for details)

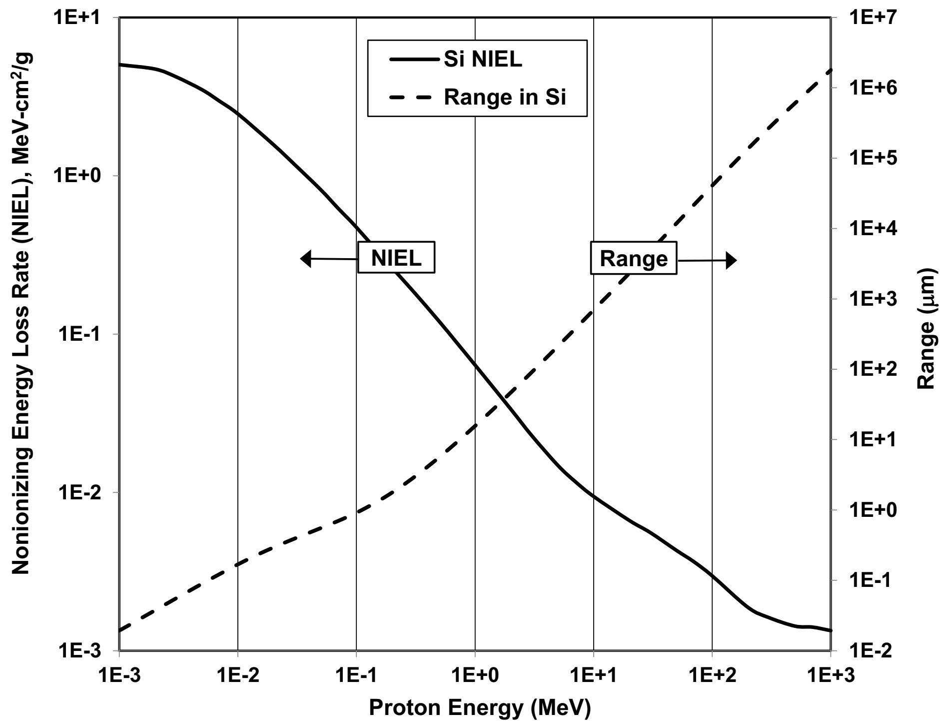

Figure A3. NIEL [*Jun et al., 2003*] and range (*www.srim.org)* for protons in silicon. (Note regarding units: 1 mil = 25.4 µm.)

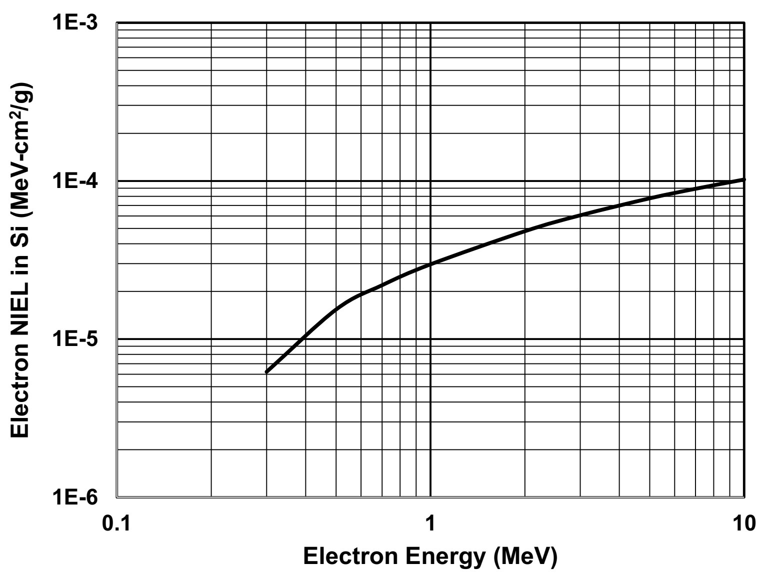

Figure A4. Electron NIEL in Si versus electron energy [*Jun et al., 2009*].

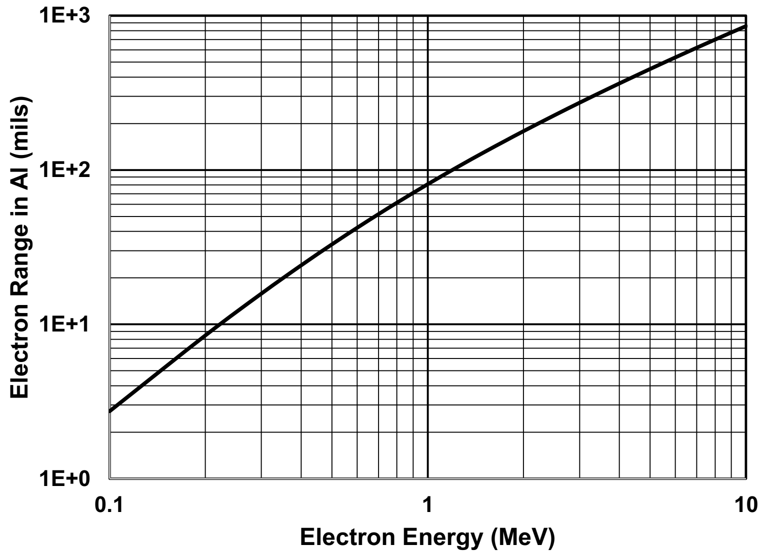

Figure A5. Electron range in Al versus electron energy [*Berger et al., 1984*].

dose as having the same effectiveness as the proton dose is not expected to impose an unnecessary penalty on electronics with typical shielding. The only case presently envisioned in which overestimating the electron dose might be too restrictive is for devices in which radiation-induced dark current is an important consideration. That restrictive situation would only occur if the shielding for such devices is relatively thin (e.g., less than 100 mils), which would be unusual and, if necessary, could be dealt with on a case-by-case basis by determining device-specific electron degradation behavior. This scenario emphasizes the importance of specifying the environment (particle fluxes and fluences) as the requirements in program documents. Dose-depth and damage-depth curves can be provided in program documents as supporting information meant to be used to demonstrate that a given design meets the requirements without having to do a more detailed (and less conservative) analysis of shielding and sensitivities. Making the dose-depth and damage-depth curves themselves the requirement would necessitate a waiver whenever a design needs to loosen one of the conservative idealizations in those curves (e.g., by accounting for non-spherical shielding, or addressing device-specific electron displacement damage effects).

In general, the NIEL and range information for electrons and protons shown in Figures A3 through A5 can be used in making more quantitative comparisons of the relative importance of electron and proton displacement damage doses deposited for different shielding thicknesses.

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AE9/AP9 Electron Displacement Damage Kernels

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