SPENVIS IMPLEMENTATION OF END-OF-LIFE SOLAR CELL CALCULATIONS USING THE DISPLACEMENT DAMAGE DOSE METHODOLOGY

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INTRODUCTION

This paper presents a method for using the SPENVIS on-line computational suite to implement the displacement damage dose (D_d) methodology for calculating end-of-life (EOL) solar cell performance for a specific space mission. This paper builds on our previous work that has validated the D_d methodology against both measured space data [1,2] and calculations performed using the equivalent fluence methodology developed by NASA JPL [3]. For several years, the space solar community has considered general implementation of the D_d method, but no computer program exists to enable this implementation. In a collaborative effort, NRL, NASA and OAI have produced the Solar Array Verification and Analysis Tool (SAVANT) under NASA funding, but this program has not progressed beyond the beta-stage [4]. The SPENVIS suite with the Multi Layered Shielding Simulation Software (MULASSIS) contains all of the necessary components to implement the D_d methodology in a format complementary to that of SAVANT [5]. NRL is currently working with ESA and BIRA to include the D_d method of solar cell EOL calculations as an integral part of SPENVIS. This paper describes how this can be accomplished.

Solar Cell Response to the Space Radiation Environment

As an introduction to our discussion of a methodology for calculating solar cell EOL performance in space radiation environment, we will briefly review the basic mechanisms controlling the response of a solar cell in the space radiation environment. This review will be used to setup the problem to be solved by the computational methodology.

The space radiation environment consists of a spectrum of electrons and protons that is (to a close approximation) isotropic and omnidirectional. The spectral content and intensity of the radiation environment depends on the specific orbit. With the orbit specified, the environment can be calculated using existing models like the NASA AP8 and AE8 models. As an example, the differential proton and electron spectra for a circular orbit having a 5093 km radius at a 57^o inclination are shown in Figure 1. These data represent the radiation environment that a solar cell will be exposed to in this particular orbit. Before these particles reach the solar cell active region, they must pass through any materials in contact with the solar cells, like the solar array substrate on the rear of the cell and the coverglass on

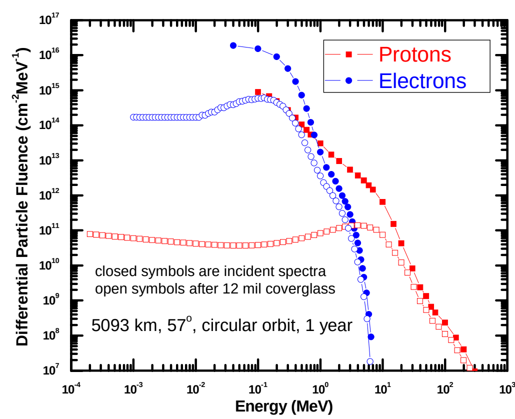

Figure 1: Proton and electron spectra for the specified Earth orbit. The solid symbols represent the incident particle spectra. The open symbols represent the spectra after attenuation by shielding.

the front of the cell. These materials partially shield the solar cell since they tend to attenuate the incident spectra, and these shielding effects must be accounted for in an EOL performance calculation. As an example, the attenuated spectra assuming a 12 mil thick piece of coverglass are also shown in Figure 1.

The solar cell radiation response is different for electron as compared proton irradiation, and the cell response is dependent upon the energy of the irradiating particle. To illustrate typical solar cell radiation response, we take the extensive single junction (SJ) GaAs ground test dataset created by Anspaugh of JPL [6] shown in Figure 2. In this figure and those to follow, the data measured after irradiation are plotted normalized to their pre-irradiation value. These data show that proton irradiation is more damaging than that for electron. The proton degradation rate increases with decreasing energy while the opposite is true for electron irradiation. These data also give a good description of a typical ground test dataset, namely a series of monoenergetic, normally incident irradiations performed on bare solar cells. Since the space environment can be approximated by an omnidirectional spectrum of particles incident upon shielded solar cells, a method is needed by which these data can be used to predict the on orbit solar cell performance.

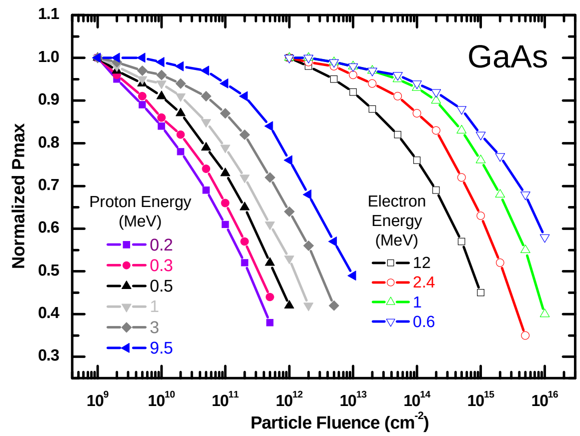

Figure 2: Proton and electron irradiation data measured in a SJ GaAs solar cell. The cell response varies with particle and particle energy.

There are two methodologies currently available [3] to perform on-orbit solar cell performance predictions. One is the Equivalent Fluence Method developed by JPL. This method has been incorporated into SPENVIS. The other is the Displacement Damage Dose (D_d) Method developed by NRL. The purpose of this paper is to describe how the D_d method can also be implemented through SPENVIS.

Description of the Displacement Damage Dose Method

In this section, a brief overview of the D_d method is given. The D_d method entails two primary parts. One part deals with the analysis of the ground test solar cell radiation data while the other part deals with the analysis of the space radiation environment. Both parts are based on a physical quantity referred to as the nonionizing energy loss (NIEL). When an irradiating particle interacts with matter, energy is transferred to the target lattice by two mechanisms: ionizing and nonionizing events. It is nonionizing events that most strongly control the radiation response of most space solar cell technologies. NIEL is the rate at which energy is transferred from the irradiating particle to the target lattice through nonionizing events. NIEL is a calculated quantity, and the values calculated for typical space solar cell materials are shown in Figure 3. The total absorbed nonionizing dose is referred to as displacement damage dose (D_d) and is expressed in units of MeV/g. This quantity is analogous to ionizing dose typically expressed in units of Rad (i.e. 100 erg/g)

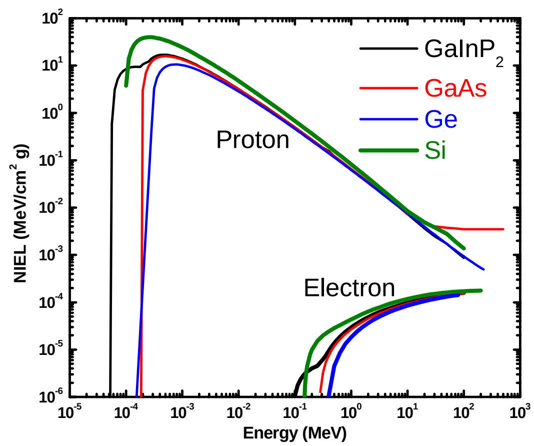

Figure 3: Nonionizing energy loss (NIEL) values calculated for various space solar cell materials.

Solar Cell Data Analysis

Considering the solar cell data analysis part of the D_d methodology, the goal is to correlate the degradation data measured after exposure to different particles at different energies. Within the D_d methodology, this correlation is achieved by analyzing the radiation data in terms of the value of D_d equivalent to the specific irradiation. The equivalent value of D_d is determined as the product of the particle fluence ($\Phi(E)$) with the appropriate NIEL value according to the following expression:

$$D_d(E) = \Phi(E) \bullet \mathrm{NIEL}(E)\left[\frac{\mathrm{NIEL}(E)}{\mathrm{NIEL}(E_{ref})}\right]^{n-1} \qquad \textbf{Equation 1}$$

The quantity in the square brackets is included to account for cases where the solar cell damage coefficients for a given parameter do not vary linearly with NIEL as a function of energy. This is similar to the quality factor applied in ionizing dose analyses. For solar cell analysis, this is only an issue for electron irradiation data. Proton irradiation data have been consistently shown to vary linearly with NIEL. The n parameter in the exponent is an experimentally determined parameter, and E_{ref} is an arbitrary reference energy typically set to 1 MeV. Returning to the SJ GaAs data of Figure 2, with E_{ref}=1 MeV, a value of n = 1.7 has been found to describe the data for P_{max} degradation well. The data correlated in terms of D_d are shown in Figure 4. The electron data are given in terms of 1 MeV electron equivalent D_d.

The correlation of the data in terms of D_d is seen to reduce the full degradation data set to two curves, one for the electron and the other for the proton irradiation data. The solid curves shown in Figure 4 represent fits of the data to the following expression:

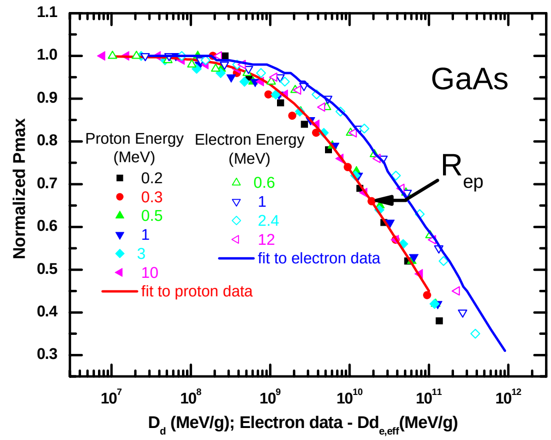

Figure 4: SJ GaAs degradation data correlated in terms of D_d.

$$\frac{P(D_d)}{P_0} = 1 - C \cdot \log\left[1 + \frac{D_d}{D_x}\right] \quad \textbf{Equation 2}$$

In this expression, P_o is the pre-irradiation value and C and D_x are the fitting parameters. Typically, the fits can be performed with a common C parameter used to describe both the electron and proton data, while an individual D_x value is determined for each (designated by D_{xe} and D_{xp} for the electron and proton datasets, respectively). This gives four parameters required to describe a particular dataset: C, D_{xe}, D_{xp}, and n.

As is apparent in Figure 4, the electron and proton data, when correlated in terms of D_d, do not necessarily fall on the same curve. Therefore, an electron to proton damage equivalency factor (R_{ep}) is required to collapse the electron data onto the proton curve. R_{ep} can be determined graphically from the separation of the electron and proton curves along the D_d axis or as the value of D_{xe}/D_{xp}. Thus, in total, within the D_d method, five parameters are required to parameterize the radiation response of a specific solar cell technology: C, D_{xe}, D_{xp}, n, and R_{ep}.

Analysis of the space radiation environment

Considering the space radiation environment analysis part of the D_d methodology, the first step is to determine the particle spectra that emerge from the backside of the shielding materials and are, thus, directly incident upon the solar cell active region. Within the D_d methodology, these spectra are calculated based on knowledge of the incident spectra and the material properties of the shielding materials, and the spectra emerging from the shielding materials is referred to as the slowed-down spectra. As implemented within the SPENVIS web suite, the slowed-down spectra are calculated using the MULASSIS code. Examples of slowed-down spectra have been shown in Figure 1.

The next step in the analysis of the space radiation environment is to reduce the slowed-down spectra to an equivalent value of D_d. This is accomplished by expanding Eq. 1 to an integral over energy. The integration is performed separately for the electron and proton spectra, and the results are summed using the R_{ep} factor as shown in Eq 3.

$$D_d = \int \frac{d\Phi(E_p)}{dE_p} \cdot NIEL(E_p) dE_p + R_{ep} \int \frac{d\Phi(E_e)}{dE_e} \cdot NIEL(E_e) \left[\frac{NIEL(E_e)}{NIEL(1\,MeV)}\right]^{n-1} dE_e \quad \textbf{Equation 3}$$

In Eq. 3, $d\Phi/dE$ refers to the differential particle spectrum, and the reference energy for the electron contribution has been set to 1 MeV. Because values of n and R_{ep} are required in this calculation, a specific cell technology must be specified at this point in the analysis.

With the equivalent value of D_d determined from Eq. 3, one simply returns to the ground test data, expressed in terms of D_d, and reads the expected EOL degradation factor (Figure 4), which completes the analysis. The remaining sections of this paper will describe how this can be accomplished using SPENVIS.

Implementation of the Displacement Damage Dose Method in SPENVIS

Step 1: Determine Incident Particle Spectra

The first step in the D_d methodology as implemented within SPENVIS is to determine the incident particle spectra. This process begins with the orbit generator windows which are pictured in Figure 5. In these windows, the user enters the orbital parameters for the mission of interest. With the orbital parameters of the mission now defined, the incident electron and proton spectra are calculated within SPENVIS using calls to AP8 and AE8, for example (Figure 6). SPENVIS does have other radiation models to chose from such as that obtained from SAMPEX and CRRES.

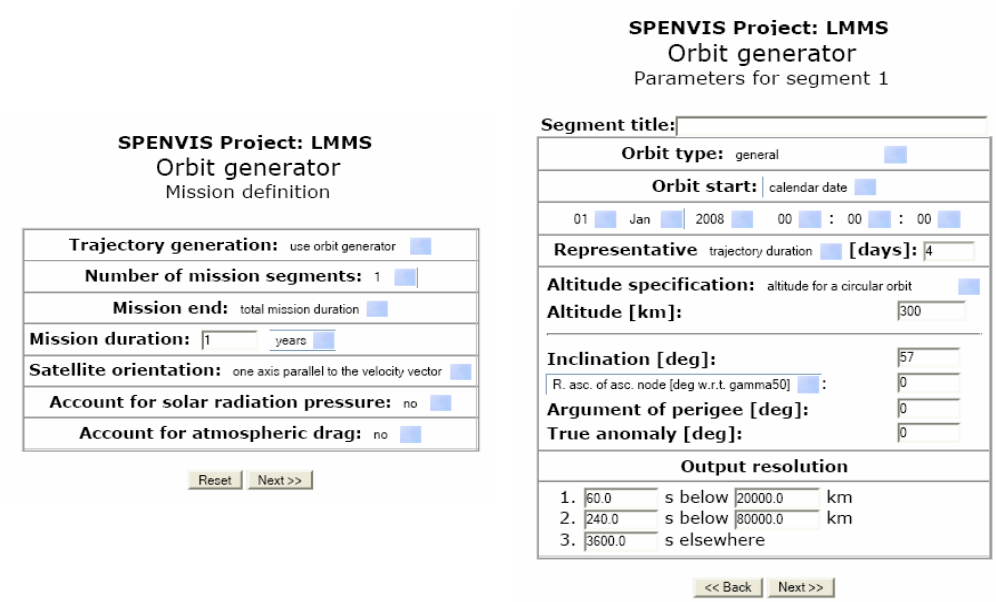

Figure 6: These are the SPENVIS orbit generator windows. These windows allow the user to define the orbit for the mission of interest. This is the first step in defining the space radiation environment.

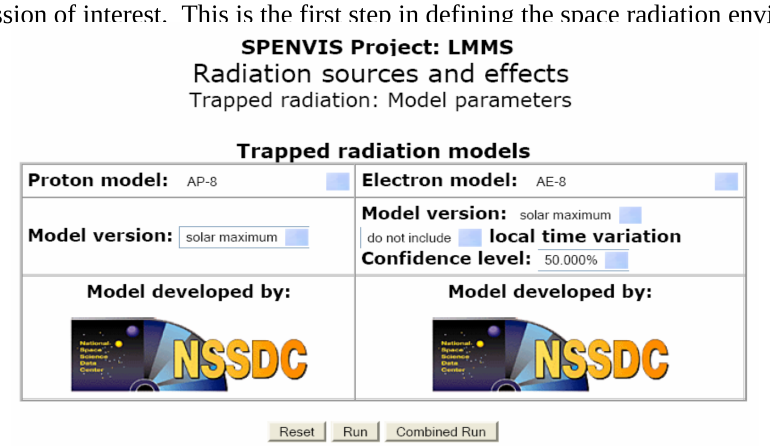

Figure 5: This is the Radiation Sources and Effects window within SPENVIS where calls are made to AP8 and AE8 to calculate the incident particle spectra for the given mission.

Step 2: Choose a Solar Cell Technology

The second step in this analysis is to choose a solar cell technology. This choice sets the radiation degradation parameters: C, D_{xe}, D_{xp}, n, and R_{ep}. This section of SPENVIS is currently under construction. The section will consist of a drop-down menu choice of possible technologies. The possible technologies will be those for which data are currently available for analysis. These cells include the SJ GaAs data shown in Figure 2 [6], Emcore triple-junction (3J) cells (Figure 7) [7], Spectrolab 3J cells (Figure 8) [8], and CIGS cells (Figure 9) [9]. There will also be a user input option where the parameters can be entered manually.

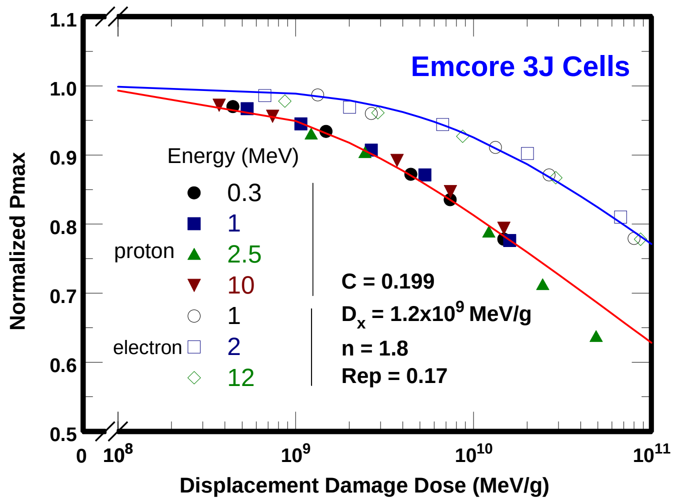

Figure 8: Emcore radiation data from the ATJ 3J solar cell [7] analyzed as a function of D_d. Some of the degradation parameters are shown in the figure, and these parameters will be included in SPENVIS. The D_x value shown is the D_{xp} parameter.

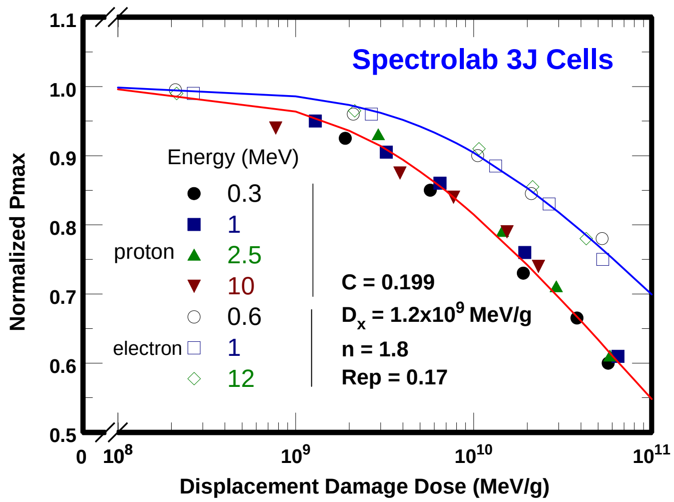

Figure 7: Spectrolab radiation data for a 3J solar cell optimized for EOL [8] analyzed as a function of D_d. Some of the degradation parameters are shown in the figure, and these parameters will be included in SPENVIS. The D_x value shown is the D_{xp} parameter.

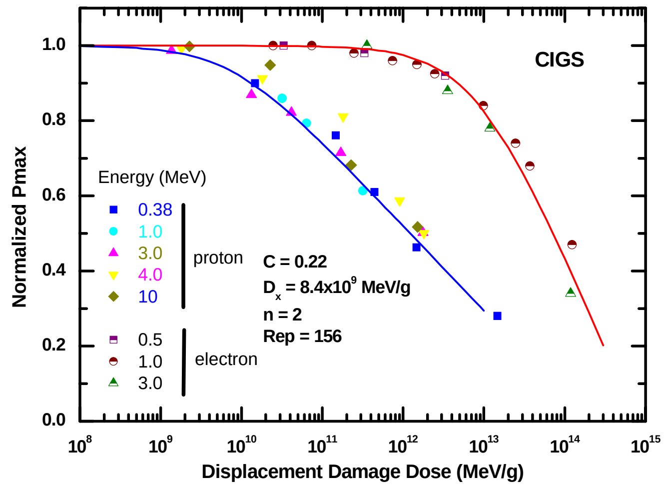

Figure 9: CIGS solar cell data plotted as a function of D_d. These data come from several sources as summarized in [9].

Step 3: Determine the Slowed-down Spectra and Equivalent D_d ***value***

The third step in this analysis is to determine the slowed-down spectra. These calculations are performed using the MULASSIS code. The MULASSIS calculation begins with entering information about the shielding materials through the Geometry window (Figure 10). Several layers (up to 20) may be specified within a single geometry to accommodate the various materials comprising the array substrate and any coatings and adhesives on the coverglass. The second MULASSIS window allows definition of the source particle spectrum, which can be set to accept the spectrum generated in Step 1, and the spectrum can be analyzed as isotropic (Figure 11). The third window allows the choice of the analysis type (Figure 12). The "Fluence" analysis option produces the slowed-down spectra as the output. The "NIEL" analysis option performs the integration of the slowed-down spectrum with the NIEL to produce the equivalent value of D_d for the given mission using the R_{ep} and n parameters for the specific solar cell of choice.

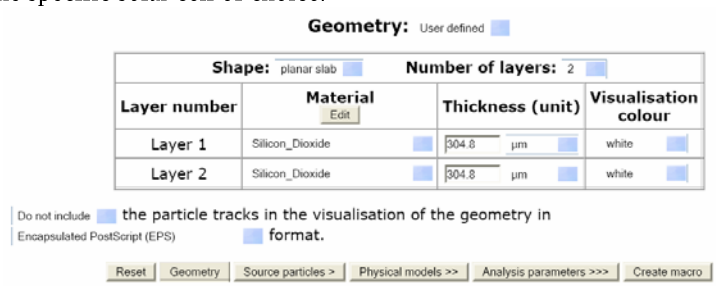

Figure 10: This is the first window within the MULASSIS calculations where the shielding layers are defined. Multiple layers (up to 20) may be defined to accommodate the multiple layers of the solar array substrate and the coverglass with coatings and adhesive.

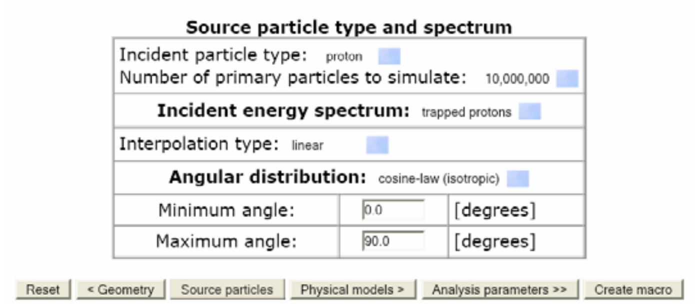

Figure 11: This is the second MULASSIS window where the irradiating particle source is defined. This can be set to accept the spectra generated in the orbit generation steps (**Figure 5**). The spectra can be modeled as omnidirectional.

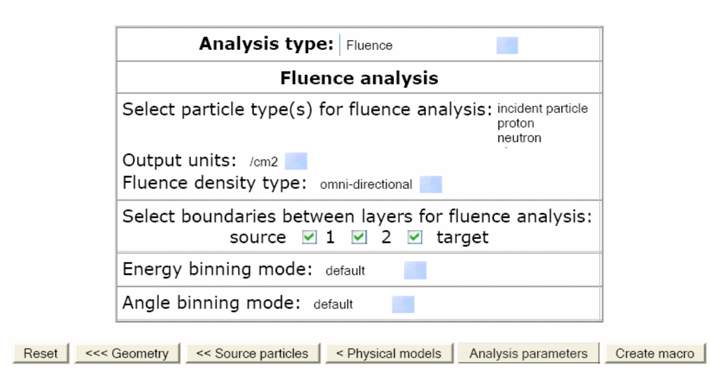

Figure 12: The third MULASSIS window allowing choice of the analysis type. "Fluence Analysis" produces the slowed-down spectra as the output. A "NIEL Analysis" option is also available that performs the integration of the slowed-down spectrum with the NIEL to produce an equivalent value of D_d.

At this point in the discussion, it may be useful to address the accuracy of the SPENVIS calculations. This is done here by comparing the SPENVIS calculations with calculations performed using the SAVANT code. The SAVANT code has already been validated against calculations made using the equivalent fluence methodology implemented with the EQFLUX program [3] and against measured space data [2,3,4]. The slowed down spectra for the orbit considered in Figure 1 assuming a 12 mil coverglass are shown in Figure 13 where both MULASSIS and SAVANT calculations are shown. For the proton spectra, the data are seen to agree very well. There is some scatter in the MULASSIS data at low energies due to limited statistics in that energy range. This can be improved by increasing the number of incident particles. The Web-based version of MULASSIS is currently limited to 10^7 incident particles to limit individual user run-times. A stand alone version of SPENVIS is available that has no limit.

The electron spectra also agree well for energies above about 200 keV. For lower energies, the values calculated with MULASSIS are less than those determined from SAVANT. This is due to the method of calculation in each case. MULASSIS is a Monte Carlo computational algorithm, while SAVANT is an analytical calculation which uses stopping power data and applies the continuous slowing down approximation (CSDA). For electrons in this low energy range, the CSDA may not be valid, so the MULASSIS values may be more accurate. However, the appropriate method for calculating the electron slowed down spectrum in this energy range is currently a matter of discussion. In any event, this discrepancy between the electron data sets has only a slight effect on the solar cell degradation calculations since the NIEL decreases very rapidly for electron energies below 200 keV (Figure 3).

The equivalent values of D_d for the proton and electron slowed-down spectra determined by SPENVIS and SAVANT are given in Table 1. In the proton case, the D_d values agree to within < 2%. In the electron case, the MULASSIS D_d value is about 10% less than the SAVANT Dd value, which is well within the typical uncertainty for dosimetry measurements. Therefore, since both computational methods use the same solar cell degradation curves, it can be concluded that the SPENVIS and SAVANT calculations are in agreement.

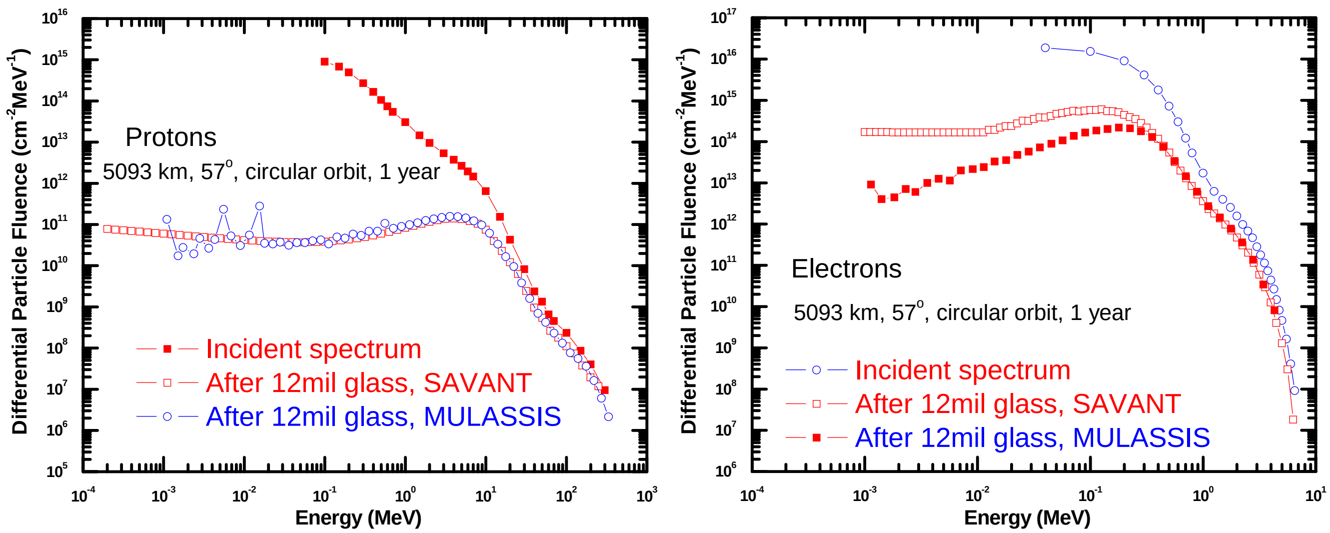

Figure 13: Slowed-down spectra data calculated for the indicated Earth orbit using the SAVANT and MULASSIS codes. These comparisons serve to validate the accuracy of the SPENVIS calculations against those of SAVANT.

Table 1: Comparison of equivalent D_d values for the slowed-down spectra shown in Figure 13 calculated using SAVANT and SPENVIS.

	D_d (MeV/g) (Protons)	D_d (MeV/g) (Electrons)
MULASSIS	3.8E+10	5.4E+08
SAVANT	3.3E+10	6.0E+08

Step 4: Determine the EOL Solar Cell Performance

The final step in this analysis is to calculate the predicted EOL solar cell performance. This is done by taking the equivalent value of D_d determined in Step 3 and substituting it into Eq. 2. This is a straight-forward task that will be implemented in a SPENVIS window that is currently being developed. In its final version, SPENVIS will allow the calculation to be performed as a function of time in orbit so that the power profile of a specific mission can be predicted.

Summary

This paper has presented a description of how the displacement damage dose solar cell radiation response analysis methodology can be implemented within the SPENVIS web suite. Almost all the necessary components to do this currently exist within SPENVIS, and those parts to be added involve relatively simple calculations. The website is currently being revised to include a separate interface window for the D_d implementation.

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