Effects of Secondary Particles on the Total Dose and the Displacement Damage in Space Proton Environments

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Abstract—MCNPX, a powerful Monte Carlo charged particle transport code, is introduced in this paper for space-radiation effect applications. By using MCNPX version 2.1.5, the enhancement of the total dose and the displacement damage due to secondary particles generated by the protons in the typical space radiation environments was assessed, then the results were compared to those obtained by the continuous slowing down approximation (CSDA) method. The comparison showed that the effects of the secondary particles were up to $\pm 7\%$ for the total dose and up to $\pm 25\%$ for the displacement damage when compared to the respective CSDA results in heavy shielding applications where trapped and solar protons dominate. Also presented in this paper is a method to compute the neutron/proton displacement cross sections by using MCNPX. The cross sections obtained show an excellent agreement with previously published values.

Index Terms—Displacement damage, nonionizing energy loss, secondary effects by protons, spallation reactions, total dose.

I. INTRODUCTION

SPACE radiation causes harmful effects on materials and electronics used in satellites. Both electromagnetic and corpuscular radiation is present in space. The origins of the electromagnetic radiation in space are either solar or galactic. Lower energy electromagnetic radiation (infrared, visible, and UV) impacts on the spacecraft design including passive and active thermal control system design, radiator sizing, material selection, power allocation, and/or solar array design, etc.

High-energy electromagnetic and corpuscular radiation include X-rays, $\gamma$-rays, solar flare particles, trapped (Van Allen radiation belts) electrons/protons, and galactic cosmic rays (GCR). The electronics and materials used in a satellite are required to be designed to withstand degradation due to this radiation over the mission lifetime of the satellite. The most common effects against which a satellite should be hardened are total dose, displacement damage, and single event effects (SEE). As the particles pass through the material, they lose their energy by atomic/nuclear interactions. The total energy deposition per unit mass is called the total dose, and the portion of energy deposition that displaces the atom from its lattice site is related to the displacement damage. An SEE occurs when a single ionizing particle event produces a burst of hole-electron pairs in a microelectronic circuit that is large enough to cause detrimental effects on the circuit.

As the energy of the incident particle becomes higher, a new nuclear interaction type, known as spallation reaction, starts to occur. Spallation refers to nuclear reactions that occur when energetic subatomic particles interact with an atomic nucleus. Spallation is viewed to take place in two stages. In the intranuclear cascade stage, the high energy incident particle undergoes a series of direct reactions inside the target nucleus. High-energy secondary particles (or small groups of nucleons and mesons) and low-energy cascade particles are ejected from the nucleus leaving the nucleus in a highly excited state. In the evaporation stage, the excited nucleus relaxes, primarily by emitting low energy “evaporation” neutrons [1]. The products of the spallation reaction that are important for the accurate assessment of the radiation effect includes, but is not limited to, secondary protons, neutrons, pions, deuterons, alphas, etc. Among the particulate space radiation, high-energy protons and other types of cosmic rays are potential candidates that can lead to spallation reactions. Two important questions from the satellite designer’s point of view are: in a typical space environment and shielding configuration, 1) what kind of secondary particles are possible and what are their relative fluxes? and 2) which particles are considered important when designing a satellite? These questions have not been easy to answer precisely, since there have not been any complete physics tools that can treat all possible secondary particles over wide energy ranges of concern in the general space radiation environment.

The main objective of this paper is to answer these two questions for long-term radiation effects in space, such as total dose and displacement damage. Thus, only the trapped and solar proton environment were considered as an input in this study. Other types of particles (e.g., the solar heavy ions, or GCRs) are not important in assessing the long term radiation effects in space because of their low populations or fluxes. This is true for orbits above lower LEOs [e.g., for Shuttle, Mir, and ISS (~400 km)] where GCR dose dominated by secondaries is an important factor.

There have been similar studies on this subject [2]–[4] using various physics tools available to them. In this paper, the recently developed Monte Carlo code, MCNPX version 2.1.5 [5] was chosen as the representative computational tool, because it is capable of treating the extensive charged particle transport by using either nuclear model calculation or nuclear cross section data, in addition to coupled neutron/photon and electron/photon...
transport. The results reported in this work can serve as one representative analysis of which previous and future works can be compared against.

During the course of the study, it was necessary to expand the existing neutron/proton displacement damage energy cross sections to higher energy range. A method to compute the damage cross sections is also presented, and it forms the second major part of this paper.

II. SPACE PROTON ENVIRONMENTS

The representative proton environments considered here are: 1) the NASA model for emission of solar protons (ESP) [6] and 2) the NASA AP8MIN model for trapped protons [7]. For the solar proton models, we used the seven active-year total-proton integral fluence with a 95% confidence level. No geomagnetic shielding was considered in the study. For the trapped proton, the integral flux obtained for the 600 nautical mile (~1110 km) altitude/90 degree inclination circular orbit based on the AP8MIN model was used. The AP8MIN model was chosen over the AP8MAX model for the worst case assessment. The spectra for both environments are shown in Fig. 1.

III. CALCULATIONS

In order to simplify the calculations and to draw a broader and more general conclusion, only the simple spherical geometry was considered in the study. The problem geometry consists of a 0.5-cm radius silicon sphere surrounded by various thicknesses of aluminum and by various thicknesses of tung-
Aluminum and tungsten were chosen as the representative light (low/medium atomic number) and heavy (high atomic number) shielding materials in this study, respectively. The shielding thicknesses ranged from 1.35 g/cm$^2$ to 8.10 g/cm$^2$ for either material. The source spectra defined above were assumed to be isotropically incident on the outer surface of the shielding material. Then, the volumetric total dose and displacement damage (in terms of the damage energy deposition) over the silicon region were computed using MCNPX, which is three-dimensional (3-D) Monte Carlo code, and capable of treating the following particles: neutrons, anti-neutrons, photons, electrons, positrons, muons, anti-muons, electron neutrinos, anti-electron neutrinos, protons, anti-protons, positive pions, negative pions, neutral pions, positive kaons, negative kaons, short K-0s, long K-0s, deuterons, tritons, helium-3s, and alphas. Therefore, it was possible to compute the radiation effects resulting from a broad range of the secondary particles produced by interactions of the primary source protons with the shielding material.

Obviously, the work reported in this paper is just one example of many possible MCNPX applications for particle transport calculations. Interested readers are advised to see [5] and the references therein for their specific applications and for a better understanding of the MCNPXs treatment for low- to high-energy interaction physics.

### IV. RESULTS AND DISCUSSION

We computed the particle fluxes (both for the secondary and for the primary), the total dose, and the displacement damage energy deposition. The results for each quantity are discussed in this section.

#### A. Flux

The track-length estimation (F4 tally in MCNPX) of the fluxes was obtained for the following particles: neutrons, protons, electrons, muons, pions, deuterons, tritons, helium-3s, and alphas. Table I summarizes the typical results for the 2-cm aluminum or 0.2798-cm tungsten shielding case. All numbers were normalized per one source proton incident on the surface, and the total 12 million protons were simulated for each case. Both spectra showed that a broad range of secondary particle production is possible, even though the computed production rates for some of the particles are statistically unreliable. However, the order of magnitude of those fluxes indicates that only protons and neutrons are important for the radiation effects of concern in this paper (as will be explained in Sections IV-B and IV-C). The fluxes shown in the table are the integral fluxes with the lower energy limits defined here. These limits are the same as the inherent MCNPX low-kinetic energy cutoff for each particle.

In order to examine the importance of the secondary neutrons for the two different shielding materials considered in this study, the volume-averaged neutron fluxes in the silicon region are depicted in Fig. 2(a) for the trapped proton case. The results indicate that the secondary neutron productions in the aluminum shieldings decrease as the shielding thickness increases, and that the secondary neutron productions in the tungsten shieldings become saturated as the shielding thickness increases. This is somewhat misleading because the fluxes in Fig. 2(a) are normalized to one source proton/cm$^2$ incident on the outer surface. The comparison should be made based on the one source proton/cm$^2$ to have a fair comparison that shows the relative importance of the secondary neutrons for the same source flux. Fig. 2(b) shows the secondary neutron fluxes normalized to one source proton/cm$^2$ incident on the outer surface isotropically. As shown, the secondary neutron fluxes increase as the shielding thicknesses increase for both shielding materials. Regardless of how the comparisons are made, the results show that the secondary neutrons are produced more in tungsten than in aluminum for a given density independent shield thickness.

#### TABLE I

<table>
<thead>
<tr>
<th>Particle</th>
<th>2 cm Al shielding</th>
<th>0.2798 cm W shielding</th>
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<tr>
<td>Neutron</td>
<td>6.10$\times$10$^4$</td>
<td>1.12$\times$10$^7$</td>
</tr>
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<td>Electron</td>
<td>3.60$\times$10$^6$</td>
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<td>Muon-</td>
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<td>0.00$\times$10$^7$</td>
</tr>
<tr>
<td>Proton</td>
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</tr>
<tr>
<td>P$^+$</td>
<td>0.00$\times$10$^7$</td>
<td>1.46$\times$10$^7$</td>
</tr>
<tr>
<td>P$^0$</td>
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<td>4.65$\times$10$^7$</td>
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<tr>
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<tr>
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<tr>
<td>Alpha</td>
<td>4.37$\times$10$^8$</td>
<td>10.2$\times$10$^8$</td>
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</table>
Fig. 2. (a) Volume averaged neutron fluxes for aluminum and tungsten shieldings as a function of density independent shield thicknesses (gm/cm²). The fluxes are normalized to one proton incident on the outer surface isotropically.

B. Total Dose

The +F6 energy deposition tally was used to compute the volume-averaged total energy deposition in the silicon region. The +F6 tally is the special tally to score the energy deposited from all particles that are transported in the problem, over all energy ranges, in selected tally cells [5]. Two separate calculations were performed in order to differentiate the contributions from the secondary particles other than the protons. In the first set of calculations, the problem involved the transport of the protons only. Note that the version of MCNPX used in the current study does not distinguish between the primary protons and the secondary protons. Therefore, the results obtained in the first set of calculations are due to both the primary and the secondary protons. In the second set of calculations, other secondary particles were included in the problem setup. Figs. 3 and 4 summarize the results for the total dose calculations for the ESP and the trapped proton models, respectively. The figures show the ratios between MCNPX and NOVICE [8] calculations where the latter only accounts for the primary protons in the calculations and uses the continuous slowing down approximations. In the figures, MCNPX(1) represents the results obtained transporting the primary and secondary protons, and the MCNPX(2) results include other secondary particles in addition to the primary and secondary protons. Thus, the difference between the MCNPX(1) and the NOVICE results originates from the secondary protons only, and the difference between the MCNPX(1) and the MCNPX(2) results stems from secondary particles other than protons. The uncertainties of the MCNPX results are within ±2% while the uncertainties of the NOVICE results are less than 0.5%. Several observations of the results are as follows. 1) The maximum deviation between MCNPX and NOVICE is about...
Fig. 2. (Continued) (b) Volume averaged neutron fluxes for aluminum and tungsten shieldings as a function of density independent shield thicknesses (gm/cm²). The fluxes are normalized to one proton/cm² incident on the outer surface isotropically.

7%. However, the fact that the MCNPX(1) results are very close to the MCNPX(2) results and that the stopping powers used in both codes for calculating the energy deposition are essentially the same as shown in Fig. 5 over the energy range of interest in this study suggests the secondary effects to the total doses are mostly due to the secondary protons. 2) The ratios obtained for the ESP protons are in general larger than those obtained for the trapped proton. Therefore, even though the “absolute” production of the secondary particles is larger for the trapped protons than for the ESP protons (Table I), the effect of the secondary particles is “relatively” more important for the ESP protons than for the trapped protons in the shielding configuration considered in this study. 3) Unusual data points in Figs. 2 and 3 (for example, higher MCNPX(1) results than MCNPX(2) at several shield thicknesses) can be understood from the context of the uncertainties associated with the results. 4) A dip at 8.1 gm/cm² is also due to the statistical uncertainties of the results. A further analysis showed that the ratio of MCNPX(2) to NOVICE for the ESP/aluminum case increases again as the shielding thickness increases (for example, the ratio becomes about 1.08 at 10.8 gm/cm²).

C. Displacement Damage Energy Deposition

The displacement damage energy deposition can be calculated if the non-ionizing energy loss (NIEL), or the damage-energy cross sections and the particle spectrum are known in the region of interest. NIEL is a quantity that describes the rate of energy loss due to atomic displacement as a particle traverses a
Fig. 3. Ratio between MCNPX and NOVICE results for the volume averaged total dose in the silicon region based on the ESP proton model. MCNPX(1) is the results obtained using MCNPX where only the protons (primary + secondary) were transported. MCNPX(2) is the results obtained using MCNPX where all other secondary particles were included in the transportation calculations. The error bars are not shown for clarity. The uncertainties of the results are within ±2%.

The displacement damage energy per unit mass of material, and the product of the NIEL and the particle fluence gives the displacement damage energy per unit mass of material. The NIEL is related to the microscopic cross section as [9]:

\[
S_{\text{NIEL}}(E) = \left( \frac{N}{A} \right) \sum_i \sigma_i(E) T_i
\]

where

- \( S_{\text{NIEL}} \) nonionizing energy loss rate in MeV-cm²/g;
- \( N \) Avogadro’s number;
- \( A \) gram atomic weight of the material;
- \( \sigma_i \) cross section of the \( i \)'th interaction;
- \( T_i \) average energy of the atomic recoils corrected by applying an appropriate law (such as Lindhard theory [10]) to account for the portion of energy that goes to ionization process.

The summation term in (1) is also known as the displacement damage energy cross section, \( \sigma_d \).

In order to compute the displacement damage energy deposition in our problem, it is necessary to know both the NIELs of the primary and secondary particles on silicon and their spectrum in the silicon region. The spectrum determination is done automatically by MCNPX. But, the NIELs of the relevant secondary particles are not available over the entire energy range for our problem. Thus, for an accurate estimation of the displacement damage, we need to have the NIELs of all of the particles shown in Table I up to the maximum energy in the problem. However, as indicated in the previous section, the production of secondary particles other than the
protons and neutrons is not significant, so their contributions to the total radiation effects would be negligible. Although the NIELs of heavier charged particles (such as deuteron, triton, pion, or helium) are larger than those of protons and neutrons, the fluxes of heavier particles are orders of magnitude lower than the fluxes of protons and neutrons. Furthermore, the fluxes of photons and electrons are not negligible, but their NIEL’s are orders of magnitude smaller than that of the proton. Therefore, the displacement damage calculation in our problem concentrated on the effects of protons (both by the primary and by the secondary) and neutrons.

1) Energy Partition: The damage energy is obtained from the recoil energy using a representation due to the Robinson formulation [11] of the Lindhard partition function [10]. The fraction of the recoil energy that goes to the displacement process is given by

\[ L(T) = \frac{1}{1 + F_L (3.4008 \varepsilon^{1/6} + 0.4024 \varepsilon^{3/4} + \varepsilon)} \]  

where

\[ T = \text{recoil energy} \]  

\[ \varepsilon = \frac{T}{E_L} \]  

\[ E_L = 30.724Z_R Z_I (Z_R^{2/3} + Z_I^{2/3})^{1/2} \frac{A_R + A_I}{A_L} \]  

\[ F_L = \frac{0.0793Z_R^{2/3}Z_I^{2/3}(A_R + A_I)^{3/2}}{(Z_R^{2/3} + Z_I^{2/3})^{3/4}A_R^{3/2}A_I^{1/2}}. \]
In the above equations, $A_R$ and $Z_R$ are the atomic weight and number of the moving particle and $A_L$ and $Z_L$ are the like quantities for the lattice atoms, which, in our case, is for silicon. Fig. 6 illustrates the relation between the primary recoil energy and that available for displacement in the silicon lattice.

2) Neutron Damage Energy Cross Section: The neutron damage energy cross section up to 150 MeV was computed by using NJOY97 [12] with the recently evaluated Los Alamos National Laboratory high energy cross section library [13]. Above 150 MeV, the NIELs were computed in this paper by using the thin target approximation. The method to calculate the damage energy cross section is described in Pitcher et al. [14] and Wechsler et al. [15]. A 1-cm slab of silicon with a normalized density of 0.01 atoms/barn-cm was modeled, and a pencil beam of neutrons was launched onto the slab. Using the damage energy tally, then the history tape written by MCNPX was analyzed to calculate the mean damage energy per source particle, $T_{\text{dam}}$, which is the portion of the energy of the moving atom that is transferred to nuclei. The damage energy cross section $\sigma_d$ is then given by:

$$\sigma_d = \frac{T_{\text{dam}}}{N_a x} \quad (4)$$

where $N_a$ is the atom density and $x$ is the target thickness. Fig. 7 shows the neutron damage energy cross section in eV-barn from 1 MeV to 1000 MeV. Below 150 MeV, the cross section computed by NJOY97 is shown, and above 150 MeV, the cross section computed in this study is included. The figure also illustrates the separate contributions from elastic and inelastic scattering above 150 MeV. While the inelastic scattering is the dominant contributor over this energy range, the elastic scattering is responsible for the inflexion of the curve around 300 MeV. As shown, the MCNPX resulted in a $\sim 25\%$ larger damage energy cross section than that obtained by NJOY97 at the 150 MeV boundary. It is believed that...
the discrepancy stems from the contribution of the spallation reaction products to the damage energy cross section. MCNPX includes the spallation effects, whereas NJOY97 only accounts for elastic scattering, inelastic scattering, and other types of particle emanating reactions such as \((n, p), (n, \alpha)\), etc. However, the high energy neutron damage energy cross section computed here agrees well with those shown in earlier literature [14], [16]. The discrepancy at 150 MeV between NJOY97 and MCNPX emphasizes the importance of spallation reactions when computing the damage energy cross section in high neutron energy range.

3) Proton NIEL: We used the proton NIEL up to 200 MeV from Summers et al. [17]. Above 200 MeV, the NIEL’s were computed in this study. It is well known that the proton NIEL calculations involve atomic Coulomb, and nuclear elastic/inelastic interactions. For the contribution from the Coulomb scattering, the relativistic kinematics formulated by Seitz et al. [18] or Burke [19] were used, and the “correct” form of equations are repeated here. The relativistic differential cross section that describes the PKA spectrum is given by

\[
d\sigma(E, T) = \frac{\pi T^2 T_{\max}^2}{4\gamma^2} \left[ 1 - \beta^2 \frac{T}{T_{\max}} + \pi \alpha \beta \right] \cdot \left( \sqrt{\frac{T}{T_{\max}}} - \frac{T}{T_{\max}} \right) \frac{dT}{T^2} \tag{5}
\]

where

\[
b = \frac{2Z\gamma c^2}{mc^2\beta^2}, \quad \beta = \frac{\gamma}{c} = \sqrt{1 - \left( \frac{mc^2}{mc^2 + E} \right)}
\]

\[
\gamma = \frac{1}{\sqrt{1 - \beta^2}} \quad \alpha = \frac{Ze^2}{\hbar c} = \frac{Z}{137.036}.
\]

Fig. 6. Lindhard partition function based on the Robinson formulation for selected recoil particles on silicon lattice.
In this equation, \( v, m, z \) and \( E \) are the proton velocity, mass, charge, and energy, respectively. \( M \) and \( Z \) refer to the silicon mass and charge. \( T \) is the energy transferred to silicon atom. \( T_{\text{max}} \) is the maximum possible energy transferred to the silicon atom, and is given by

\[
T_{\text{max}} = \frac{2E(E + 2mc^2)}{(1 + \frac{m}{M})^2 Mc^2 + 2E}.
\] (6)

Burke et al. [19] first computed the average energy transferred to the recoils, and then applied the energy partition function to this average energy transferred. However, in this paper, we used a more rigorous approach. The damage energy cross section due to the Coulomb scattering is obtained by integrating the above equation from the threshold energy for atomic displacement \( T_d \) (21 eV was used in this study [20]) to \( T_{\text{max}} \), and applying the Lindhard partition function \([2]\) in the integrand

\[
\sigma_{d,\text{Coulomb}}(E) = \int_{T_d}^{T_{\text{max}}} L(T)d\sigma(E,T).
\] (7)

The contribution of the nuclear interactions to the total damage energy cross section was computed by utilizing MCNPX based on the thin target approximation method as discussed in Section IV-C.2. A 0.1-cm slab of silicon with a normalized density of 0.01 atoms/barn-cm was modeled, and a pencil beam of protons was launched onto the slab. The thinner slab was used for the proton case to ensure that the thin target approximation would still be valid. Then, by using the damage energy tally, \( T_{\text{dam}} \), the damage energy cross sections \( \sigma_{d,\text{nuclear}} \) were calculated from (4). The final NIEL is computed using

\[
S_{\text{NIEL}}(E) = \left( \frac{N}{A} \right) (\sigma_{d,\text{Coulomb}} + \sigma_{d,\text{nuclear}}).
\] (8)

The nuclear elastic scattering treatment in MCNPX can be found in Prael et al. [21], whereas the background spallation physics adopted in MCNPX is described in [5].

Fig. 8 summarizes the proton NIEL’s used in this study, in terms of MeV-cm\(^2\)/g. Below 200 MeV, the curve is based on the results by Summers et al. [17]. Above 200 MeV, the NIEL computed in this study is depicted. The figure also includes
Fig. 8. Protons on silicon NIEL. Below 200 MeV, the data were taken from Summers et al. Above 200 MeV, the NIELs were computed in this study based on the method described in the text.

the separate contributions of Coulomb, nuclear elastic, and inelastic reactions to the total proton NIEL over 200–1000 MeV. As shown, the nuclear inelastic scattering is dominant over this energy range. In general, the agreement with Summers et al. [17] at 200 MeV and with Dale et al. [16] over 200–1000 MeV is excellent. The nuclear elastic scattering is responsible for the leveling off of the curve above ~350 MeV.

4) Calculation of Damage Energy Deposition: The damage energy cross sections obtained above were used as the input to MCNPX and NOVICE to compute the damage energy deposition in the silicon region in our problem. The results are summarized in Figs. 9 and 10, respectively, for the ESP and the trapped proton models. Again, the figures show the ratios between MCNPX and NOVICE CSDA results. Note that MCNPX(1) represents the results obtained transporting the primary and secondary protons, and the MCNPX(2) results include the contribution of the secondary neutrons in addition to the primary and secondary protons. Thus, the difference between the MCNPX(1) and the NOVICE results originates from the secondary protons only, and the difference between the MCNPX(1) and the MCNPX(2) results stems from the secondary neutrons. The uncertainties of the MCNPX results are within ±2%, and the uncertainties of the NOVICE results are less than 0.5%. From the figures, it is observed that: 1) the enhancement of the displacement damage is largely due to the secondary neutrons; b) the effects of the secondary neutrons on the displacement damage energy deposition is up to +25% of the CSDA results, which is consistent with the results observed by Dale et al. [2] for similar shielding configurations; and c) as in the total dose cases, the ratios obtained for the ESP protons are in general larger than those obtained for the trapped proton. This again indicates the “relative” importance of the secondary particles in the solar proton environment than in the trapped proton environment.
V. SUMMARY AND CONCLUSIONS

The recently developed MCNPX version 2.1.5 was introduced in this paper in order to show possible applications to space radiation effect analyses. Especially, the effects of the secondary particles generated by the representative solar and trapped proton environments on the total dose and the displacement damage energy deposition were investigated. The problem geometry consisted of the 0.5-cm radius silicon sphere surrounded by either aluminum or tungsten shields with the shielding thickness ranging from 1.35 to 8.10 g/cm². Two different proton environments were used as the source spectra in the problem. 1) The NASA model for emission of solar protons (ESP), and 2) the NASA AP8MIN model for the trapped protons. Fig. 1 shows each spectra. The radiation responses were then calculated in the silicon region.

The accurate estimation of the secondary particle effects was made possible by using the up-to-date nuclear model calculations and by adopting the cross section libraries incorporated in the MCNPX code package. The results (Table I) showed that in our shielding configurations the protons and neutrons are important among many possible secondary particles. It was found that their contributions to the total dose (Figs. 3 and 4) and the displacement damage energy deposition (Figs. 9 and 10) are up to 7% and 25%, respectively, when compared to CSDA results obtained by using NOVICE. It has been shown that the secondary protons are mostly responsible for the total dose enhancement, and the secondary neutrons for the displacement damage enhancement. The results obtained in this study agree very well with other results previously reported, and show the applicability of MCNPX to the space radiation effect community. The results re-iterated the importance of the secondary neutrons on the radiation effects in space environments, especially its contribution to the displacement damage energy deposition in high energy proton environments with thick high-Z shielding materials. Even though it has not been addressed in detail in this work, the secondary particles other than neutrons such as pions, deuterons, or alphas, etc. would increase the radiation responses even higher. Further work is planned to investigate this issue.
Fig. 10. Ratio between MCNPX and NOVICE results for the volume averaged displacement damage energy deposition in the silicon region based on the trapped proton model. MCNPX(1) is the results obtained using MCNPX where only the protons (primary + secondary) were transported. MCNPX(2) is the results obtained using MCNPX where the neutrons as well as the protons were included in the damage energy calculations. The error bars are not shown for clarity. The uncertainties are within ±2%.

Also, in this study, the damage energy cross sections (Fig. 7 for neutrons on silicon and Fig. 8 for protons on silicon) were obtained up to 1000 MeV by using the thin target approximation method. The cross sections were in excellent agreement with those obtained using other methods. The method presented in this paper demonstrates that we can expand the damage energy cross section or NIEL to other materials to higher energy ranges for various particles, which has not been easy until now.

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