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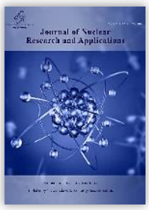

Optimum Radiation Shield Design for Orbital Transfer Scenario Using OMERE and SPENVIS

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ABSTRACT

One of the most important factors in designing space systems is pay attention to space's radiation environment. The presence of these dangerous rays causes radiation damage to subsystems and can create problems for the entire system. Space radiation falls into three categories: trapped particles, solar particles, and galactic cosmic rays. Due to the high flux of trapped particles in the Van Allen belts, orbital transfer maneuvers receive the most radiation from these particles. One way to mitigate radiation damage is to use radiation shields. This study investigates radiation damage during orbital transfer from LEO to GEO. Theresearch was conducted simultaneously using OMERE and SPENVIS simulation software programs. The results were almost identical when determining TID and TNID damage with both software. OMERE results were more conservative in determining SEE damage. The findings indicate that COTS, Rad Tolerant, and Rad Hard systems require aluminum shields of at least 2.85 mm, 0.97 mm, and 0.22 mm thickness, respectively, to address ionization dose damage. There are no specific requirements for mitigating TNID damage. The results of SEE damage determination from both software programs suggest that a 1 mm thick shield can significantly reduce SEE damage. Increasing the thickness does not further reduce this damage. In this orbital transfer scenario solutions other than shielding should be considered to minimize SEE damage.

Keywords: Space radiation; Radiation damage; Orbital transfer; OMERE; SPENVIS.

1. Introductions

One very important parameter in the design and construction of space systems is to pay attention to the difference between the space environment and the terrestrial environment. Space includes galactic cosmic rays, solar proton rays, atmospheric drag, ionosphere flow, etc, which have destructive effects such as spacecraft charging, solar cell damage, single-event errors in memories, and lack of safety for astronauts [1].

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Investigating space radiation is crucial in the design and construction of space systems. Space radiation is typically categorized into three groups: trapped particles in the Earth's magnetic field, solar particles, and cosmic rays. The density of all types of particles in the radiation environment can vary greatly depending on factors such as altitude, orbit inclination, solar activity, and spacecraft shielding (which affects scattering) [2,3].

The Earth's magnetic field is a geomagnetic cavity that traps low-energy charged particles. The regions where radiation particles are trapped are known as the Van Allen belts. These trapped particles contain electrons, protons and many heavy ions, and they make an oscillating movement between magnetic field lines and the distance between the poles [2,3].

Another class of particles exists, known as solar particles, whose frequency and intensity usually depend on the level of solar activity. Solar particle events occur randomly, but follow an 11-year cycle of solar activity. Solar minimum is associated with periods of minimal solar activity, while solar maximum is associated with periods of peak solar activity [4].

Galactic cosmic rays (GCRs) originate from sources outside the solar system. These particles in the heliosphere interact with the solar magnetic field created by the solar wind. When determining the most optimal method of orbital transport maneuvers, several parameters should be considered. There are different strategies for orbit transfer from LEO (Low Earth Orbit) to GEO (Geosynchronous Equatorial Orbit). The flux of protons and electrons around the Earth changes according to longitude, latitude, and altitude, so finding a balance between propellant usage, travel time, and engine fuel consumption is necessary to minimize the amount of radiative effects. When radiation constraints are critical for a given mission, positioning control can help achieve optimal flight trajectories. Thrust status can also affect travel time and radiation exposure [5].

Radiation damage is divided into two categories: cumulative and immediate. This classisifaiction is based on the mechanism of radiation interaction and the effect it has on materials.

This classification is based on time. Cumulative effects are divided into ionizing and non-ionizing effects. Ionizing effects can be calculated and measured using the Total Ionizing Dose (TID) parameter. Non-ionizing or displacement effects can be calculated and measured with a 1 MeV neutrons equivalent flux or 50 MeV protons equivalent flux. Single-event effect is also commonly represented by SEE or Single Event Effect [6]. TID effects can cause failure or loss of efficiency in electronic equipment and parts, ultimately affecting the lifespan of the satellite [7].

Displacement damage caused by non-ionizing dose or Non-Ionizing Energy Loss is known as NIEL. This damage is cumulative and is caused by energetic particles, impacting optoelectronic components, bipolar semiconductors, and solar cells. The damage mechanism occurs when the beam strikes the atoms that make up the crystal lattice of the material, resulting in the formation of atoms and vacancies within the lattice. These intra-lattice atoms and vacancies are mobile and can combine or create stable defect centers with impurities in the network structure. As a result, new energy levels are created in the forbidden energy band [8].

One parameter used in the field of displacement radiation damage is the 1 MeV neutron equivalent flux, 50 MeV proton equivalent flux, or 1 MeV electron equivalent flux. For example, the 1 MeV neutron equivalent flux is equal to the equivalent flux of 1 MeV neutrons, causing the same amount of damage [9,10].

Single-event damage is caused by random collisions of ions, protons, and neutrons with electronic components, varing in energies and angles. Heavy ions produce more energy per unit length in the material compared to protons, making single-event damage more noticeable [11]. The Radiation Effects Association has developed various models to describe the physical mechanisms and estimate the probability of space environment effects [12]. The SEE cross-sectional area means the probability of the impact of a single SEE event and is measured by the recorded number of events per unit flow. SEE heavy ion cross sections are typically expressed as a function of LET or Linear Energy Transfer [13,14].

The effects caused by SEE on a part depend on the type and energy of the incident particle, as well as the characteristics of the part such as material, geometry, and thickness. SEU (Single Event Upset) is a single-bit flip in digital elements caused by direct ionization of moving particles or repulsive nuclei in a nuclear interaction. This event does not damage the basic elements, as they can be rewritten with the correct values. SEU occurs in memory and logic circuits such as DRAM (Dynamic Random-Access Memory), SRAM (Static Random-Access Memory), microprocessors, and more. Most manufacturing technologies for electronic components are sensitive to this event [13].

The SEU error probability is the likelihood that the stored energy exceedsthe threshold energy and LET of the component. The threshold values of sensitive nodes are not the same, but rather form a distribution that can be modeled with a Weibull function. Expressing the data as a Weibull curve after adjusting for geometric effects is shown in Equ. 1.

$$F(LET)=1-\exp\left[-\left(\frac{LET-LET_{\circ}}{W}\right)^{S}\right] \quad (1)$$

In this equation, LET_0 is equal to the threshold LET for the fragment.
so that for $LET < LET_0$, $F(x)=0$.

W is the width parameter and s is the shape parameter, which is dimensionless. Therefore, the direct ionization SEE cross-sectional area is expressed in Equ. 2 [16].

$$\sigma=\sigma_{sat}\times F(LET) \quad (2)$$

One way to determine the cross-section of a single event effect is to use a 4-parameter Weibull function fit (S, W, L_0, σ_{lim}).

This information is based on experimental results of irradiating of electronic components using different technologies. By using these parameters and fitting the Weibull curve, the SEU defect can be determined under the desired conditions. Components exhibit varingresistances to these three types of radiation damage.

Depending on the level of tolerance of electronic components against radiation, the components can be divided into three categories: RADHard (RADiation-Hardened), RADTolerant, and COTS or Commercial off The Shelf components. RADHard components have the highest tolerance to space radiation and COTS have the lowest tolerance to that radiation. Table 1 displays the radiation resistance levels of various quality components [15,16].

Numerous studies have been conducted in this field to examine the impacts of protection through simulation and experimental research [17,18,27-32,19-26].

In the study conducted by NASA experts, calculations related to dose comparison were analyzed for eight different orbit transition scenarios from LEO to GEO [5]. The aim of this study is to examine the impacts of space radiation on the most vulnerable component of the space system during the transition from LEO to GEO orbit. TID, TNID and SEE are calculated in an orbital transfer scenario using OMERE and SPENVIS software.

In these softwares, users can utilize four types of simple geometries to determine TID and TNID damage. The geometric shapes include 1- sphere, 2- shell sphere, 3- semi-infinite flat, and 4- infinite flat geometry. Spherical geometry is the default setting in the software. This sphere is filled with aluminum material, with a very small silicone sphere located in the center. The dose calculation is based on the thickness of the aluminum shield in silicon. The choice of aluminum material is due to its common use in the design of space system main structure s.

Table 1. Radiation resistance levels for different grade component.

grade	TID (krad)	SEUrate errors/bit-day
COTS	2-10	10^{-5}
Rad Tolerant	20-50	10^{-8} - 10^{-7}
Rad Hard	200 krad-1 Mrad	10^{-12} - 10^{-10}

The innovation of this work lies in determining of radiation damage by simultaneously using the calculations of OMERE and SPENVIS software for the orbital transfer flight scenario from LEO to GEO orbits.

2. Material and methods

Various software programs can calculate the values associated with the damage parameters. In order to calculate radiation damage, particles need to be transported through the radiation environment and into the target material that is impacted by the radiation [33].

OMERE is a freeware program that focuses on the space environment and its effects on electronic devices from radiation. This tool was developed by TRAD with support from CNES, based on the requirements of our partners: THALES ALENIA SPACE, AIRBUS DEFENSE & SPACE, ONERA, CEA, ESA, and OHB. OMERE calculates particle fluxes and radiation impacts on electronic equipment, including dose, displacement damage, single event effects, and solar cell degradation. Various environment models, including all standard (ECSS-10-04) models, can be utilized with OMERE [34].

The ESA’s SPace ENVironment Information System known as SPENVIS, is a web interface that provides access to models of the space environment and its effects, including galactic cosmic rays, solar energetic particles, natural radiation belts, plasmas, gases, meteoroids, and debris. Through the General Support Technology Programme (GSTP), a consortium with the Royal Belgian Institute for Space Aeronomy (BIRA-IASB) is creating the SPENVIS system for ESA's Space Environments and Effects Section. The system is maintained by the development team at BIRA-IASB [35].

The software programs SPENVIS and OMERE are utilized for calculating the damage parameters of space systems. These programs are specifically designed to simulate the effects of cosmic radiation. They are both free and user-friendly. SPENVIS in particular, is more comprehensive and is capable of modeingl magnetic fields, spacecraft charging, meteorites and debris as well as radiation effects.

To predict the effects of space radiation on materials, the interaction mechanisms available in any such software must be utilized. Since these two software programs work with the Monte Carlo method, the probability of each nuclear interaction, or the cross-section of these interactions, must be available in the software's database. The aim of this work is a preliminary assessment of the dose caused by space radiation in electronic components using OMERE and SPENVIS software. Three different orbits are considered in this orbital transfer task from LEO to GEO orbit. This mission includes one day in LEO orbit at 200 km altitude, two days in GTO (Geostationary Transfer Orbit) orbit and one day in GEO orbit. Fig. 1 shows the general scenario of the mission in two dimensions in the OMERE software.

The models related to the flux of radiation particles for two software are shown in Table 2.

Aluminum is used as a shield and silicon as a target to evaluate the damage. Furthermore, because SEE damage relies on Weibull parameters, the data related to the default component available within the OMERE software has been considered as the basis.

3. Results

This section discusses the calculation results of the two software OMERE and SPENVIS.

3.1. Radiation Flux

Fig. 2 shows the flux values of trapped electron particles in OMERE and SPENVIS software.

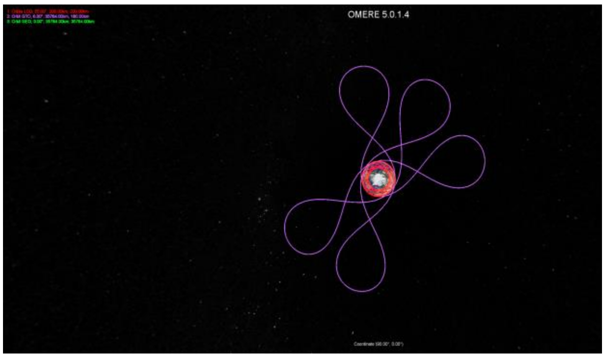

Fig. 1. Image of the general scenario of the mission in two dimensions in the OMERE software.

Table 2. Space radiation models in OMERE and SPENVIS software.

Particle	Models in software
Trapped electrons	AE-8 max
Trapped Protons	AP-8 min
Solar Protons	ESP
Solar Ions	HELIUM ONERA
Solar Flare	CREME96 worst case 1 day
Galactic Cosmic Rays	GCR-ISO

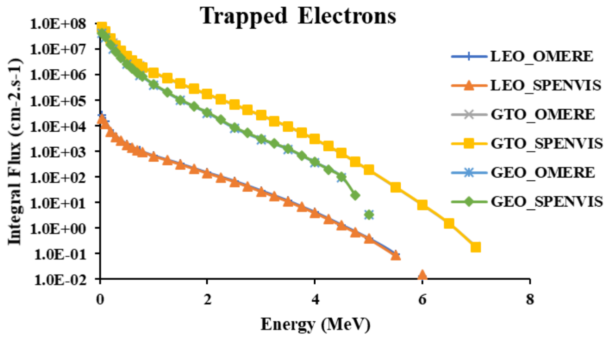

Fig. 2. Comparison between the flux of trapped electrons in SPENVIS and OMERE software.

It is known that the cumulative flux of trapped electron particles in GTO and GEO orbits is 4 orders of magnitude higher than in LEO orbit. Therefore, most of the effect of particles will be from trapped electron particles passing through GTO and GEO orbits. The energy range of the trapped electrons is almost up to 8 MeV. Figure 3 shows the trapped protons flux values in OMERE and SPENVIS software. In this figure, the flux values of both softwares are almost the same.

The percentage of the relative difference in trapped electron particle fluxes for LEO, GTO, and GEO orbits is approximately 8.5%, 1.1%, and 4.0%, respectively. These calculations are based on the output data from both software programs. It seems that this minor difference is attributed to the consideration of different energy ranges in the modeling.

Since trapped proton particles are less insignificant in the GEO orbit, their values are not displayed in the figure above. The cumulative flux values in the GTO orbit are approximately 5 orders of magnitude higher than those in the LEO orbit. The energy range of trapped protons is up to 300 MeV. It is evident that the values of the total flux values of trapped electron and proton particles at lower energies are nearly equivalent.

The percentage of the relative difference in flux values for LEO, GTO, and GEO orbits for trapped proton particles is approximately 77.9%, 12.6%, and 6.6%, respectively. These calculations are based on the output data from both software programs. The energy range for obtaining the flux of trapped protons in OMERE and SPENVIS software is up to 300 MeV and 400 MeV, respectively. Additionally, different ranges are considered in the modeling process. Therefore, there is a difference in obtaining the flux of trapped protons, even though the flux of particles has an order of magnitude.

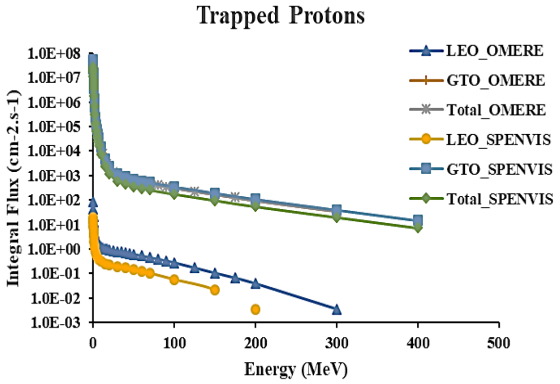

Fig. 3. Comparison of the flux of trapped protons in SPENVIS and OMERE software.

Fig. 4 shows the cumulative flux of solar protons in various orbits using the OMERE and SPENVIS software. As depicted in the figure, the solar particle flux values in LEO orbit are almost 4 orders of magnitude smaller than the flux values in GTO and GEO orbits. The energy range of solar protons extends up to 300 MeV.

When comparing the flux of trapped electrons and proton particles shown in Figs. 2 and 3, respectively, to the flux of solar particles in this mission scenario, it is evident that the importance of these particles as a cause of radiation damage is relatively lower. This is due to the significantly lower flux of solar particles by 3-4 orders of magnitude.

The results show a relative difference of almost 128% in the solar proton fluxes between the two software programs. This disparity is a result of differences in the calculations used to determine the flux of solar protons and variations in the energy range covered by each software.

Fig. 5 shows the cumulative plot of the cosmic proton flux in the OMERE and SPENVIS software. The energy range of these particles is much greater than that of solar and trapped particles, but their flux is significantly lower. Comparing the flux of trapped electron and proton particles in Fig. 2 and Fig. 3 and the flux of solar particles in Fig. 4 with the flux of galactic cosmic protons in Fig. 5, it is evident that these particles are 7.6 and 2 orders of magnitude smaller than trapped and solar particles, respectively. Therefore their contribution in terms of radiation damage is relatively less.

As depicted in Fig. 5, the flux of these particles remains relatively constant across different orbits.

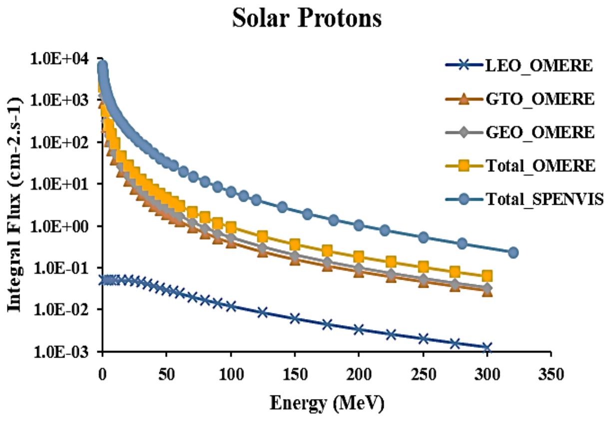

Fig. 4. Flux of solar protons in terms of energy.

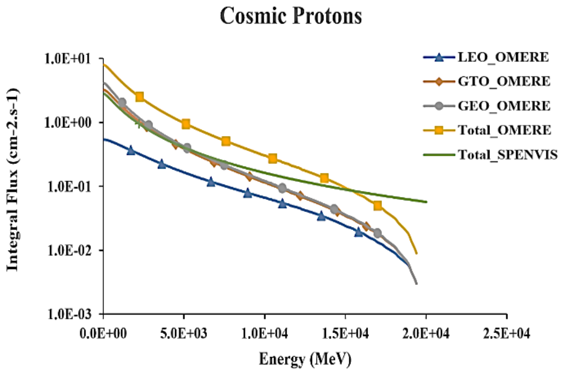

Fig. 5. Flux of cosmic ray protons in terms of energy in OMERE and SPENVIS software.

3.2. Determination of radiation damage

Fig. 6 compares TID damage versus thickness in SPENVIS and OMERE software. Shown in the figure, the values obtained by both softwareprograms are nearly are almost identical.

The relative difference in dose amounts obtained from both software programs is approximately 20.4. This discrepancy is attributed to the use of different geometric and input flux of particles when calculating the dose.

As is well-known, increasing the thickness of shielding can have a significant effect in reducing the dose by several orders of magnitude. Therefore, it can be concluded that one of the most effective ways to resist the effects of TID is through the use of shielding.

Considering the proximity of the values, it can be concluded that the values necessary to protect components of different classes are the same when using the two software.

Only the OMERE software results are presented because the two software produce the same total ionization dose. Fig. 7 shows the values of the total ionization dose in different orbits according to the aluminum thickness in the OMERE software. As shown in this figure, the dose values decrease with increasing thickness. The COTS, Rad Tolerant, and Rad Hard components have radiation tolerance threshold values for TID of 2, 20 and 200 krad. The minimum thickness that can withstand the effect of TID in different orbits and also during the entire mission period is calculated from Table 3. The LEO orbit may have no special requirements to deal with this effect. To pass the Van Allen belts in GTO orbit and reach GEO orbit in its short 2-day period, using COTS requires at least 2.74 mm of aluminum to protect sensitive electronic components. Generally, if COTS is used, 2.85 mm aluminum is required during the mission. Rad Tolerant and Rad Hard parts require 0.97 mm and 0.22 mm of aluminum, respectively.

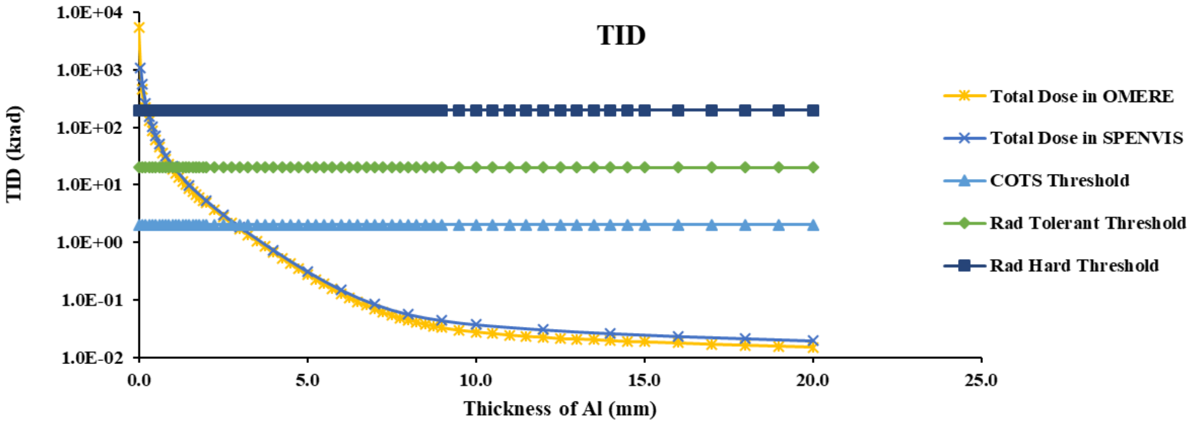

Fig. 6. Comparison of determining TID damage according to thickness in SPENVIS and OMERE software.

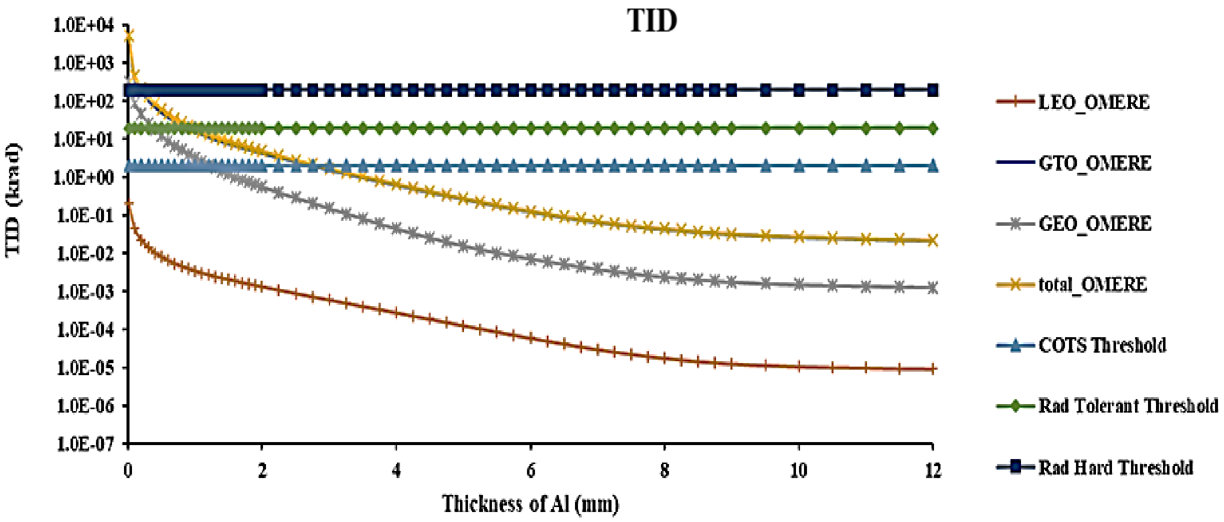

Fig. 7. Mission TID according to the thickness of aluminum in OMERE software.

Table 3. The minimum thickness required to put components with different grades in the intended mission.

Minimum thickness of aluminum (mm)	**LEO**	**GTO**	**GEO**	**Total time of mission**
COTS	No requirements	2.74	1.24	2.85
Rad Tolerant	No requirements	0.86	0.37	0.97
Rad Hard	No requirements	0.19	0.05	0.22

Fig. 8 compares TNID (Total Non-Ionizing Dose) damage by thickness in SPENVIS and OMERE software. As shown in this figure, the values obtained for both software programs are almost identical.

The relative difference in obtaining the TNID value from both software programs is equal to 19.1%. This amount of difference is due to the use of different geometric models as well as different values of input flux in achieving this type of damage. As it is known, increasing the thickness can be effective in reducing the effects of TNID, although in thicknesses over 6 mm, increasing the thickness does not have much effect and the value of TNID does not change much.

Fig. 9 shows the 50 MeV proton equivalent flux at different orbits of the proposed mission based on aluminum thickness for silicon target in OMERE software. In the standard, to consider displacement damage, 50 MeV protons equivalent flux is considered as 2×10^{11} p/cm^2.

As can be seen from this figure, the 50 MeV protons equivalent flux obtained according to the diagram is lower than the value considered in the standard, so there is no special requirement for displacement damage in the mission period.

Considering the similarity of the results in the SPENVIS software, it can also be concluded in this case that the components do not have special requirements for TNID vulnerability. It is known that the magnitude of SEU damage depends on the parameters of the electronic component, and therefore the magnitude of single-event effects varies from one component to another. For a better comparison, the default component of the OMERE software is taken as a basis, and these parameters are entered as input to the SPENVIS software. The Weiball parameters of this component are shown in Table 4.

Fig. 10 shows the SEU values in error/bit/day for OMERE and SPENVIS software programs. As shown in Figure 10 the values obtained for SEU damage in the OMERE software are larger and more conservative. As it is known, increasing the thickness up to 1 mm effectively reduces the SEU effects, but after that, this effect does not change much with the increase in thickness, and therefore, protection cannot effectively reduce this damage.

A COTS component is used in this work, and due to passing through the Van Allen belts and thus reaching GEO orbit, the SEU occurrence is a large value and higher than the standard value considered for commercial components. Therefore, non-commercial components should be used to deal with this damage.

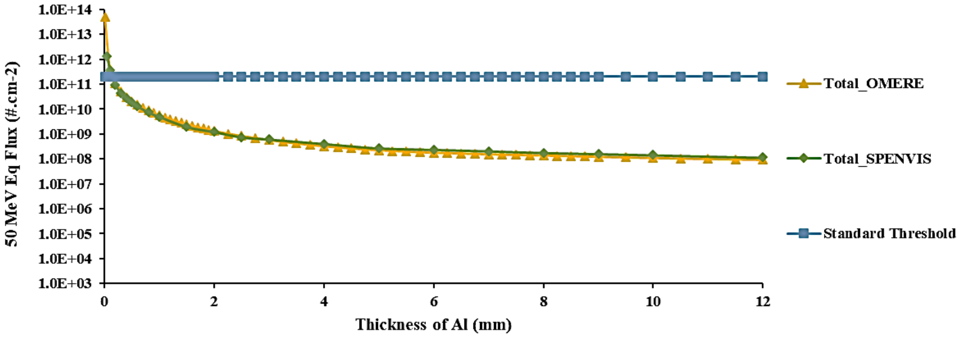

Fig. 8. Comparison of TNID damage determination according to thickness in SPENVIS and OMERE software.

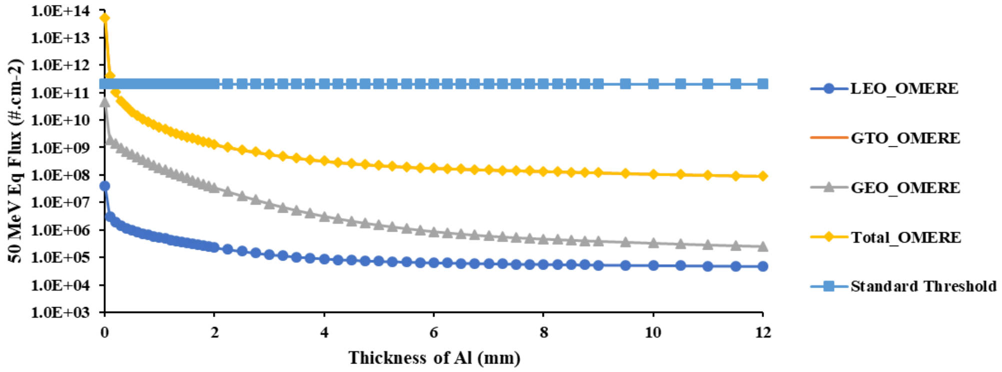

Fig. 9. 50 MeV protons equivalent flux obtained in LEO orbit.

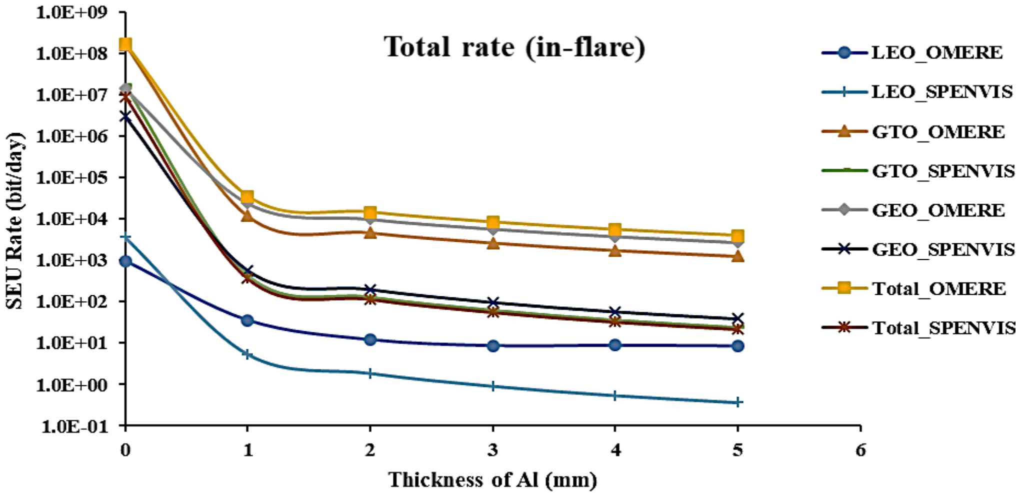

Fig. 10. Comparison of determination of SEE damage according to thickness in SPENVIS and OMERE software.

Table 4. Component specification to achieve SEU.

# Component :	HF459046
# Number of sensitive cells :	1
# Cell depth :	2.000 Âµm
# Heavy ions method:	WEIBULL
# Heavy ions let threshold :	3.97e+00 MeV.cmÂ^{2}/mg
# Heavy ions limit cross section :	9.91e-02 cmÂ^{2} /bit
# Weibull W :	20.03
# Weibull S :	1.49
# Protons method: WEIBULL	
# Protons energy threshold :	2.30e+01 MeV
# Protons limit cross section :	2.59e-08 cmÂ^{2} /bit
# WEIBULL W :	0.26
# WEIBULL S :	0.23

4. Conclusion

In this study, the radiation damage caused by space radiation and the solutions to deal with its protection in the orbital transfer block scenario from LEO to GEO was investigated. Calculations were performed using OMERE and SPENVIS software. The results show that the information related to the determination of TID and TNID damage is the same from both software programs. Generally, when using COTS components, 2.85 mm of aluminum is required to deal with the total ionization dose damage. Rad Tolerant and Rad Hard components require 0.97 mm and 0.22 mm aluminum.

There are no specific requirements for treating TNID damage. The SEE damage determination results from both software show that 1 mm shielding can reduce SEE damage by several orders of magnitude. However, increasing the thickness has no effect on reducing this defect, and in this orbital transfer scenario, solutions other than shielding should be sought to deal with this defect. To determine SEE damage, OMERE has more conservative results.

5. Declarations

5.1. Availability of data and materials

The datasets used and/or analyzed during the current study are available from the corresponding author upon reasonable request.

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Conflict of interest

The authors declare no potential conflict of interest regarding the publication of this work.

Refrencess

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