

## On the Radiation Shielding of Autonomous Spacecraft Intended for Artemis Camp Development

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### Abstract.

Modeling of elemental composition and properties of heterogeneous layers in multilayered shields to protect spacecraft onboard equipment from space radiation engulfing the Moon may cause malfunctioning of semiconductor elements in electronic equipment and result in a failure of the spacecraft as a whole. Different shield designs are considered and compared to the most conventional radiation-protective material for spacecraft - aluminum. A comparative analysis of homogeneous and multilayered protective coatings of the same chemical composition showed heterogeneous protective shields advantageous in weight and shielding properties over its homogeneous counterparts and aluminum. The dose characteristics and transmittance calculated by the Monte Carlo method further showed spacecraft and electronic boxes layout provides effective protection from radiation as well. The main activities of a radiation hardness assurance program not only describe the impactful radiation environment at the component part level and its failure level but characterizes the failure propagation through a circuit that impacts subsystem- and system- functions. This paper aims to investigate relevant strategies what the Artemis or any lunar program needs to consider in space weather for a successful mission.

Keywords: radiation flux-to-dose equivalent conversion, radiation shielding materials, micrometeoroid (MMOD) protection, Boron nitride nanotubes (BNNTs), Radiation Design Margin

### I. Introduction

Radiation of galactic cosmic ray (GCR) particles and particles from solar events (coronal mass ejections and flares) constitute the natural space radiation environment of Earth, the Moon, and beyond. Solar eruptions and their 11-year cyclic peak activity periodically produce energetic protons, alpha particles, heavy ions, and electrons. Radiation damage on the surface of the Earth is quite minimal due to its natural magnetosphere shield. The Moon lacks such defensive measures and has been bombarded by solar and cosmic radiation for nearly 4 billion years [1]. Unlike the Earth surface and its lower orbits, the Moon is not protected from fast moving/high energy particles and waves until interacting with other particles and posing harmful damage to electrical equipment. Table 1 shows that much of the environment is high energy; therefore, shielding is not effective for many types of radiation effects.

Table 1: Maximum Energies of Particles

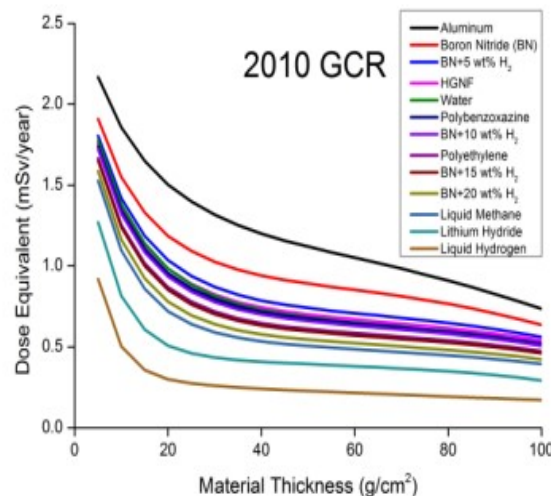
| Particle Type                  | Maximum Energy* |
|--------------------------------|-----------------|
| Trapped Electrons              | 10s of MeV      |
| Trapped Protons & Heavier Ions | 100s of MeV     |
| Solar Protons                  | 100s of MeV     |
| Solar Heavy Ions               | GeV             |
| Galactic Cosmic Rays           | TeV             |

\* For engineering applications

There are 2 major sources of lunar radiation for which spacecraft and astronauts require protection:

- 1) Galactic Cosmic Radiation (GCR) threatens space electronic components and computer systems operations. In 2010, a malfunction aboard the Voyager 2 space probe was credited to a single flipped bit, likely caused by a cosmic ray.
- 2) Solar Particle Events (SPE) will also threatens operations of electrical instruments of spacecraft on the moon.. Any equipment sensitive enough for such high energy particles needs to be turned off to avoid malfunction [2]. Radiation environment generated from post-particle bombardment of material consist of secondary space electrons and neutrons impacting operations of spacecraft as well as spacecraft electronic devices. The resultant displacement damage dose (DDD) and an ongoing cumulative total ionization dose (TID) over time prove harmful. The former disrupts molecular-lattice structure; the latter dose material absorption progressively accumulates to a damaging threshold. Devices intended for high radiation environments need radiation hardening to resist such effects through design, material selection, and fabrication methods [3]. TID mitigation results from material shielding as a boundary between cosmic radiation and the hardware at risk. Alternatively, radiation-hardened semiconductor manufacturing modifications also mitigate radiation-induced faults in sub-systems.

Figure 1 shows a comparative representation of dose equivalents absorbed according to increasing thicknesses of candidate radiation shielding materials. Radiation flux is converted to a more commonly used measurement of dosage from OLTARIS (online tool for the assessment of radiation in space) and HZETRN programs [4]. Liquid Hydrogen is a good space radiation shielding material for a given thickness, followed by Lithium Hydride, Liquid Methane, Polyethylene, BN+10 wt% H<sub>2</sub>, Polybenzoxazine, Water, BN+5 wt% H<sub>2</sub>, BN+15 wt% H<sub>2</sub>, BN+20 wt% H<sub>2</sub>, HGNF, Boron Nitride (BN), and then aluminum [5].



**Figure 1.** Annual dose equivalent for different shielding materials of varying thickness against 2010 solar minimum GCR using OLTARIS

## II. Mission Shielding for Lunar Radiation

Artemis Base Camp suggests human astronaut presence of much longer duration than experienced during Apollo missions. Yet, end of mission dose equivalents have not been tested nor effectively tolerated for the intended long-term space operations that software-hardware will autonomously perform in lieu of human operations. Hardware-driven robotic systems designed for autonomous operations will precede human operations. Since command and control of lunar autonomous systems will be limited due to distance and cost, their actions will likely be ordered with onboard and orbital space computers. In mitigating radiation risk to autonomous robotic systems (ARS), e.g. orbiters, smallsat probes, landers, and rovers on the lunar surface, their exteriors are likely the first radiation shield layer for protection where weight, vibration tolerance, natural frequency range and ability to withstand space radiation should be considered in the design process. The impracticability of Earth-Moon transits for repairs, replacements affords a need for greater self-reliability of lunar spacecraft needed as a preemptory safeguard for

Artemis mission hardware and eventually astronauts. Resiliency provides not only a lower failure probability and higher survival probability when subjected to disruptive events, but most importantly, a rapid recovery from a disruption to an acceptable level for providing service [6]. In the first level of protection, spacecraft structures absorb all or some of the emitted flux, depending on its material and thickness. Additionally, electronic equipment used in the satellite missions is another layer of vulnerability with ionizing particle encounters. So, in the second interior level, local interior shielding needs to protect holder boxes, metal boxes containing electronic boards, and other sensitive equipment. The shielding material type, optimal shielding thickness, material type, and sorting of the shielding layers vary depending on the intended radiation environment. Lightweight materials cannot efficiently attenuate the energetic electrons and protons, and heavy materials can create secondary particles.

When energetic particles and photons interact with solids, energy is transferred from the incident radiation to the target material. The major consequences of energy transfer include ionization, electronic excitations and atomic displacement, all of which can result in serious functional degradation [7]. NASA developed several radiations shielding concepts among which was a multifunctional composite architecture for deep space mission. One such multifunctional concept for radiation and thermal protection had an outer layer of polyethylene composite reinforced with open cell carbon foam and plasma-deposited B<sub>4</sub>C [Sen et al, 2010]. The ultra-high molecular weight (UHMW-PE) polyethylene fiber composite with epoxy matrix had higher specific ultimate tensile strength (2.8 times lighter) and higher specific modulus (2.5 – 4 times greater) when compared with aluminum alloys such Al 2024 and Al 219. These alloys were typically used for International Space Station (ISS) and space shuttle fuselage. Polyethylene based composites are distinctively better shielding material for SPE and GCRs in deep space missions. Since breaking up of heavy ions in GCR flux into smaller fragments with lower ionizing power is the only realistic solution for passive radiation design, shielding with polyethylene (a low Z) material maximizes the likelihood of projectile fragmentation while producing minimum number of target fragments. The incorporation of open cell carbon foam and plasma deposition of B<sub>4</sub>C coating on the exterior of surface of the polyethylene composite further enhances the multifunctional nature of the composite with thermal management. The inner layer made up of inter-ply or intra-ply layers of ultra-High molecular weight polyethylene (UHMW-PE) fibers (fiber/ layer volume, V<sub>f</sub> content = 30 - 42%) provides radiation shielding, and its combination with graphite fiber (V<sub>f</sub> = 18 - 30%) in an epoxy matrix results in a strong lightweight composite. The middle layer is composed of UHMW-PE fiber (68%) in a polyethylene matrix provides both radiation shielding attributes and micrometeoroid (MMOD) protection. The outermost layer comprises of ceramic materials (e.g. aluminium oxide, boron carbide or silicon carbide) further provides MMOD protection.

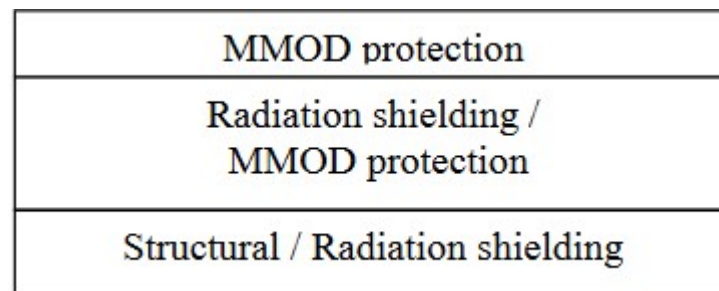


Figure 2: Schematic of multi-functional layered structure having structure and radiation shielding attributes [8]

#### Radiation-protective material for spacecraft

Satellite onboard electronic units require protection from space radiation causing malfunctioning of navigation and telecommunication systems [9]. Modeling the effect of ionizing radiation on various materials is important in the development of compositional materials for protective shields [10]. The materials are analyzed based on the following properties: the absorbed dose, mass thickness, mass attenuation coefficient, and the number of penetrated particles. Research and development in spacecraft protection from ionizing radiation suggests a shield with better protective qualities and less mass than its aluminum counterpart [11].

**Table 2.** Comparing properties of the materials

| Material  | Density, kg/m <sup>3</sup> | Thickness, m | Mass thickness, kg/m <sup>2</sup> | Amount of penetrated electrons | Mass attenuation coefficient, m <sup>2</sup> /kg |
|---|----------------------------|--------------|-----------------------------------|--------------------------------|--|
| B <sub>4</sub> Na <sub>2</sub> O <sub>7</sub>                         | 1904                       | 0.001        | 1.90                              | 0.0069                         | 2.6088   |
| B <sub>4</sub> C  | 1881                       | 0.001        | 1.88                              | 0.0079                         | 2.5684   |
| T-10  | 1596                       | 0.001        | 1.60                              | 0.0071                         | 3.0270   |
| Ni  | 3898                       | 0.001        | 3.90                              | 0.0006                         | 1.9044   |
| Al  | 2700                       | 0.001        | 2.70                              | 0.0031                         | 2.1384   |
| Homogeneous shield with B <sub>4</sub> Na <sub>2</sub> O <sub>7</sub> | 2156.4                     | 0.001        | 2.16                              | 0.0044                         | 2.5146   |
| Homogeneous shield with B <sub>4</sub> C                              | 2134.4                     | 0.001        | 2.13                              | 0.0032                         | 2.6873   |

Composite materials, made of resins e.g. polyether ether ketone (PEEK), polyimide (PI) and polypropylene (PP), enhance mechanical strength. Carbon fiber (CF) or silicon carbide reinforces composite materials not only with structural strength but radiation shielding by their relatively higher stopping power and larger nuclear fragmentation cross section per unit mass compared to aluminum [12]. Properties of composite materials compare favorably to conventional materials of polyethylene as a shielding material and aluminum as a structural material in spacecraft. Composite materials shield intermediate between that of polyethylene and aluminum: >30% higher shielding efficiency than aluminum and <30% lower than polyethylene. By using a commercially available composite CF/PEEK, the effective dose equivalent due to galactic cosmic ray particle absorption was found to be comparable to that with the aluminum Japanese H-II Transfer Vehicle despite its small mass by a density ratio factor of 1.67. The 35–70% larger CF/PEEK fragmentation cross section per unit mass provides effective radiation shielding.

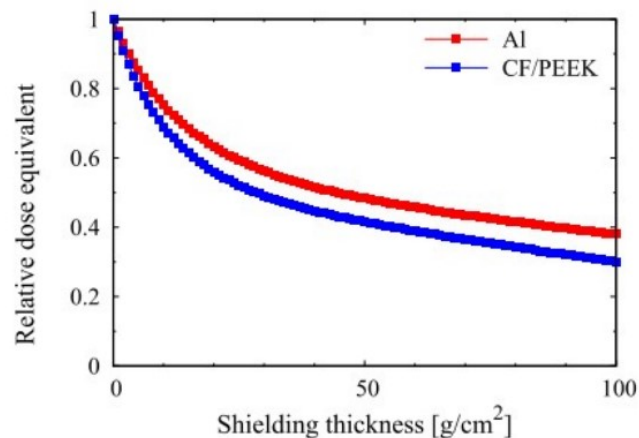


Figure 3. Normalized effective dose equivalents as a function of shielding thickness of Al and CF/PEEK.

Anti-radiation nanostructures solutions create an anti-radiation effect with a reduced density ( $d \leq 1.7 \text{ g cm}^{-3}$ ) compared to traditional lead-based protective anti-radiation suits. Boron nitride nanotubes (BNNTs) offer similar qualities as carbon nanotubes as well as properties of high heat resistance and the ability to block radiation. Multilayer composite structures in providing high neutron shielding, alternate high density polyethylene/ hexagonal boron (HDPE/hBN) with low density polyethylene (LDPE) layers, the former with a percentage of transmitted neutrons of only 4.16%. [13]. Boron-containing and nickel coatings deposited onto a finished housing of spacecraft equipment makes the heterogeneous shield preferred to aluminum. The protective shield consists of three layers (Table 1) arranged according to the growing atomic number of the basic absorbing substance of the layer. The first layer is a boron compound (boron carbide and sodium tetraborate shields have been considered). The second (structural) layer is a T-10 glass fabric containing aluminum, silicon and boron oxides and having a higher attenuation coefficient than aluminum. The last layer is nickel, having the highest atomic number..

| Shield/Layer | 2.75/2.5 mm                                   | 1.7 mm       | 1.75 mm |
|--------------|---|--------------|---------|
| 1            | B <sub>4</sub> C                              | Glass fabric | Ni      |
| 2            | B <sub>4</sub> Na <sub>2</sub> O <sub>7</sub> | Glass fabric | Ni      |

Table 2. Protective shield structure

Research further suggests protective shields consisting of three layers (Table 2) arranged according to the growing atomic number of the basic absorbing substance of the layer. The first layer is a boron compound (boron carbide and sodium tetraborate shields have been considered). The second (structural) layer is a T-10 glass fabric containing aluminum, silicon and boron oxides and having a higher attenuation coefficient than aluminum. The last layer is nickel, having the highest atomic number. The choice of these materials is due to the reaction cross-sections in these media. Boron has the largest photon trapping - ( $0.0092 \cdot 10^{-24} \text{ cm}^2$ ) and scattering ( $3.6 \cdot 10^{-24} \text{ cm}^2$ ) cross-sections among the inexpensive, light and commercially available materials [14]. Nickel possesses the best characteristics such as  $4.43 \cdot 10^{-24} \text{ cm}^2$  trapping cross-section and  $17.3 \cdot 10^{-24} \text{ cm}^2$  scattering cross-section, which is an order of magnitude higher than the reaction cross-sections of other heavy elements; for instance, copper density being about the same. So nickel is a good material to protect against gamma-radiation; therefore, it is efficient as the last protective layer [15]. Different shield designs may be compared to aluminum. Out of light and heavy chemical elements, materials with high reaction cross sections and low density are compared for shielding. The mass attenuation coefficient of boron-containing compounds is 20% higher than that of aluminum. Heterogeneous shields consisting of three layers (e.g. a glass cloth, borated material, and nickel) are also considered [16]. Boron nitride nanotubes (BNNTs) when loaded with 20% hydrogen per simulation studies shield 25% more radiation compared to AL2195 for particles in the galactic cosmic radiation spectrum as well as those seen in solar particle events [17]. Hydrogen (H), with the highest charge-to-mass ratio of any element, provides the best shielding against GCR. However, a shield of pure hydrogen is not practical. Nanotubes are favored to store hydrogen over particles due to their greater surface areas and higher hydrogen binding energies. Boron nitride nanotubes (BNNT) bonds, because of their ionic character, offer a 40% higher hydrogen binding energy than CNT bonds [18]. Additionally, hydrogenation of BNNTs occurs when hydrogen is bonded covalently with boron or nitrogen or both. Combining both, hydrogen-storage and hydrogenation approaches, provides synergistically improved radiation shielding effectiveness because modified  $sp^2$  bonds on BNNTs can afford more hydrogen storage.

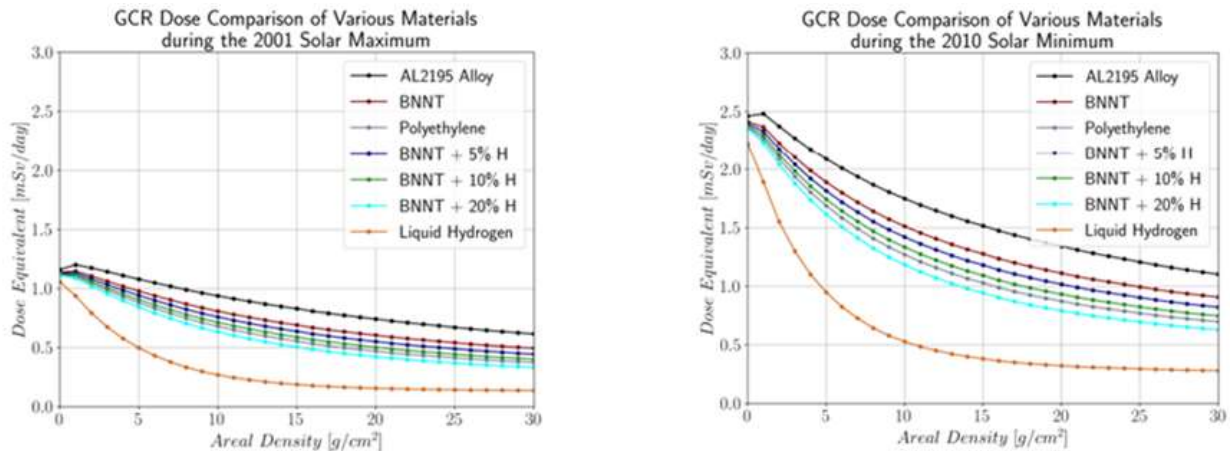


Figure 4. HZETRN calculation of the shielding comparisons of various materials as a function of areal density (thickness) of GCR during the 2001 solar maximum vs 2010 solar minimum.

#### Other mitigating strategies for spacecraft radiation-protection

Because of the ease in stopping some part of space radiation, all components of a spacecraft shield one another. Consider mass surrounding a radiation-sensitive part as a shield or protection although serving other primary, usually structural, purposes. For instance, electronic box platforms, box covers and circuit boards provide shielding. And, a part in the center of a stack of printed circuit boards may be exposed to only one tenth of the dose received by the same circuits on the uppermost board of a stack. So, spacecraft and electronic boxes layouts have a



fundamental importance in the design of a radiation tolerant spacecraft. Therefore, an accurate model of the spacecraft and a radiation analysis will allow defining the lowest radiation levels.

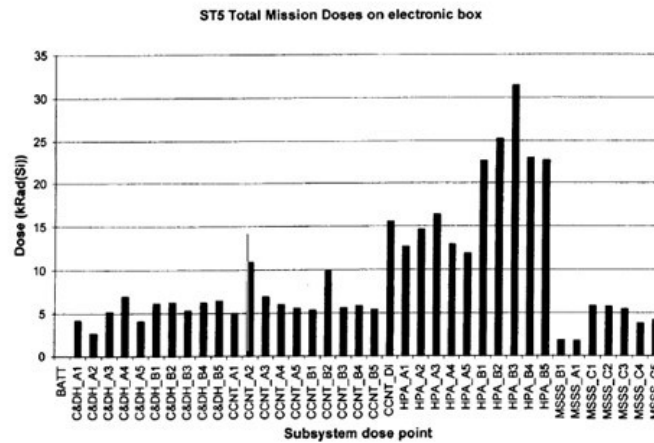


Figure 5. ST-5 Dose levels within the spacecraft

The spacecraft and electronic boxes layout has a fundamental importance in the design of a radiation tolerant spacecraft. Therefore, an accurate model of the spacecraft and a radiation analysis will allow defining the lowest radiation levels. Moreover, spacecraft composed of a large number of small components of widely varying materials fabricated within it, is preemptively evaluated for operations based on all radiation-absorbing masses present. The impracticality to consider every material in the dose analysis suggests the "equivalent thickness" of a representative atomic number like Aluminum for calculating dose levels at a given point within a given box and more generally the spacecraft. All their radiation-absorbing masses constitute an extremely complex array of masses, but an accurate model indicates how they contribute to radiation stopping [19]. Figure 5 shows the results of a Monte Carlo radiation analysis performed on different locations within the electronic box of the ST5 spacecraft showing the significant effect of a location within a spacecraft. When radiation shielding is considered in the spacecraft layout, significant shielding provides for the most sensitive parts without adding any extra weight. In the case of the ST5 example, the Command and Data Handling (C&DH) subsystem in an enclosure at the center of the spacecraft was decided at the beginning of the project. Hence, dose levels for the different points analyzed in the C&DH subsystem were lower than 5 krad, thus allowing the use of commercial memories for the subsystem.

If built-in mass on the spacecraft cannot be arranged so as to protect all sensitive components, then, as a last resort some *add-on* absorber may be used to interpose a few millimeters of suitable material between the device of interest and the external environment. This local shielding bestows a given dose reduction in a given volume for the minimum weight penalty. Protective insulation of a single integrated circuit, for example, may result from a blob of filled plastic applied directly to the package or by heavier materials such as Kovar or Tantalum. The 'spot shield' as it is called, in a proton-dominated environment differs from that in an electron-dominated one [20]. Heavy materials like Tantalum and Kovar have a better shielding efficiency for electron-dominated environments. A better shielding efficiency means that the same shielding is provided for less weight of shielding material.

Light materials e.g. Aluminum oxide (Al2O3) have a better shielding efficiency for proton-dominated environment. When a single event upset (SEU) occurs, the device functional output propagates to its associated circuitry. Subsequently, an impact analysis of the upset at subsystem-, system-, and spacecraft- levels is recommended. For example, a SEU occurring in an Analog to Digital converter may cause a single incorrect data sample to be gathered that shows an incorrect data point such as a star location or a misleading telemetry value. The concept of propagated SEUs is similar to what is performed in a standard circuit simulation, i.e. how a signal pulse, transient, or state affects a circuit's performance instantly or in future clock cycles. Important questions to answer include (1) where and what type of SEU occurred, (2) how the affected device in its specific application impacted overall performance of the system. Parameters such as access rates, operational modes, clock frequency, power supply voltage, etc., have definitive impacts not only on the occurrence, but also on the observed effect of an SEU [21]. Exploring the apparent effect the SEU has on device performance indicates the following possibilities:

- improper device operation
- incorrect device output

- errors in memory structures to be accessed externally
- noise spikes on transmission lines
- device mode change such as going from an active to standby mode; functional interrupt
- incorrect device timing

Circuit level analysis focuses on circuit operation and performance. As with device level analysis, determination of which devices have SEUs and what those SEUs look like, operational parameters and their impacts on SEU performance are described. Once the operational analysis is performed, the engineer performs a circuit simulation using digital or analog tools. The output of this analysis is a list of the potential SEUs in a circuit and their effects on circuit operation. When the circuit level analysis is complete, subsystem level analysis looks for performance aspects of the SEU-induced anomaly. The system level takes this one step further. The spacecraft level of analysis then would take the output of the system level analysis and determine, in this case, whether the incorrect command affected the overall spacecraft operation, or not. Once the acceptable event rates are defined, they are compared to the device event rates. Generally a Radiation Design Margin of at least 2 is required. If a part is found to be unacceptable, the alternatives are to redesign the system (to increase the acceptable error rate) or substitute a harder part. Hardness assurance is then based on derating of maximum operating values [22].

### **Radiation-protective material for spacecraft components**

Modern spacecraft needs several kilowatts of electric energy [23] which is usually produced through photovoltaic (PV) technologies because of solar energy abundance and safety requirements. Currently, the main materials used as light harvesters in solar cells (SCs) for space applications are silicon and multijunctions based on III–V semiconductors. Several studies reported that multijunction SCs exhibit a performance degradation of about 25% after receiving proton doses of  $10^{12}$  particles  $\text{cm}^{-2}$  [24], which can be accumulated in 3 years of exposure outside the Van Allen belts [25]. There is an urgent need to find new materials alternative to the space PV scenario. An interesting candidate is  $\text{Cu(In,Ga)Se}_2$  (CIGS) with lightweight gravimetric power about  $3 \text{ W g}^{-1}$  [26], and radiation-resistance (showing only 10% decrease of high power conversion efficiency (PCE), with incredibly high doses of  $10^{17}$  electrons  $\text{cm}^{-2}$  with 1 MeV energy [27] sunlight absorber that can be exploited for the realization of flexible devices through low-cost processes. During the past decade, metal halide perovskites (MHPs) have attracted the interest of the PV terrestrial community because of their physicochemical properties that allow the realization of perovskite solar cells (PSCs) with PCEs exceeding 25%, rivalling the performances of much older technologies such as Si, CIGS, and CdTe [28].

Surface charging can bring about electrostatic discharge, electromagnetic pulse jamming, solar array power loss and short circuit, material performance degradation, and accelerating contamination. Figure 3 displays the burnt damage of the solar array owing to secondary discharge.



Figure 6. The damage of solar array caused by arcing in ESA EURECA

Statistically, the anomalies caused by radiation account for approximately 40% of the total problems induced by the space environment [29]. The high-energy particles generating radiation are mainly protons, electrons, and heavy ions, which are originated from sediment in high latitude, Van Allen radiation belt, the solar cosmic ray, and the galactic cosmic ray.

Analysis of radiation effects on spacecraft components purposely enable selective production of radiation tolerant Neuromorphic Computing processor chips with innovative radiation-induced fault mitigation. The goal is to execute radiation hardening effort using new neuromorphic chips and to quantify the benefit of the multiple methods, ranging from hardening the semiconductor devices themselves, adding shielding to reduce dose, adding circuits for monitoring and redundancy (i.e. watchdog timer and error correcting code for memory) and finally using dual or triple cross-checking processor architecture for covering errors. There are two effects resulting from radiation exposure in semiconductors. The first is damage due to accumulated radiation dose that alters the characteristics of the transistors resulting in functional failure over time. The radiation dose can also cause damage in the Silicon crystal lattice, which can also cause functional failures. Failures due to TID cannot be reversed and it is the accumulation of radiation damage over time that is of concern.

There are established methods for calculating the rate of SEE upset in semiconductors, based on atomic physics. The charge deposition from a radiation particle in a Silicon circuit is given by the interaction cross section of that particle with Silicon. The Linear Energy Threshold (LET) is the energy required to deposit an electron-hole pair into the active layer of a semiconductor. The LET is the distance a given energy particle travels in the Silicon before it is stopped. Low energy particles deposit their energy in the surface layer and are blocked by the avionics shielding. High energy particles just shoot through the semiconductor without depositing any energy in the semiconductor. Therefore only a certain range of particle energies (which differ by species) can create charge effects in semiconductors leading directly to SEEs. Radiation test conditions are orders of magnitude higher than mission environments, yet the method of integrating incident energy with LET works well even over such a range. The LET values required for space missions are actually well established and very few commercial devices meet them; hence the need for radiation engineering at the fab and device level. LET values apply to the active devices within the semiconductor chip.

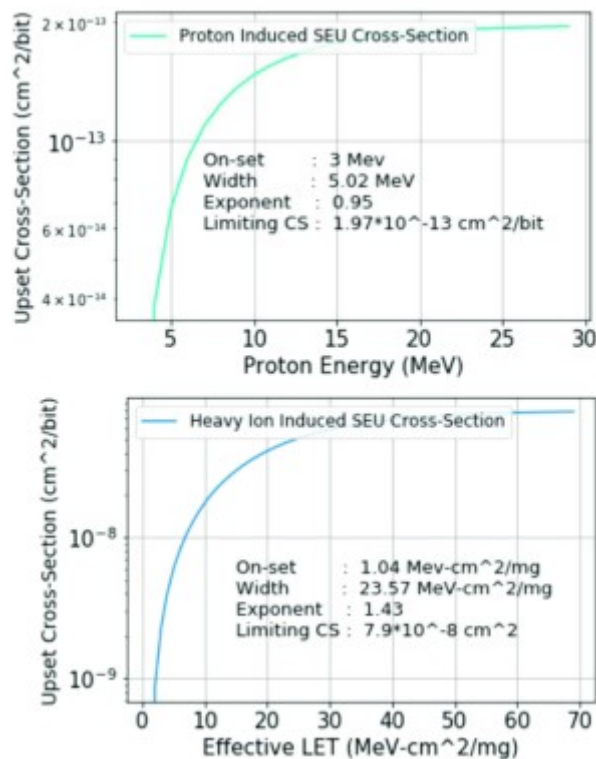




Figure 7.

### III. Radiation-protective materials for spacecraft components

#### Solar Cell Panels

Currently, the main materials used as light harvesters in solar cells (SCs) for space applications are Si and multijunctions based on III–V semiconductors. Several studies reported that multijunction SCs exhibit a performance degradation of about 25% after receiving proton doses of  $10^{12}$  particles  $\text{cm}^{-2}$  [30], which can be accumulated in 3 years of exposure outside Van Allen belts [31]. An interesting alternative to the space PV scenario is Cu(In,Ga)Se<sub>2</sub> (CIGS), a lightweight, radiation-resistant sunlight absorber that shows only 10% decrease in high power conversion efficiency (PCE), with high doses of  $10^{17}$  electrons  $\text{cm}^{-2}$  with 1 MeV energy [32]. During the past decade, metal halide perovskites (MHPs) have attracted the interest of the PV terrestrial community because of their physicochemical properties that allow the realization of perovskite solar cells (PSCs) with PCEs exceeding 25%, rivaling the performances of much older technologies such as Si, CIGS, and CdTe [33].

#### Semiconductors

Statistically, anomalies caused by radiation account for approximately 40% of the total problems induced by the space environment [34]. Analysis of radiation effects on well-intended spacecraft components purposely enable selective production of radiation-tolerant neuromorphic computing processor chips with innovative radiation-induced fault mitigation properties. The goal is to execute radiation hardening effort using new neuromorphic chips and to quantify the benefit of the multiple methods, ranging from hardening the semiconductor devices themselves, adding shielding to reduce dose, adding circuits for monitoring and redundancy (i.e. watchdog timer and error correcting code for memory) and finally using dual or triple cross-checking processor architecture for covering errors. The most important function to preserve is the memory, which suffers bit upsets that may not be detectable nor correctable. Unfortunately, all memory will suffer bit upsets, with only the *rate of upset* capable of mitigation by increases in semiconductor energy tolerance as expressed by the LET curve. Therefore, only architectural mitigations coupled with hardened memory chips can provide reliable operation. There are two effects resulting from radiation exposure in semiconductors, one of which is damage due to accumulated radiation dose that alters the characteristics of the transistors, resulting in functional failure over time. In the other, radiation also causes damage in the silicon crystal lattice, producing functional failures. Failures due to TID cannot be reversed and it is the accumulation of radiation damage over time that is of concern.

#### Radiation-protective material for space computers

Space computers suffer from the unwanted effects of cosmic energy. A single-event upset (SEU) occurs when high energy particles or heavy ions strike a complementary metal oxide semiconductor (CMOS) device and cause unintended, logic-level transitions—an essentially instantaneous impact on performance. Such transitions can be divided into three subcategories, depending on their effects within the fabric. A single-event transient (SET) occurs when an energized particle changes the voltage of a logic line and therefore changes its logic value. When such a change is stored in a memory device, such as a latching circuit or a D-Flip Flop, an SEU has occurred. Space radiation effects on computing platforms may be single-event effects (SEE) and/or total ionizing doses (TIDs). Where SEEs are momentary, TIDs are gradual and demonstrate cumulative effects that are measured as the amount of energy per unit of mass trapped in the material. While smaller feature sizes reduce the possibility of damage due to trapped charge, the probability of functionality interruption caused by high-energy particles is drastically increased. Thus, the need to mitigate the damaging effects from SEEs becomes a greater concern than TID in modern computing systems, particularly since space computers are not in space long enough to accumulate TID damage (Artemis Program will change that practice).

### IV. Conclusion

The emergence of commercial off-the-shelf (COTS) parts show limited control and frequent processing changes by design engineers [35]. Consequently, variability and the unpredictability of the radiation response ensue. All the potential radiation hazards should be known at the beginning of the design process in order to implement tolerant designs. Another issue with emerging technologies is their increased complexity. Electronic parts (integrated circuits) have grown in complexity such that determining all failure modes and risks from single particle event testing is impossible [36]. For example, Single Event Functional Interrupt (SEFI) is now a common failure mode.

First observed on processors, now SEFI is observed on Synchronous Dynamic Random Access Memories (SDRAM) and Analog to Digital Converters (ADC). Removal of power supply and subsequent re-initialization are required in the radiation tests to solve such problems to resume proper operation. In the future, design engineers will have to be more involved.

The two main activities of a radiation hardness assurance program describe the impactful radiation environment at the component part level and its failure level as the failure propagates through a circuit that impacts subsystem- and system- functions. The more employment of TID sensitive component parts, the greater need for a top-level requirement that monitors the effectiveness of different mitigation techniques (e.g., moving boxes to locations that offer more protection or adding spot shielding to parts). The radiation characterization is the first step of the definition of the part failure level. Then, the part radiation sensitivity is compared to the part uses in the different applications and the impact at the circuit level, box level, subsystem level, and system level. Design mitigation techniques allow the use of radiation sensitive parts. All these activities affect the spacecraft and electronic box layout, system design, and system operations. The radiation hardness assurance process is no longer confined to the part level. With a single point of contact for all project radiation issues (environment, device selection, testing), a radiation effects expert would be responsible for ensuring performance in the radiation environment of each device onboard the spacecraft and contribute to cost reduction strategies. Radiation hardness has to be taken into account at all the stages of the system development.

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