Radiation effects on composite materials used in space systems: a review

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ABSTRACT

The interactions of the composite materials with the space radiation environment are a considerably complex process. These interactions can lead to the occurrence of collective and extensive effects on the composite materials. These effects have resulted in damage and degradation of the electronics and components of satellites and spacecraft, and anomalies in the operational parts of space devices and other aerospace systems. The prediction of the material performances in this complicated environment is essential and considered the fundamental item for the success of any space mission. The presented research work focuses on studying the impact of space radiation sources on the composite materials used for satellite and spacecraft systems. The effects of some of the irradiation sources on a variety of composite materials are discussed. The protection and mitigation techniques from radiation damages are addressed.

1. Introduction

For aerospace applications and technology, the concepts of the materials used in particular for structural and configuration should be developed. This needs more information about the influence of space environment components, particularly the radiation sources on these materials. Commonly, the radiation hardness of the used material plays a great task in the determination of space system functionality and satellites’ lifetime. Modelling and simulation process for the radiation hardness of a space material allows the developers to arrive at a superior choice of materials satisfying the reduction of the design cycle time, and a safety improvement. The hardness is an important matter for the materials utilised in space flight of long-duration during the mission lifetime (Milkovich et al. 1986; Burchell 1996; Shen et al. 2019).

Many systems and subsystems of satellites and spacecraft are subject to attack by radiation environments like nuclear constituents, electromagnetic radiation, and high energy particles resulting from ambient space environments and onboard sources. For some space missions, the exposure to radiation is sufficient to cause degradation of the main properties of spacecraft material structures and endanger flight worthiness (Milkovich Scott et al. 1986; Jibir et al. 2011). One of the major onboard sources of radiation is the “Nuclear Reactor” in place on the spacecraft. On the other hand, neutrons, gamma “γ” rays, and beta “β” particles constitute essential sources of radiation onboard satellites (Atxaga et al. 2012; Sporea 2016; Anwar et al. 2017). Once the charged particles interact with spacecraft materials, the actively charged particles of energies greater than their rest energies are slowing down over a very short distance. This causes the production of the bremsstrahlung radiation. The concerned bremsstrahlung radiation sources, X-rays and γ-rays, are in general more penetration than the incident particles produced them (NASA – SP 1970). The energies associated with the bremsstrahlung are inversely proportional to the rest mass of the particle m². For energies of values equal to 100 GeV, the bremsstrahlung radiation sources contribute significantly to energy losses in the subject of electrons. Non-availability of the radiation-hardened components in some areas can lead to the use of technologies that are sensitive to radiation effects. In particular, the factors that determine the harshness due to the radiation effects on spacecraft structural materials include the identification of the radiation environment according to the mission objective, the existence of the onboard radiation source, the restricted conditions concerning temperature and pressure, as well as the sensitivity of the material properties against the exposure to radiation (https://www.unscear.org/docs/publications/2000/ UNSCEAR_2000_Report_Vol.I.pdf). Because of the passage of high-energy particles, the physical damage to the material implies power loss in solar cells and modules, degradation followed by the failure of microelectronics, and darkening of the optical components (Niemen 2001; Claey and Simoen 2002; Rancoita 2007; Joyce et al. 2012).

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The presented review article focuses on studying the space radiation environment and its effects on the composite materials used for satellite systems and aerospace application industries. Radiation sources concerning the classification and properties are discussed. Moreover, the composite materials used in space systems and aerospace applications are presented. The radiation environmental effects on these materials are outlined. The possible techniques for the protection of spacecraft and satellite systems are reported. In section two, the classification and properties of the space radiation sources are described. Section three gives information on the composite materials used for spacecraft and aerospace applications. Section four discusses the impact of several space radiation sources on composites. In the last section, protection from radiation damages is presented followed by the conclusion.

2. Radiation environment

Under the practical and innovative information, the radiation sources are classified into the external and internal sources together with the natural and onboard sources. These radiation sources are including neutrons, protons, heavier ions, electrons, and photons (gamma rays, X-rays, and ultraviolet rays). Both of these sources must be taken into consideration. The differentiation of radiation sources is dependent on many factors. These factors are the types, energy spectra, radiation intensity, sequential variation, as well as spatial and local distribution. For space vehicles, the ambient temperature and pressure of the neighboring atmosphere must be taken into account. Generally, for the study of all proper steps of space exploration missions, the reservations resulting from restricted knowledge of the environment should be also considered.

2.1. External radiation sources

In a NASA report, the authors classify the external sources of radiation environment according to the particle densities, fluxes, and particle energies. This is confirmed in the schematic diagram shown in Figure 1. (http://msis.jsc.nasa.gov/images/Section05/Image186.gif).

The characteristics and main components of the environmental space radiation are shown as given in the following Table 1 (NASA 1970).

2.2. Internal radiation sources

The main and important onboard source of radiation is known as the “Nuclear Reactor”. This is designed for the process of propulsion and/or for supplementary electric power. Throughout the reactor, the γ rays and neutrons are emitted with energy spectra and intensity values dependent on the designation of the reactor and the used shielding. Table 2 gives some examples of the kind and the amount of radiation expected at specific positions. These positions are enclosed to the following two exact internal nuclear power sources representing first the "SNAP-8" power reactor and second the SNAP-I 9 radioisotope thermoelectric generators (NASA 1970). At stated positions, the intensity levels are approximated values indicative of the degree and amount of the hazard.

3. Composite materials in space applications

Composite material is a material made from two or more constituent materials with significantly different physical or chemical properties that, when combined, produce a material with characteristics different from the individual. These materials combine high strength and low weight, while at the same time it is non-corrosive and has thermal and electrical insulation properties. The

![Figure1](http://msis.jsc.nasa.gov/images/Section05/Image186.gif)
Table 1. Classification and properties of the external radiation sources.

| Radiation source      | Type of radiation | Energy (E)                  | Flux (particles/cm²·sec) | Peculiar characteristics                                                                 |
|-----------------------|-------------------|----------------------------|--------------------------|-----------------------------------------------------------------------------------------|
| Galactic cosmic rays  | Protons (~90%)    | 10⁻² GeV-10¹⁰ GeV          | 2                        | Least significant                                                                        |
|                       | Alpha (~10%)      |                            |                          |                                                                                         |
| Solar wind            | Protons (~95%)    | ~1 keV                     | 2x10⁶ at 1 AU            | Low energy confines risk to surface impact                                              |
| Solar cosmic ray      | Protons (~95%)    | Spectrum is very steep     | See footnote c           | Energy and number of particles released per event varies, 10⁵ particles/cm² for medium flare |
| ray events (solar     |                   | above 30 MeV (~ E⁻¹) below |                          |                                                                                         |
| flares)               |                   | 10 MeV, spectrum ~ E⁻¹     |                          |                                                                                         |
| Solar electromagnetic | Infrared, visible | 6000 K⁰ black body        | Spectrum lower than 1200 | Spectrum lower than 1200 A⁰ is strongly dependent on the solar cycles                   |
|                       | soft X-rays       | radiating, erratic below 1200 A⁰ |                          |                                                                                         |
| Trapped and           | Protons and       | Energy of protons (Eₚ) < 30 | Flux varies with magnetic latitude; electron populations of both belts are subject to perturbations due to high altitude nuclear bursts; outer-belt protons are nonpenetrating |
| attential radiation   | electrons         | 30 MeV (90%), electrons   |                          |                                                                                         |
| sources               |                   | energy (Eₚ) < 5 MeV (90%)  |                          |                                                                                         |
| (1) Innerbelt (1.2 to | Virtually all protons less | Protons: 5 x 10⁵ (E > 1 MeV); electrons: 2 x 10⁷ (E > 0.5 MeV) Protons: 10⁴ (E > 10 keV); electrons: 5.2 x 10⁶ e⁻¹⁸/(E in MeV) |
| 3.2 Earth radii)     | than 1 MeV        |                            |                          |                                                                                         |
| (2) Outer belt (3 to  |                            |                            |                          |                                                                                         |
| 7 Earth radii)        |                   |                            |                          |                                                                                         |
| Aurora                | Electrons and     | Eₑ between 2 and 20 keV, Eₑ | Observed between 65⁰ and 70⁰ north and south magnetic latitudes at altitudes between 100 and 1000 km |
|                       | protons           | between 80 and 800 keV, 10¹⁵ |                          |                                                                                         |
|                       |                   | (electrons) during auroral storms; <10⁶ protons |                          |                                                                                         |

Footnotes: a) A⁰ = 0.1 nm, b) AU = 149.6 Gm, c) precise prediction for the activity of the solar flare cannot be done.

Table 2. Classification and properties of the internal radiation sources.

| Sources          | Kind of radiation | Energy spectra | Intensities of radiation | Measuring positions                      |
|------------------|-------------------|----------------|--------------------------|------------------------------------------|
| SNAP-8 (reactor) | Neutrons          | Modified fission| 1.5x10⁹ n/cm²·Sec (E > 0.1 MeV) | At power conversion system (10 ft below reactor) |
| SNAP-19 (isotope)| Gammas            | Fission        | 1.5 rad (c)/sec          | At converter package                      |
| Pu-238           |                   | Degraded spontaneous fission (9%) | 1.5x10⁸ n/cm²·Sec (E > 10 keV) |                                            |
|                   |                   | (a, n) reaction (91%) Mono energetic, 0.75 MeV | 5 x 10⁻⁸ rad (c)/sec |                                            |

composite materials are used as radiation shielding with particulate-filled composite encapsulations, coatings, adhesives, and structural materials (Abu Saleem 2021). These materials can be classified through the examples given as follows; (Sporea and Sporea 2016; Anwar et al. 2017).

1.- Fibre glass  
2.- Carbon fibres (more expensive than fibreglass),  
3.- Carbon nano-tubes (lighter and stronger but expensive),  
4.- Aluminium – based composites /Alloys,  
5.- Titanium – based composite/Alloys,  
6.- graphite-epoxy and Kevlar-epoxy,  
7.- Rubber, Ceramics, and glasses,  
8.- Polymers, synthetic plastics, and thermoplastics  
9.- Nano and polymeric/polymer-matrix composites [NC’s and PMC’s]  

The main important composites exploited in space vehicles include, but are not limited to, alloys, polymers, ceramics, graphite, glasses, and thermal-control coatings. For these composites, the effects of radiation must be determined.

4. Radiation environment interaction and effects

The main properties of the materials that are affected by radiation can be divided into the following three categories; (Rai et al. 2016; Anwar et al. 2017; Pavlenko et al. 2019)

- Mechanical: this includes the tensile power and strength, degree of flexibility and elasticity, the elongation level, crash properties, strengths of weariness, rigidity, cut-off forced, and the rate of steadiness and stabilities at all sides. Milkovich et al. (1986), showed that electron irradiation degrades the epoxy matrix due to the interaction with the matrix chemistry. This could lead to changeable in the mechanical properties of these composites. Sl semp and Santos (1981) investigated the effect of electron radiation on selected applicant composite materials. By the identification of the damaging mechanisms and the measurements of the thermal expansion coefficient for each type of composite material, the authors concluded that the physical and mechanical properties of the polysulphones films and
the polysulphones and epoxy composites are changed under the impact of excess 1 × 10 to the 9th power rads of electrons. Based upon these data, the 5208 and 934 epoxies and the P1700 polysulphones composites are acceptable for GEO Earth environment missions receiving 1 × 10 to the 9th power rads of electron radiation.

- The thermal property: This concerns the variation of the thermal conductance and the energy stored inside the material.
- Optical property: the parameters representing emissivity, absorbance, and reflectance are considered the main optical parameters affected by radiation sources.

The fundamental properties of exterior spacecraft surfaces are structural integrity and thermo-optical properties. Due to space radiation interactions, displacement damage and other problems can be occurred because of the following conditions. First, if the materials of spacecraft become very thin for supporting a required load, and/or if the layer films, used as protective and thermal insulators, break and eliminate from the spacecraft (David and Kleiman 2006). The changes in the material properties resulting from the radiation-induced displacement damage are a function of the kind of incident particle, the spectrum energy, the flux and fluence rate, the temperature, as well as the chemical composition and microstructures (Wang et al, 2002). On the other hand, the degradation of thermal and optical properties leads to a changeable in the temperature and thermal stability of the devices and components of spacecraft. Loss of transmittance through solar cell cover glass materials and communications can result in a decrease in the output of solar arrays and therefore a reduction in spacecraft power. In the electrical wiring and cables connecting to spacecraft, the resistivity of polymer insulation can be decreased upon radiation exposure (Dever et al. 2012; Nwankwo et al. 2020). However, Table 3 shows the influence of space radiation on some of the satellite systems.

A summary of space radiation effects on the material–based composites are explained and given as follows;

### 4.2. Effects on polymers

Polymers and polymer-based composites are important classes of materials having different applications in various fields of space engineering and technology. These materials reduce the weight of the final products, operating costs, and fuel consumption (Rachid et al. 2021). Consecutively, polymeric materials are extensively used as structural materials in LEO- orbital spacecraft because of their high strength to weight ratio and they have relatively superior thermal, mechanical, electrical, as well as thermo-optical properties. Owing to the more sensitivity of the polymeric materials to radiation, several important effects could be predictable. The properties of polymers are changed under exposure to radiation sources.

Due to the exposure of these materials to the ionising radiations (electrons, ion beam, and X rays), for example, a change in the chemical properties is taking place. In this case, the ionising radiation causes the initiation of the breaking of chemical bonds followed by the variation in surface and bulk characteristics and an otherwise ideal crystal. The result of this effect is obtained as a whole extension and dilation leading to the decrease in the density of the material. In the case of the metalised-based composites irradiated with neutrons at ambient temperature, the examinations have shown the elastic module of metals is not affected by neutrons below an fluence of 10^{17} n/cm (https://www.nrc.gov/docs/ML1533/ML15334A202.pdf). The plastic properties of metals are markedly affected by radiation. These properties include yield strength, ultimate tensile strength and elongation, reduction in area, creep, rupture stress, fatigue stress, hardness, impact strength, and ductile-to-brittle transition temperature. In general, metals exhibit reduced plasticity and ductility and increased hardness following irradiation. Experimental tests which are carried out to investigate the influence of space radiation, such as neutron irradiation, on the mechanical and thermal properties of metal-based composites have shown the dependency of many factors (NASA 1970; Rawal 2001; Hoffman and Skidmore 2009). These factors are the time of exposure, the temperature thermal energy during the duration of exposure, fluence, the distribution of the energy spectra, and the physical characterisation of the exposed material such as the composition, the amount of cold work, the prior of heat processing and treatment, quenching as well as the grain sizes. These factors are the most important variables. Furthermore, the accumulated fluences of radiation dosage can lead to the degradation in the mechanical properties and hazards in the structural metals, ceramics, and metal–matrix composites (NASA 1970; Rawal 2001).

### 4.1. Effects on alloy composites

The main effect of space radiation sources on the metals and alloy composites is the creation of lattice opportunities and the interstitial atomic grains through
essentially the degradation of the mechanical properties. This behaviour may lead to physical damage to the materials (http://holbert.faculty.asu.edu/eee560/spacerad.html; Nevarez et al. 2013).

For ceramics and polymer-based composites, the high radiation-dose rates enable, significantly, changes in the overall physical properties and can lead to damage effects (Nambiar and Yeow 2012). For example, Table 4 represents the different ranges of gamma doses which lead to mild to moderate, moderate to severe effects on different samples of polymeric materials used for satellites and aerospace systems. Moreover, Nevarez et al. (2013), studied the effects of gamma irradiation on specimens of Epon 862/W. This is shown in Figure 2. The figure illustrates specimens of Epon 862/W after the specimens were irradiated with a respective absorbed dose of gamma radiation. The figure shows that more darkening of the sample is observed with the increase in gamma doses. The figure clarifies the dense darkened for the sample exposed to 1.6 Mrad than that exposed to 0.8 Mrad. This indicates the variation in the physical properties of the material due to the exposure to high doses of radiation. The results confirmed that the level of darkening is increased with the duration of exposure (Wirtenson and White 1992; Nevarez et al. 2013).

Nambiar and Yeow (2012), confirmed that polymer composites reinforced with micro/nanomaterials have become attractive applicants for the materials designed to effectively attenuate and reduce photon or radiation particulates, and used as radiation shields. Burchell, (1996), found that neutron irradiation-induced dimensional change mechanism of carbon-carbon composite materials. This causes the altering in the physical properties through the reduction of the thermal conductivity of the carbon composite and the increase in the composite strength to a maximum, which is attributed to form the cracks of the fibre-matrix interface. The energetic photons can break the molecular bonds causing the degradation mechanism and a changeable of material properties (physical as absorptivity, reflectivity, transmissivity, and mechanical) with the changing of the performance characteristics. This can result in material damage depending on the total doses and thus total sun hours with material radiation sensitivities.

Inorganic polymers, these materials are capable to absorb ultraviolet “UV” radiation. This leads to the occurrence of photochemical reactions. These reactions have occurred within the molecules of the organic component resulting in such effects as discoloration of the material (increasing the solar absorption) and loss of the mechanical property due to the chemical changes and dislocation of the atomic structures in the material (Hsissou et al. 2021).

Polymer-matrix composites are subjected to severe degradation from long-term exposure to the space radiation environment. The polymer epoxies that make up polymeric mats can undergo micro-cracking and chemical and molecular changes from radiation exposure which alter anticipated mechanical characteristics (Rawal 2001; Moises et al. 2013).

| Table 4. Effects of gamma radiation dose on polymers of satellite systems. |
|-------------------------------------------------|
| Material                              | Doses of gamma radiation (rad) |
|                                     | Mild to moderate damage | Moderate to severe damage |
| Teflon (FE)                         | 1E6-8E6                   | 8E6-2E7                   |
| Teflon (PTFE)                       | 2E4-1E5                   | 1E5-2E6                   |
| Kapton, Polyimide                   | 1E8-1E10                  | 1E10-1E11                 |
| Mylar, Polyethylene                 | 4E6-1E8                   | 1E8-1E9                   |
| terephthalate (PET)                 |                           |                           |
| Polyethylene                        | 1E7-8E7                   | 8E7-2E8                   |
| Polyurethane                        | 1E9-5E9                   | 5E9-2E10                  |
| Silicone                            | 1E8-1E9                   | 1E9-5E9                   |
| Epoxy                               | 2E8-8E8                   | 8E8-5E9                   |
| Nylon, Polyamide                    | 3E5-2E6                   | 2E6-2E7                   |
| Polyvinyl chloride (PVC)            | 1E7-7E7                   | 7E7-2E8                   |

Figure 2. Epon 862/W after the specimens irradiating with gamma doses.
Considerations become very important for matrix composites, which are exposed to damaging protons from the Van Allen radiation belts. Protons can induce mechanical property changes in the matrix materials by enhancing cross-linking mechanisms through the free fundamental formation and scissoring through main chain breakage. Also, electrons and protons trapped in the earth’s magnetic field can change the dimensional stability and thermomechanical properties of the organic matrix composites (Mauri and Crossman 1983; Rawal 2001).

Furthermore, the degradation responses of matrix materials have been tested using a liquid epoxy “Epon 862” /W specimens, and after the irradiation with gamma-rays resulted from a 60,000 Ci, 60Co source (Moises et al. 2013). The authors reveal that the detection of increasing trends in ultimate tensile strength and a significant increase in hardness suggests γ-radiation exposure, induces degradation mechanisms in Epon 862/W, and provide insight into the possible degradation processes in the low-Earth orbit environment. Hoffman and Skidmore (2009) studied the microstructural behaviour and the variation of properties for the epoxy matrix exposed to total gamma doses of 0.5, 1.0, and 2.0MGy. The tests revealed changes in hardness, thermal properties, and spectroscopy results with increasing the gamma irradiation. The results quantify the changes in the epoxy within the composite as a result of exposure to gamma radiation.

In the case of polymeric films irradiated with the UV-radiation, and for films of thicknesses more than the attenuation depth of UV- radiation source, the undegraded section of the polymer width can reinforce a degraded and destroyed surface. On the other hand, the polymeric films with a thickness of the same order as the UV- attenuated depth, the potential for degradation of UV radiation is more important because this effect can lead to damaging and cracking over all the film thickness.

On the other hand, the applications of polymers in GEO orbit are restricted and with limited uses. At LEO, the polymers are regular and commonly used. Conversely, the GEO space environment is dangerous and with bad and worst effects on polymers. Major hazards resulting from the normal GEO environmental effects may include;

i. The energetic particles of the external sources such as the high energy electrons, photons, protons, alpha particles, neutrinos, adding to the thermal neutrons, and any other natural elements happening isotopes;

ii. The internal sources include the neutrons, gamma “γ” rays, and beta “β” particles;

iii. The braking radiation sources containing X-rays and gamma radiation are usually penetrated with great values than the incident particles. This can lead to damage to materials.

### 4.3. Effects on ceramics, graphite, and glasses

The glass and ceramic materials undergo UV radiation-induced darkening. UV light interactions in glass and ceramic materials can cause the formation of electrons and holes, which are trapped in various defects. UV darkening is harmful to spacecraft materials, for example, the white paint coating films and the cover glasses of the solar cells. In the case of ionising radiation, the mechanical properties of ceramics are not appreciably changed by exposure to ionising radiation doses of less than 10³ rad (ceramic) or by neutron fluences of less than 10¹⁵ n/cm². At higher exposure levels, effects resulting from lattice displacement and gas formation become important. The latter effect is particularly important in boron- or beryllium-containing ceramics owing to the formation of gaseous helium following exposure to thermal neutrons. Large changes in the thermal conductivity of ceramics have been observed at neutron fluences of 10¹⁸ to 10¹⁹ n/cm² (NASA 1970; Milkovich Scott et al. 1986; Wirtenson and White 1992). For the radiation effect on graphite, because this material finds extensive use as a moderator in nuclear-reactor systems, more extensive studies of the influence of neutron radiation sources on graphite have been carried out. The impact of the neutron radiation source on the graphite properties is shown in Table 5 (NASA 1970). The ground tests of graphite irradiation demonstrate the significant effects at high neutron fluence of more than 10¹⁹ n/cm² (NASA 1970; Tenney et al. 1982).

On the other hand, theoretical modelling is performed to study the interaction between graphite-epoxy composite and charged particles present in the space environment. The theoretical studies of radiation damage to epoxy materials showed that an elliptical equatorial orbit of 300 Km perigee by 2750 Km apogee can accumulate enough radiation dose, in two years or less, comparable to GEO orbital environment for 30 years (Chang and Kamaratos 1982).

To investigate the influence of radiation sources on the glass, a variety of allotropic systems of silica and combined silica have been widely studied. In a NASA report (NASA 1970), the authors confirmed that, at fluence of the value 1.5 × 10²⁰ n/cm², both fused silica cristobalite, tridymite, and quartz are closed to a limited density around 2.20 g/cm³. This density

| Property                  | How affected       |
|---------------------------|--------------------|
| Mechanic strength         | increase           |
| Hardness                  | increase           |
| Thermal conductivity      | reduces            |
| Energy stored             | Be Increasing      |
| Chemical reactivity       | Be Increasing      |
| Dimensional stability     | Anisotropic expanding |
value is corresponding to the energy \((E > 1 \text{ keV})\). In this case, the system of both fused silica is completely disorganised and with an optical isotropic. Otherwise, the low-temperature thermal conductivity of neutrons irradiated fused silica increases as the density is increased and tends to be double the initial value after exposure to the \(6 \times 10^{19} \text{n/cm}^2\) (NASA 1970).

The investigations of the mechanical properties have shown that the change in mechanical properties concerning Young’s modulus, shear modulus, and compressibility are generally negligible to the minor (lower than 5%) after the irradiation of glasses with neutron and gamma-rays. On the contrary, for borosilicate glass irradiated with a considerably higher thermal-neutron, the helium gas is produced causing the occurrence of cracking and eventually, the breaking down of the glass. Furthermore, the less transparency and darkening of glasses consequent the exposure to the ionising radiation sources is one of the fully notarised phenomena.

### 4.4. Influence on thermal control coating materials

The optical characteristics of spacecraft surfaces are one of the main important properties affected by exposure to a radiation environment. Some of the optical parameters concerning the absorption, reflection, and emission are more sensitive to appropriate thermal and temperature control of the whole system. Therefore, the impact of space radiation sources on the optical properties of the surface is of concern in all phases for the steadiness of spacecraft. The stability of coatings within a radiation environment can be achieved through the determination of the mechanical and chemical matrix stabilities. This coating stability is affected by the kind of the used surface in which the coating is applied and put on it, and also by adding some of the additive and chemical constituents such that plasticisers and pigments (Finckenor 2018; Ghidini 2018). The group of heteroaromatic polymers exactly “pyrones” is probably used as a coating matrix. These materials can keep their original and essential tensile property after the irradiation of electrons with a dose of \(10^{10} \text{rad (c)}\) and energy of about 2 MeV. Generally, the high pigment and more colour coatings are more resistant to radiation than that containing fewer amounts of pigment materials. Besides, extensive studies had been conducted to find out the impact of the environmental components referring to the ultraviolet “UV” radiation, and energetic particles on the physical characteristics of both inorganic and organic materials considered for thermally controlled coating. The tests are performed to investigate the effects of these radiation sources on the pigment of zinc oxide “ZnO”. The obtained results clarified that this material has low solar absorbance, and is considered fairly stable under the effects of the exposed “UV” radiation (Finckenor 2018; Ghidini 2018).

### 4.5. Effects on adhesives

Because most adhesive materials consist of an organic base, it is reasonably vulnerable to radiation damage. Almost of radiation sources such as neutrons, “γ” and “β” rays, of them can cause the same damage to these materials due to the absorption of the same doses. The influence of radiation sources on the adhesives has been found using the measurements of the change in the shearing strength, tensile and power strength, as well as the peeling fatigue, and weariness examinations subsequent irradiation (Lucas et al. 2011). Unluckily, most of the experimental investigations have not been conducted under the dynamical load and weight conditions. In general, several adhesives performed for applications with high-temperature conditions, are mainly more resistant to radiation. These adhesives are including epoxy-, nylon-, and vinyl-phenolics, and all of them are retained to the degree that “60 %” of the initial strengths of bond following the irradiation to a dose of \(10^9\) rad (NASA 1970).

The impact of radiation sources on different types of composite materials used for aerospace engineering are summarised and presented in Tables 6, 7, 8, and 9 respectively (NASA 1970). The data tables show the conditions of the irradiation and doses required to perform significant changes in the properties of these composites.

### 5. Mitigation and protective materials

The composite materials performed for space applications have verifications to be more resistive to radiation environments. In particular, space systems designers need to determine the best conditions required for increasing the performance of the components and instruments of space systems operating in harsh radiation environments. Therefore, protection and mitigation methods can lead to increase efficiency and verify the best performance of space systems allowing satellites and spacecraft to operate with enhanced mission lifetimes (Naito et al. 2020). The protective materials of composites can lead to

### Table 6. Estimation of the predicted changeable on the mechanical characteristic of the alloys exposed to neutron radiation.

| Condition                  | The detectable damaging threshold \((n/cm^2)\) \((E > 1 \text{ keV})\) |
|----------------------------|-------------------------------------------------|
| Temperature \(\geq 300^\circ \text{K}\) | Engineering materials Two orders of magnitude \((10^{17} \text{ to } 10^{19})\) |
| Cryogenic temperatures \(< 100^\circ \text{K}\) | Estimated data \((10^{16} \text{ to } 10^{18})\) |
improving the physical properties (mechanical, thermal). The composite materials have verifications to be more resistive to radiation environments. These materials have a potential for use as structural materials with relatively high shielding efficiency (Naito et al. 2020). Accordingly, various techniques are carried out to mitigate the occurrence of degradation, damage, and failure for the composite materials due to the radiation effects.

For satellite thermal stability and control, the factors representing the emissivity and absorptivity are of particular importance for obtaining the optimum performance. Therefore, black and white thermal coatings are designed to have particular radiative properties that are tailored for specific missions. As an example, for solar orbiters, the radiative surfaces should be coated with a white coating for obtaining low absorbance and high emissivity surfaces. On the other hand, Fibre-Reinforced Polymeric Composites such that Lithium doped polyethylene and Al-Be alloys are selected as radiation mitigating materials. Also, the epoxy coating reinforced with nano graphene is considered to improve the properties of the polymer composite coating (Rojdev et al. 2009; Shruti and W 2012). For satellite and spacecraft structures, carbon fibre/epoxy composite material with the protective material MWCNTs is used for radiation protection (Axtaga et al. 2012). (Firas Awaja et al. 2011; Thibeault et al. 2015) estimate the carbon fibre reinforced polymer with different protective materials such as carbon nanotubes and carbon nano-clay under the simulation of the LEO space environment. According to NASA research, polyethylene is considered a better material used in space radiation protection (Zicai et al. 2019). The advanced polymeric composite (cyanate-epoxy blend reinforced with carbon fibres) ensures high resistance when operating at negative and positive temperatures from the range of $(-55^\circ C)$ to $(+185^\circ C)$ (Mihaela et al, 2018).

Additionally, the metal oxide is suitable to be used for reinforcement (reinforced-composites) and is preferred for alloy improvement. Such that, (MgO) is a probable choice to enhance the alloys of Aluminium Al6061 due to its high melting point, compressive strength, hardness, and excellent thermodynamic stability (Abd El-Hameed Afaf and Abdel Aziz 2021). Ezzat et al. (2021a) “paper one”, evaluated

Table 7. Conditions of the ionising radiation sources influenced the properties of thermosetting plastics.

| Material                          | Property                  | Doses, Fluo (C) | Effects                      |
|-----------------------------------|---------------------------|-----------------|------------------------------|
| Un-failed phenolic                | Tensile and impact strength | $5 \times 10^7$ | Slight reduction 50% reduction |
| Epoxies                           | Flexural strength         | $10^8$          | >80% of original when cured with aromatic agents; and 50% to 80% when cured with aliphatic agents |
| Phenol formaldehyde with asbestos filler | Tensile strength          | $3.9 \times 10^8$ | 25% reduction |
| Polyurethane foam sandwich construction | Ultimate flexural strength; flatwise compressive strength | $10^8$ | No changes observed |

Table 8. Conditions of the ionising radiation sources influenced the properties of thermoplastics.

| Material       | Property                  | Doses, rad (C) | Effects                          |
|----------------|---------------------------|----------------|----------------------------------|
| Polystyrene    | Tensile strength and elongation | $5 \times 10^5$ | Decrease by only 5% to 10% Marked losses in elongation and impact strength after $10^7$ rad (C) |
| Nylon sheet    | Elongation and impact strength | $8.6 \times 10^5$ | Threshold of damage 25% reduction |
| Polypropylene  | Impact strength           | $6 \times 10^5$ | Reduced by 7% Less than 50% and the material becomes more weak and brittle |
| Cellulose acetate | Impact strength          | $2 \times 10^7$ | No changes observed |

Table 9. Results of the impact on radiation on coatings and alloy composites.

| Material     | Property                  | Fluence for appreciable change | Effects                          |
|--------------|---------------------------|-------------------------------|----------------------------------|
| BeO          | Density $10^{11}$ n/cm²  | Decreases                     | $10^{11}$ to $10^{12}$ n/cm²     |
|              | Thermal conductivity $(E > 1$ keV) |                           | Great decrease; to 1/2 initial value by $10^{10}$ n/cm² |
|              | Modulus of elasticity $(E > 1$ keV) |                           | 5x$10^6$ n/cm² decrease by as much as 50% |
|              | Compressive strength $(E > 1$ keV) |                           | $10^9$ n/cm² substantial decrease |
|              | Mechanical integrity $(E > 1$ keV) |                           | $10^8$ n/cm² with increasing dose |
| Al₂O₃        | Density $10^{19}$ n/cm²  | Decreases about 1% by         | $6 \times 10^{20}$ n/cm²          |
|              | Thermal conductivity $(E > 1$ keV) |                           | Decreases to less than 1/2         |
|              | Thermal conductivity Co-60 |                           | 2 initial value                     |
|              | 10 rad (Al₂O₃)           |                             | Reduction to about 50 percent of the original value by $3 \times 10^6$ n/cm² |
| MgO          | Mechanical integrity $3 \times 10^{10}$ n/cm² |                           | Decreases 40% |
| B₄C          | Thermal conductivity $(E > 1$ keV) |                           | Cracking and eventual disintegration |
the effect of hybrid nanocomposite $\text{Cs}/\text{ZnO}/\text{GO}$ on the electronic properties and thermal stability of certain NP polysaccharides. The authors confirmed that Hybrid nanocomposite $\text{Cs}/\text{ZnO}/\text{GO}$ is an innovative new technology for a wide variety of uses, including coatings and adhesives. On the other hand, polymers such as polytetrafluoroethylene (PTFE) microfibers could be modified with ZnO and graphene (G), to improve their electrical properties. These materials are important for the nanoelectronic devices used in space (Hegazy et al. 2022). Also, Ezzat et al. (2021b) “paper two”, have shown that the nanocomposite natural polymer/metal oxide (NP/MO) is an attractive new material with efficient expense, more stable (physically and chemically), and thermally stable.

Moreover, radiation shielding is considered one of the most interesting methods against radiation hazards. The purpose of shielding is to attenuate the energy and the flux of ionising radiation as they pass through the shield material, such that the doses absorbed in silicon is sufficiently below the maximum dose ratings of electronic components. In space hardware, aluminium is used as both a radiation shield and structural enclosure (SIDER project 2013). Many thin films are also used as radiation shielding such that the hybrid composite consisting of metalised polymer-based films and polymer composite layers like (Al/ [CFC/PFC] 4s /Al) with aluminium as the structural material of satellite and spacecraft (Emmanuel 2017; Abu Saleem et al. 2021; Chaitali et al. 2021). Masayuki et al. (2021) confirmed that the exploiting of composite materials in place of aluminium in spacecraft is a good option for mitigation of radiation exposure. In the report of the SIDER project, the calculations conducted with the theoretical tools indicated that the composite shielding material reduced the overall dose, particularly of electron and proton irradiation up to 32 % (SIDER project 2013). Moreover, conservative circuit design and the hardening of sensitive components in satellites designed by the manufacturers can lead to mitigating the displacement damage and cumulative effects of the total ionising dose (Nwankwo Victor et al. 2020).

Polyamides, like Kapton, have been exploited in NASA missions to insulate spacecraft and electronic equipment. It is used as multilayer insulators (MLI) to protect spacecraft from space radiation and thermal effect. These materials possess a wide range of thermal stability and have lightweight and chemical resistance to degradation by radiation. (Radiation shielding “Patent”2013; Schiavone 2013; Elena et al 2019).

Likewise, for the Teflon FEP used for the protection of satellite and spacecraft surfaces, Hegazy et al. (2021) studied the model and techniques required to enhance the physical properties of this material. The results have confirmed the addition of a layer of OZn and SiO$_2$ on Teflon FEP leads to improving the physical, chemical, thermal, and electrical stability of Teflon FEP.

Polymers made of low atomic numbers (Z) (similar to polyethylene), carbon (c), hydrogen (H), oxygen (O), and nitrogen (N) are considered the best shielding materials against several radiation sources such as the galactic cosmic radiation (GCRs), the electrons, and solar protons (Emmanuel 2017; Cucinotta et al. 2006; Chaitali et al. 2021). Naito et al., (2021a, 2021b) investigated the radiation shielding properties of composite materials compared to conventional materials of polyethylene considered a shielding material, and aluminium as a structural material in spacecraft. The authors have shown the composite materials had shielding efficiency intermediate between that of polyethylene and aluminium: >30% higher shielding efficiency than aluminium and <30% lower than polyethylene. The authors also confirmed that the use of composite materials in place of aluminium in spacecraft is a promising option for the mitigation of space radiation exposure.

Moreover, composites made of polymers and high atomic number fillers should allow obtaining material with low weight, good flexibility, and good processability (More et al. 2021).

For space system structures, novel materials like hydrogenated boron nitride nano-tubes show particular characteristics such as thermal resistance, flexibility, and high strength, and confirm properties capable of radiation shielding (Spillantini et al. 2007; Thibeault et al. 2015; Cheraghi et al. 2021). Klamm (2015) used the Tungsten-doped PolyPhenolic and Polyethylene resins to optimise the shielding performance. In the work of (Cai et al. 2022), experimental and simulated studies are carried out to investigate the shielding performance of new composites developed with more hydrogen content. The results show that hydrogenous-rich composite has a higher shielding ability for 80 and 400 MeV/n 12C particles. The tested data confirmed that these materials are more advantageous in space radiation shielding and could be used in huge spacecraft. More efforts had been done by the authors to produce a protective plasma, electrostatic, or magnetic field around the spacecraft that can repel the incoming radiation (Ferrone 2020; Cheraghi et al. 2021).

6. Conclusion

The presented research focuses on studying the space radiation sources impact on the characterisation of composite materials used for space systems and aerospace industries. The discussion quoted above
indicates that the composite materials exposed to radiation environment undergo degradation, damaging as well as the changeable in the optical, thermo-physical and mechanical properties. Ground-based tests have been carried out to determine how well and how long these materials will survive the space radiation. The results have confirmed that the increase in radiation dose can cause a decrease in material strength leading to fracture and damage to the surface. Electron and particulate radiation can produce a reduction in the molecular weight material. High energy protons can affect the overall composite durability. These results have also confirmed that the degree to which the impact of the space environment on composite materials is dependent upon the conditions of the radiation environment and the susceptibility of these materials to being altered by the radiation exposures. Besides, using composite materials, the protection and mitigation process is considered to increase the efficiency and the performance of the space systems. Several composite materials used for radiation shielding, protective coatings, and adhesives are capable to reduce the anomalies and failure of space systems due to the radiation impact. These materials are considered to be non-contaminating, resistant to attack, high-strength, cost-effective, easily scalable to large dimensions, stiffness, and more stable in radiation environment as well. It could be concluded that this study can give information helping to find out the feasibility of further enhancement for the properties of the composites, especially new space materials used in new technology to carry out the optimal performance, particularly in a harsh radiation environment.

Disclosure statement

No potential conflict of interest was reported by the author(s).

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References

Abd El-Hameed Afaf M, Abdel Aziz YA. 2021. Aluminum alloys in space applications: a short report. Journal of Advanced Research in Applied Sciences and Engineering Technology. 22(1):1–7. doi:10.37934/araset.22.1.17.
Abu Saleem AR, Abdelal N, Alsabbagh A, Al-Jarrah M, Al-Jawarneh F. 2021. Radiation shielding of fiber reinforced polymer composites incorporating lead nanoparticles— an empirical approach. Polymers. 13(21):3699. doi:10.3390/polym13213699.

Adebayo Emmanuel. 2017. Design and Development of a Multi Functions Composite Radiation Shield for Space Applications. Ph.D. Thesis, Faculty of Graduate Studies of the The University of Manitoba.
Anwar A, Elify D, Ramadan AM, Hassan GM. 2017. Effect of gamma-irradiation on the optical and electrical properties of fiber-reinforced composites. Radiation Physics and Chemistry. 134:14–18. doi:10.1016/j.radphyschem.2017.01.008.
Atxaga G, Marcos J, Urado M, Carapelle A, Orava R. 2012. RADIATION SHIELDING OF COMPOSITE SPACE ENCLOSURES. Page 1 of 10 IAC-12, C2.6.6, x13735. Accessed: https://orbi.ulg.ac.be/bitstream/2268/132394/1/IAC-12%2cC2%2c6%2c%2cx13735.pdf
Awaja F, Nguyen M-T, Zhang S, Arhatari B. 2011. The investigation of inner structural damage of UV and heat degraded polymer composites using X-ray micro CT. Composites Part A Applied Science and Manufacturing. 42(4):408–418. doi:10.1016/j.compositesa.2010.12.015.
Burchell Timothy D. 1996. Radiation damage in carbon-carbon composites: structure and property effects. Physica Scripta. T64:17–25. doi:10.1088/0031-8949/1996/T64/002.
Chang CK, Efstrathios K. 1982. Theoretical studies of radiation effects in composite materials for space use. NASA Contractor Report 3618.
Cheraghi E, Chen S, Yeow JTW. 2021. Boron nitride-based nanomaterials for radiation shielding: a review. IEEE Nanotechnol. Mag. 15(3):8–17. doi:10.1109/MNNANO.2021.3066390.
Claeys C, Simoen E. 2002. Radiation effects in the advanced semiconductor material and devices. Berlin Heidelberg New York: Springer-Verlag.
Cucinotta FA, Kim M-HY, Ren L. 2006. Evaluating shielding effectiveness for reducing space radiation cancer risks. Radiat. Meas. 41(9–10):1173–1185. doi:10.1016/j.radmeas.2006.03.011.
da Silva LFM, Andreas O, Adams Robert D. 2011. Handbook of Adhesion Technology. doi:10.1007/978-3-642-01169-6_1.

David EL, Kleiman JJ. 2006. Space environmental effects on materials. J Spacecraft Rockets. 43:461–481.
Dever J, Banks B, de Groh K, Miller S. 2012. Handbook of environmental degradation of materials, chapter 24. Degradation of spacecraft materials. Cleveland (Ohio): NASA Glenn Research Center.
Ezzat HA, Hegazy MA, Nada NA, Osman O, Ibrahim MA. 2021a. Application of Cs/ZnO/GO Hybrid nanocomposite for enhanced inter-behavior of electronic properties and thermal stability as corrosion inhibitor. Egyptian Journal of Chemistry. 64(3):1197–1205. Paper one.
Ezzat HA, Hegazy MA, Nada NA, Osman O, Ibrahim MA. 2021b. Development of natural polymer/metal oxide nanocomposite reinforced with graphene oxide for optoelectronic applications. NRIAG Journal of Astronomy and Geophysics. 10(1):10–22. Paper two. doi:10.1007/s10502-020-09977-2020.1846246.
Ferrone K. 2020. Master’s Thesis. University of Texas MD Anderson Cancer Center; Houston (TX, USA): Active Magnetic Radiation Shielding for Long-Duration Human Spaceflight.
Finckenor MM. 2018. Materials for spacecraft. In: Bhat NB, editor. Aerospace materials and applications. NASA Marshall Space Flight Center; p. 1–29.
Ghidini T. 2018. Materials for space exploration and settlement. Nature Mater. 17(10):846–850. doi:10.1038/s41563-018-0184-4.

Hegazy MA, Ezzat HA, Nada NA, Ibrahim S, Yahia IS, Zahran HY, Elhaes H, Gomaa I, Ibrahim MA. 2022. Effect of CuO and graphene on PTFE microfibers: experimental and modeling approaches. Polymers. 14(6):1069. doi:10.3390/polym14061069.

Hegazy MA, Ghoneim R, Ezzat HA, Nada NA, Ibrahim S, Yahia IS, Elhaes H, Ibrahim MA. 2021. Electronic and physical studies for teflon FEP as a thermal control in low earth orbit reinforced with ZnO and SiO2 nanoparticles. Journal of Molecular Modeling. 27(10):1–8. doi:10.1007/s00894-021-04912-z.

Hoffman EN, Skidmore TE. 2009. Radiation effects on epoxy/carbon-fiber composite. Journal of Nuclear Materials. 392(2):371–378. doi:10.1016/j.jnucmat.2009.03.027.

Hissou S, Seghir R, Benzekri Z, Hilali M, Rafik M, Elharfi A. 2021. Polymer composite materials: a comprehensive review. Composite Structures. 262:113640. doi:10.1016/j.compstruct.2021.113640.

Jibiri NN, Nwankwo VUJ, Kio M. 2011. Determination of the stopping power and failure time of spacecraft components due to proton interaction using GOES 11 acquisition data. International Journal of Engineering, Science and Technology. 3:6532–6542.

Klamm A, Benjamian. 2015. Passive space radiation shielding: mass and volume optimization of tungsten-doped polyphenolic and polyethylene resins, 29th Annual AIAA/USU Conference on Small Satellites. SSC15-IV–3.

Kristina R, William A, Richard W, Brad G, Badavi Francis P. 2009. Evaluation of multi-functional materials for deep space radiation shielding. Henderson (NV): National Space & Missile Materials Symposium. 2009 Jun 22-26.

Mauri RE, Crossman FW. 1983. Jan 10-13. Space radiation effects on structural composites. Anon; 9 p: American Institute of aeronautics and astronauts; New York, NY (USA); 21. Aerospace sciences meeting of the American Institute of Aeronautics and Astronautics. Reno (NV (USA)).

Milkovich Scott M, Herakovich Carl T, SYKES GEORGEF. 1986. Space radiation effects on the thermo-mechanical behavior of composite materials. Journal of COMPOSITE MATERIALS. 20(6):579–593. doi:10.1177/0021983860200605.

Minghui C, Yang TL, Yang Haixia H, Jianwei H. 2022. Experimental and simulation study on shielding performance of developed hydrogenous composites. Space: Science & Technology, Volume 2022, Article ID. 9754387:11.

Moises N, Waller Jess M, Saulsbury Regor L. 2013. Characterization of space radiation effects on composite overwrapped pressure vessels for the international space station, NASA USRP – internship final report. Technical Report. doi:10.13140/RG.2.1.2397.6488.

More CV, Alsayed Z, Badawi MS, Thabet AA, Pawar PP. 2021. Environmental chemistry letters. 19:2057–2090. 16103653.

Naito M, Hisashi K, Masamune K, Kusano H, Kusumoto T, Uchihori Y, Endo T, Hagiwara Y, Kiyono N, Kodama H, et al. 2021a. Applicability of composite materials for space radiation shielding of spacecraft. Life Sciences in Space Research. 31:71–79. doi:10.1016/j.lssr.2021.08.004.

Naito M, Kodaira S, Ogawara R, Tobita K, Someya Y, Kusumoto T, Kusano H, Kitamura H, Koike M, Uchihori Y, et al. 2020. Investigation of shielding material properties for effective space radiation protection. Life Sciences in Space Research. 26:69–76. doi:10.1016/j.lssr.2020.05.001.

Naito, Masayuki M, Kitamura H, Koike M, Kusano H, Kusumoto T, Uchihori Y, Endo T, Hagiwara Y, Kiyono N, et al. 2021b. Applicability of composite materials for space radiation shielding of spacecraft. Life Sciences in Space Research. 31:71–79. doi:10.1016/j.lssr.2021.08.004.

NASA SP. 1970. Nuclear and space radiation effects on materials. NASA SP – 8053.

Niemenen P. 2001. The In-orbit radiation environment and its effects on space-borne instrumentation. Workshop on the Calibration Legacy of the ISO. Mission, Vilspa, Spain. 2001 Feb 5-9.

Nwankwo Victor UJ, Jibiri Nnamdi N, Kio Michael T. 2020. Book of satellites missions and technologies for geosciences. Chapter 5: The Impact of Space Radiation Environment on Satellites Operation in Near-Earth Space. doi:10.5772/intechopen.90115

Pavl enko VI, Cherkashina NI, Yastrabinsky RN. 2019. Synthesis and radiation shielding properties of polyimide/Bi2O3 composites. Heliyon. 5(5):e01703. doi:10.1002/j.heliyon.2019.e01703.

Plis EA, Engelhart DP, Russell Cooper WRJ, Ferguson D, Ho_mann R, Hoffmann R. 2019. Review of radiation-induced effects in polyamide. Applied Sciences. 9(10):1999. doi:10.3390/app9101999.

RADIATION SHIELDING MATERIALS CONTAINING HYDROGEN, BORON AND NITROGEN. 2013. WO2013/074134A1. accessed: http://patentimages.storage.googleapis.com/20/21/9c/9753bd372c482a/WO2013074134A1.pdf.

Rai VN, Mukherjee C, Beena J. 2016. Optical properties (UV-vis and FTIR) of gamma irradiated polymethyl methacrylate (pmma). arXiv:1611.02129, [physics.chem-ph]..

Raluca CONDRUZ M, Raluca VOICU L, Puscasu C, Sebastian VINTILA I, Sima M, Deaconu M, Draganasu L. 2018. Composite material designs for lightweight space packaging structures. INCAS BULLETIN. 10(1):13–25. doi:10.13111/2066-8201.2018.10.1.3.

Rancoita Seghiri M, Elhaes M, Elharfi M, Te. 2020. Application of particle interaction and displacement damage in silicon devices operated in a radiation environment, reports on progress in physics. 70:493–625.

Rawal SP, Rawal Suraj. 2001. Metal-matrix composites for space applications. JOM, the Journal of the Minerals, Metals & Materials Society (TMS). 53(4):14–17. doi:10.1007/s11837-001-0139-z.

Schiavone CC. 2013. Polymeric radiation shielding for applications in space: polyimide synthesis and modeling of multi-layered polymeric shields. dissertations. Theses, and Masters Projects. Paper 1539626947. doi:10.21220/s2-6mzy-sk48.

Shruti N, W YJT. 2012. Polymer-composite materials for radiation protection. ACS Appl. Mater. Interfaces. 20124115717. doi:10.1021/ami300783d

SIDER project, 2013. Final report summary - SIDER (RADIATION SHIELDING OF COMPOSITE SPACE ENCLOSURES). Final report.

Slmp WS, Santos B. 1981. Radiation exposure of selected composites and thin films. Large Space Systems Technology.

SOURCES AND EFFECTS OF IONIZING RADIATION, 2000. Available in: https://www.unscear.org/docs/publica
tions/2000/UNSEAR_2000_Report_Vol.I.pdf

Space radiation environmental effects. http://holbert.faculty.asu.edu/cece560/spacerad.html
Spillantini P, Casolino M, Durante M, Mueller-Mellin R, Reitz G, Rossi L, Shurshakov V, Sorbi M. 2007. Shielding from cosmic radiation for interplanetary missions: active and passive methods. Radiat. Meas. 42(1):14–23. doi:10.1016/j.radmeas.2006.04.028.

Sporea D, Sporea A. 2016. Book in radiation effects in materials. Radiation Effects in Optical Materials and Photonic Devices. Chapter 2. 10.5772/62547

Tenney DR, Sykes GF, Bowles DE. 1982. Space environmental effects on materials. In: Presented at AGARD, environmental effects on materials for space applications. 1982 Sept 22-26; Toronto (Canada).

Thibeault SA, Kang JH, Sauti G, Park C, Fay CC, King GC. 2015. Nanomaterials for radiation shielding. MRS Bull. 40 (10):836–841. doi:10.1557/mrs.2015.225.

Wang Jy-An J, Singleterry J, Robert C, Ellis, Ronald J, Hunter HT. 2002. Radiation effects on spacecraft structural materials. International Conference on Advanced Nuclear Power Plants (ICAPP) Embedded International Topical Meeting 2002 ANS Annual Meeting. 13 2002 Jun 9 Hollywood, Florida.

Wirtenson GR, White RH 1992: Effects of ionizing radiation on selected optical materials: an overview. Lawrence Livermore National Laboratory Report No. UCRL-ID-111453 July 1992.

Zicai S, Yan X, Yuming L, Yigang D, Chunqing Z. 2019. Protection of materials from space radiation environments on spacecraft, IOP Conf. Series: Materials Science and Engineering. 585:012089.