Reviewing Known Mitigation Methods for Space Weather's Effects on Spacecraft

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Over the past couple of decades, since the dawn of the new space age, the number of satellites being released into orbit has increased exponentially. Despite the lowering costs of building and launching spacecraft, companies still face the possible drastic financial loss that comes from premature mission termination due to being unprepared for major space weather events. This paper examines what current space weather mitigation shielding technologies and methods offer, as well as what future methods could offer. A review of their effectiveness is then evaluated. The effectiveness of each method is evaluated by its cost, adaptability, and spacecraft preservation ability. A decision matrix was used to inform space system designers of the best shielding mitigation methods to use. With the use of the decision matrix, the author recommends the use of atomic number (Z) grade material radiation shielding and pseudomorphic coverglass, as well as an investment in improved space weather forecasting.

I. Introduction

Space weather is caused by the continual dynamic activity on the surface of our Sun and can come in a multitude of different forms. The Sun's solar wind is constantly releasing a stream of energetic particles out into the Solar System, however, events such as solar flares and coronal mass ejections (CMEs) release large amounts of energy and a high concentration of these charged particles in a condensed time period [1]. When these streams of charged particles, CMEs, or solar flares come into contact with the Earth and its magnetic field, the interactions can create a geomagnetic storm. On the surface of the Earth, these storms can be accredited with the creation of aurora, however, in space, these storms can spell havoc for spacecraft.

Solar energetic particles (SEPs) and trapped energetic protons can severely damage the sensitive electronics on spacecrafts [2]. Solar electrons with energies from hundreds to thousands of keV can breach through radiation shielding and build up in dielectric materials, and once enough trapped energy has built up a sudden discharge can occur. This discharge can cause phantom signals and permanent damage to sensitive electronics. SEPs can also cause damage to the solar cells that power satellites. These SEPs can reduce a solar cell's charge carrier lifetime as well as its overall ability to power its spacecraft [3]. It becomes clear that if the damage caused by geomagnetic storms can be mitigated, even slightly, then the lifetime of a spacecraft can increase drastically. This raises the need for shielding from SEPs in order to protect a spacecraft's electronics system and solar cells. As will be described in the following sections, both coverglass and radiation shielding fill this need.

II. Radiation Shielding

A. Inherent Mass Shielding

The classic form of radiation shielding is inherent mass shielding [4]. Inherent mass shielding is based on the concept that electronic components that are not dependent on where they are in the spacecraft can be placed near the center of the spacecraft so that the spacecraft's pre-existing mass acts as a shield. Typically, this method is used for its simplicity, since inherent mass shielding consists purely of merely using a thicker extrusion of material for construction than usual. This method, however, does not block radiation particularly well, since the material used for construction, typically aluminum, is light and is optimized for structural concerns instead of being optimized for shielding from SEPs.

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B. Aluminum Shielding

An extension to inherent mass shielding is the use of aluminum for radiation shielding [4]. This form of shielding uses aluminum plates of varying thickness to shield the spacecraft. Aluminum is light, and although not the most effective way of blocking radiation, can shield radiation well if layered enough. The layers of aluminum can also be molded to protect electronics that need to be in specific locations on the spacecraft to function properly. The downside to this method is that in order to properly protect from radiation the number of layers needed is high, which results in a much heavier spacecraft.

C. Z-grade Shielding

Atomic number (Z) grade radiation shielding is a newer form of shielding that is formed from coating different metals with different atomic numbers on top of each other. This results in a thin material that can protect from internal charging effects and radiation caused by protons, electrons, and x-rays [5, 6]. This material is easily moldable, allowing for custom shielding to be made for electronics in locations that are hard to shield. Z-grade shielding with the same areal density, 3.02 g/cm^2, as aluminum shielding protects from proton radiation just as effectively at less than half the thickness [4]. For an electron environment with an ionizing doze of 4 to 6.5 MeV, Z-grade performs over 30% more effectively than aluminum at the same areal densities ranging from 1.7 to 2.2 g/cm^2 (Figure 1) [7]. The use of Z-grade material has been shown to increase the effective life of CubeSat missions from 3 months to multiple years, thus increasing the value and return investment from CubeSat missions [6]. While especially tailored to smaller spacecraft, the radiation protection offered by Z-grade shielding can also increase the effective lifespan of large spacecraft as well.

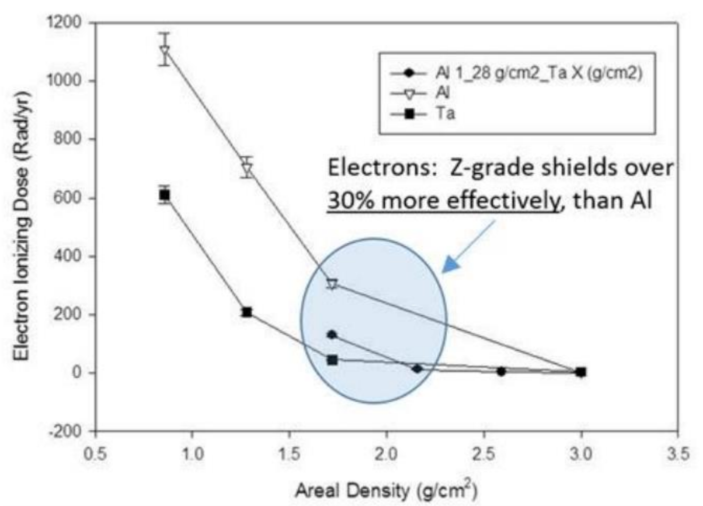

Fig. 1 Modeled ionizing dose for Al, Ta, and Al/Ta (Z-grade) samples as a function of their areal densities [7].

III. Coverglass

A. Cerium-Doped Coverglass

The traditional form of coverglass used for solar cells is composed of rigid cerium-doped glass. Cerium-doped glass is well tested and has been proven to extend the duration of usage for solar cells. When an electric powered spacecraft is rising to geostationary orbit while in active environments, increasing coverglass thickness from 100 μm to 200 μm can increase the remaining power a solar cell can output up to 10% [8]. Although differing orbits affect the total ionizing dose solar cells experience, the trend of coverglass thickness increasing remaining power and slowing degradation is consistent (Figure 2). The decreased degradation means that the spacecraft, once in its geostationary orbit, will have an extended period of functionality. The downside to traditional coverglass is that despite cerium-doped glass's successfulness in protecting solar cells, it is rigid, fragile, expensive, lacks complete encapsulation of solar cells, and is not suitable for flexible solar cells [9, 10, 11].

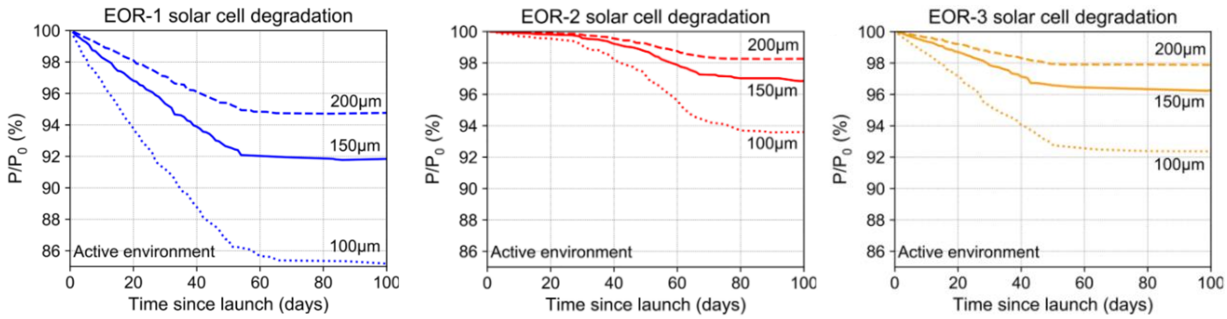

Fig. 2 Remaining power output for a solar cell depending on its orbital path (depicted by EOR-1, EOR-2, or EOR-3) and thickness of coverglass used after exposure to a nonionizing dose for 100 days. EOR = electric orbit raising [8].

B. Silicone Rubber Adhesive

Flexible solar cells are made of a thin layer of photovoltaic material placed on an underlying layer of glass or plastic, allowing them to be up to 350 times thinner than traditional photovoltaic cells [4]. These flexible cells are lightweight, lower mass, sturdier, and cheaper to manufacture [4, 9]. The rigid cerium-doped glass typically used for traditional solar cells cannot be used for such thin flexible solar cells, and so an alternative is necessary. One such alternative is using room-temperature-vulcanized silicone rubber adhesive (RTV). RTV is typically used as an adhesive to secure coverglass on to the solar arrays, however when using RTV as a form a radiation shielding, a layer of the adhesive is used instead. RTV is cheap, flexible, and can fully encapsulate solar cells, however it offers little in the form of degradation protection, as under high irradiation, RTV itself will begin to degrade [12]. This is due to RTV, unlike cerium-doped glass, not being originally designed or altered to protect from radiation.

C. Pseudomorphic Coverglass

Pseudomorphic glass (PMG) is a flexible coverglass composed of ceria doped glass beads and silicon rubber [9, 10]. The glass beads in PMG result in an increased radiation shielding per unit of thickness of over 50% when compared to a layer of RTV alone, while the silicon rubber increases its flexibility and allows it to be used on both flexible and rigid solar cells. PMG resists electron irradiation damage significantly better than RTV and has better anti-darkening behavior than RTV as well [10, 13]. PMG's greater resistance to damage and darkening allows the solar cells it is protecting to run at higher efficiencies, therefore allowing the cells to produce more energy.

Traditional coverglass is inherently more ultraviolet (UV) stable than PMG, which results in PMG needing a layer of UV rejection coating in order to protect solar cells as effectively as traditional coverglass [9]. However, PMG has a higher emissivity in the infrared spectrum than cerium-doped coverglass, thus resulting in improved heat radiation [11]. PMG's ability to effectively radiate heat leads to the solar cells it protects having a lower operating temperature and a higher energy conversion efficiency. The higher energy conversion efficiency offered by PMG can partially mitigate any power production loss due to solar cell degradation.

IV. Space Weather Forecasting

Current forecasting of CME arrival times are determined by monitoring CMEs, studying ongoing solar and magnetic field conditions, and determining CME velocity estimates from solar imagers. Due to a CME's ability to cause geomagnetic storms, having the ability to know when a CME will arrive gives spacecraft operators an opportunity to react and take any actions necessary in order to prevent or lessen possible damage, such as entering a safe mode and powering off their spacecraft. However, while having CME arrival time forecasts is important information to have, it does not fully encompass all the information necessary to have accurate geomagnetic storm predictions, as not all CMEs are strong enough to produce storms. Using only CME arrival times to forecast geomagnetic storms will therefore lead to many false alarms where operators take action when not needed. If done continuously, responding to false alarms turn out more costly than space weather damage itself [14]. Additionally, knowing the expected strength of an incoming geomagnetic storm does not protect a spacecraft from other incoming space weather, such as SEPs, which can also cause damage to spacecraft electronics.

To increase forecasting effectiveness so that it may differentiate between the CMEs that will cause storms and those that will not (geoeffective vs. nongeoeffective) more information is necessary. Improving CME transit forecasting to include an accurate estimate of its speed when it reaches Earth as well as its magnetic field intensity and orientation would significantly increase forecast value [14]. Through a CME's arrival speed, magnetic field intensity, and orientation spacecraft operators can gauge the CME's likelihood to produce a geomagnetic storm. Furthermore, this information would allow spacecraft operators to determine if it would be more valuable to protect the spacecraft or have it weather the storm as is.

In order to forecast CME arrival time some prediction of the CME's arrival speed to Earth is needed, however, much like the CME arrival time estimates, these velocity forecasts vary significantly from model to model and can be highly inaccurate. Some models, such as Ellipse Evolution model based on Heliospheric Imager observations (ELEvoHI) have managed to be fairly accurate when predicting arrival speed [15]. ELEvoHI was tested against past historical CME events and was able to predict arrival speeds with an average discrepancy of 63 km/s. However, improved accuracy and modeling is necessary. Additionally, other models seek to make improved forecasts of the impact CMEs have on Earth's space environment. This is done by improving the forecasting of the orientation and rate of change of the magnetic fields of CMEs. One such model is the Space Weather Modeling Framework (SWMF) [16]. SWMF frequently outperforms its peers when it comes to predicting the change of magnetic field strength at Earth in response to a geomagnetic storm. An increase in information and accuracy about CMEs would allow for more educated responses to how spacecrafts should be protected during space weather events.

V. Decision Matrix

A. Decision Criteria

Due to the nature of space weather forecasting and how it is not a mitigation method that can be added or integrated onto a spacecraft, it will not be included in a decision matrix as it cannot be accurately compared against other methods. Instead, emphasis here is placed on its importance and the fact that continued improvement of space weather forecasting will have the ability to benefit all spacecraft.

The decision matrices are composed of three objectives: cost, adaptability, and spacecraft preservation ability. A total of 5 points may be achieved in each objective, with cost and adaptability having a weight of 30% each and spacecraft preservation ability (labelled as mitigation effectiveness) having a weight of 40%. Score assignments range from 1 through 5 where each number represents poor, fair, good, excellent, and superior respectively. Every method will be assigned points corresponding to how well it compares to the highest-ranking method in each section. Decision matrices will be split into two, with one matrix being dedicated to radiation shielding methods and the other being dedicated to coverglasses.

B. Objective Definitions

Cost is composed of multiple factors, including the density of the material, volume/thickness needed, and manufacturing cost. Mass contributes to the overall cost of launching the spacecraft, hence its inclusion through density and volume. The cheapest mitigation method receives a score of 5 points.

Adaptability measures the method's ability to be used across various spacecraft. A method that can only be used in reference to one type of spacecraft will rank lower than one that can successfully be used in multiple spacecraft with differing features/technologies. The method that is most adaptable receives a score of 5 points.

Mitigation Effectiveness is measured by how well a mitigation method manages to protect its spacecraft from harmful space weather. Due to how shielding types may have differing thicknesses and densities, the shielding materials will be compared to how effective they are at the same areal densities. The method that offers the best protection receives a score of 5 points.

C. Radiation Shielding Matrix and Score Assignments

		Inherent Mass Shielding		Aluminum Shielding		Z-Grade Shielding	
Selection Criteria	Weight	Value	Weighted Value	Value	Weighted Value	Value	Weighted Value
Cost	0.3	5	1.5	3	0.9	4	1.2
Adaptability	0.3	1	0.3	4	1.2	5	1.5
Mitigation Effectiveness	0.4	1	0.4	3	1.2	5	2.0
Weighted Total Values	1.0		**2.1**		**3.3**		**4.7**

1. Cost

Inherent mass shielding uses a thicker extrusion of the materials used for its structure and the spacecraft's pre-existing mass to protect electronic components by placing them near the center of mass. For this reason, it was given a score of 5 as it is a low cost and simple method requiring very little extra manufacturing and materials.

Aluminum shielding uses sheets of aluminum layered together to protect from radiation. Although aluminum is a cheap lightweight material, a high volume of aluminum shielding is needed for sufficient protection, resulting in increased spacecraft weight. The cost of aluminum shielding increases furthermore when the plates must be manufactured to fit specific components. This results in aluminum shielding receiving a score of 3.

Z-grade shielding's composition of different metal layers allows it to effectively block radiation using very little material, thus resulting in a lighter overall spacecraft. Z-grade material is also flexible and easily moldable, resulting in lower manufacturing costs when being shaped for traditionally difficult to shield locations [5]. These factors result in it receiving a score of 4.

2. Adaptability

Inherent mass shielding can be used to protect sensitive electronics that don't rely on location to function. However, it cannot protect sensors or electronics that require to be in certain configurations or positions to properly function. Since most electronics on spacecraft fall under the latter category where inherent mass shielding cannot provide protection, it is assigned a score of 1.

Aluminum shielding is malleable and can be placed anywhere on the spacecraft, allowing for the shielding of electronics that inherent mass shielding could not cover. However, due to aluminum shielding's thickness, it can be difficult to mold the shield for certain electronics are in difficult shielding locations. This results in aluminum shielding being assigned a score of 4.

Z-grade material is thin and can be easily molded to fit the shielding requirements for any electronic components or location, resulting in Z-grade shielding receiving a score of 5.

3. Mitigation Effectiveness

Due to inherent mass shielding's dependence on the structural frame of the spacecraft, increasing the amount of material in these areas offers very little in terms of radiation protection, as the frames aren't designed with SEP shielding in mind. For this reason, inherent mass shielding receives a 1.

Aluminum shielding provides decent shielding for spacecrafts and their electronics from SEPs and radiation. Due to its performance, aluminum shielding receives a score of 3.

Z-grade shielding is significantly more effective than regular aluminum shielding at protecting from both proton and electron ionization [7]. Z-grade's composition of metals with different atomic masses provides protection from multiple types of SEPs at different energy levels. Z-grade shielding is awarded a score of 5 for this reason.

4. Overview

Due to Z-grade's high moldability, low volume, and ability to significantly reduce radiation dosage, Z-grade shielding is considered the most effective form of mitigation in the form of shielding with an overall score of 4.7.

Aluminum shielding comes in second with an overall score of 3.3 due to its average cost, shaping/molding abilities, and shielding capabilities. Inherent mass shielding places last with a score of 2.1 due to high simplicity but poor versatility and radiation protection.

D. Coverglass Matrix and Score Assignments

		Cerium-Doped Glass		**RTV Layer**		**PMG**	
Selection Criteria	Weight	Value	Weighted Value	Value	Weighted Value	Value	Weighted Value
Cost	0.3	2	0.6	5	1.5	4	1.2
Adaptability	0.3	2	0.6	4	1.2	5	1.5
Mitigation Effectiveness	0.4	5	2.0	1	0.4	4	1.6
Weighted Total Values	1.0		**3.2**		**3.1**		**4.2**

1. Cost

Cerium-doped glass, or traditional coverglass, is rigid, fragile, and micrometers thin. Manufacturing and cutting traditional coverglass to fit on to solar cells requires very precise work and comes out to be very costly. Traditional coverglass can also crack once already on the solar cell which then requires the cell to be replaced, causing delays, and further increasing costs [9]. For these reasons, traditional coverglass gets a score of 2.

RTV is an adhesive that is typically used to secure coverglass to solar cells. It is cheap and requires no complicated application processes, thus resulting in being awarded a score of 5.

PMG is made up of small beads of coverglass held together by a silicon adhesive. Manufacturing of PMG attributes most to its cost, but unlike traditional coverglass, it is sturdy, flexible, and not prone to cracks, meaning that it typically does not require repairs or additional work; this results in PMG receiving a score of 4.

2. Adaptability

Traditional coverglass can be used on any traditional rigid solar array and its cells. Traditional coverglass can also be used on flexible solar cells, however, since it is multitudes of times thicker than the solar cell itself, it would be counterintuitive to do so as the solar cell would lose its flexibility in the process. The difficulty of manufacturing and cutting traditional coverglass also makes it so that this coverglass very rarely fully encapsulates the entire cell. For these reasons, cerium-doped glass received a score of 2.

RTV has a flexible nature and can be applied as extremely thin layers. This allows RTV to be used on either flexible or traditional solar cells, thus resulting in it receiving a score of 4.

PMG is a versatile material that can either be formed into sheets or sprayed onto cells. Due to its versatility, PMG can either be placed on singular solar cells in the form of a sheet, or be sprayed on to an entire module, allowing it to fully encompass a solar array of any type. For PMG’s ability to be used on any solar cell, it is awarded a score of 5.

3. Mitigation Effectiveness

Cerium-doped glass is UV stable and effectively shields solar cells from nonionizing dosage, slowing down their degradation rate and extending their usable lifespans. Traditional coverglass is awarded a score of 5 for its shielding abilities.

Although RTV does block some radiation, its effectiveness is very low. This is due to how RTV, unlike traditional coverglass, was not designed to block any ionizing dose. For RTV’s poor shielding capabilities it received a score of 1.

PMG is inherently less UV stable than traditional coverglass due to its silicon components, resulting in PMG having lowing shielding capabilities than traditional coverglass, although not significantly lower. Recently, PMG has also begun to be coated by UV rejection coating, causing it to become more UV stable and therefore increasing its shielding capabilities. Due to PMG having good shielding capabilities but requiring extra processes to achieve them, PMG is given a score of 4.

4. Overview

PMG's sturdiness, flexibility, application versatility, and ability to effectively slow solar cell degradation causes it to receive an overall score of 4.2, thus considering it the most effective from of space weather mitigation for solar cells in the form of coverglass. Cerium-doped glass exceptional shielding abilities but expensive manufacturing costs, fragility, and rigidness resulted in it receiving an overall score of 3.2, placing it in second. RTV, with a slightly lower overall score of 3.1 due to its cheap and easy application but poor shielding capabilities, places in last as the least effective mitigation method.

VI. Conclusion

A review of three different forms of spacecraft radiation shielding, three different forms of coverglass for solar cell shielding, and the current state of space weather forecasting was made. The forms of shielding and coverglass are then compared using a decision matrix, and Z-grade material and PMG were found to be the most effective forms of space weather mitigation in the form of shielding currently known. Z-grade material was selected due to how it blocks radiation as or more effectively than other forms of shielding at lower thicknesses. PMG was selected due to its increased flexibility, which allows for use across multiple different types of spacecrafts, while still providing sufficient protection for solar cells.

Improvements can be made to both space weather forecasting and PMG. Improvements to the accuracy and data provided by space weather forecasting would allow spacecraft operators to make more informed decisions regarding the protection of their crafts, thus decreasing money spent from responding to false alarms while also increasing the survivability of their spacecraft. With further research, PMG could be improved to become inherently more UV stable instead of relying on UV rejection coating, so that it may offer the same kind of superior radiation protection as cerium-doped glass [9].

As the number of spacecrafts being built and launched into orbit continues to increase by the day, it is imperative that mitigation methods for space weather continue to be improved in order to prevent damage to these crafts and their missions.

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