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COMPARATIVE STUDY BETWEEN DIFFERENT SOLAR RADIATION SHIELDING MATERIALS

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ABSTRACT

This paper explores different methods to protect satellites from outer space radiation, primarily Coronal Mass Ejections (CMEs). It discusses what CMEs are and how they damage satellites. It also briefly discusses different ways to deal with such kinds of SPE, like Active Shielding, Passive Shielding, Radiation Hardening, and Redundancy. The research focuses on passive shielding and compares various materials, taking into account factors such as cost, shielding capability, and effectiveness.

KEYWORDS: CMEs, Shielding, Radiation Hardening, Redundancy, Carbon Nanotubes, Lithium Hydride, Polyethylene, Kevlar

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INTRODUCTION

Computers enable us to process massive amounts of data with great precision and efficiency. One field that is heavily reliant on this is space applications. By sending computers into orbit around the Earth in the form of satellites, we achieve several feats, including, but not limited to, telecommunications, outer space observation, and meteorology.

However, regardless of how advanced computers may appear, they remain highly delicate against harsh radiation received in outer space without the protection provided by Earth's atmosphere; in fact, the ionosphere further damages the circuits by bombarding them with a high number of electrons. There are mainly three different types of radiation that damage satellite circuitry, like Galactic Cosmic Rays (GCR), Coronal Mass Ejections (CMEs), and Solar Flares. This paper focuses on protection against Coronal Mass Ejections since they pose more frequent threats to satellites compared to the other two.

Coronal Mass Ejections (CMEs) are huge ejections of plasma from the sun's corona with the help of a strong magnetic field, which consist of charged particles like protons, electrons, and other ionized heavy nuclei (Dobrijevic, 2022). It is speculated that they are formed by explosive reconfigurations of solar magnetic fields through the process of magnetic reconnection (Moldwin & Mark, 2025). As a CME's propagation speed is dependent on many factors like solar wind, magnetic field at the time of the event, etc., their speed is highly unpredictable, ranging from 250 kilometers per second (km/s) to 3000 km/s with times ranging from under 18 hours to over several days (NWS Space Weather Prediction Center, n.d.). They share the same composition as solar wind, but at a much higher density, while also carrying their own magnetic fields.

When CMEs impact Earth, they temporarily deform the magnetosphere, which induces huge electrical ground currents on Earth and also induces magnetic reconnection in the magnetotail (Omatola & Okeme, 2012). This strips electrically charged particles like protons and electrons from the Earth's geomagnetic field, causing a sudden increase in the density of charged particles near Earth, which causes a geomagnetic storm. Therefore, a circuit in space is exposed to both direct CME exposure and proton-electron radiation, as they mostly orbit in the geomagnetic field. According to Emmanuel (2023), "These storms can damage satellites by destroying the sensitive equipment needed for them to function, degrading the solar panels that provide them with power, and even altering their orbits." More specifically, it ionizes the material that the satellite is made of, causing degradation by displacement damage, and the buildup of electrons on the circuit can cause Electrostatic Discharge, which overcharges the transistors and capacitors, resulting in short-circuit-induced damage; this poses a threat to the satellite's functionality. When a satellite is damaged by a CME, in addition to functionality, valuable data, tons of expensive fuel, years of challenging work, millions of dollars for the building of the rockets and satellite, and research are lost.

As CMEs are a highly inconsistent phenomenon, this paper uses a standard, historically relevant CME for all our calculations. It will be the September 1859 Carrington Solar Particle Event (SPE) with the data from NASA's On-Line Tool

Research Paper

for the Assessment of Radiation in Space (OLTARIS). The paper will also use OLTARIS for the calculations.

LITERATURE REVIEW

Passive Shielding

Passive shielding consists of protection from radiation with the help of radiation-absorbing materials that act as a disposable wall between the electronics and their surroundings. Most cases employ this method as it is cost-effective and does not consume any additional energy. Hydrogen provides the most shielding from cosmic radiation as it has only one electron, resulting in the highest charge-to-mass ratio of any element; this is essential in deflecting proton radiation. However, hydrogen is not used solely since it is a highly combustible gas, posing another risk to the spacecraft.

Simonsen et al. (1991) used water shielding for human lunar missions. Water is 2/3rd hydrogen, making it ideal for shielding from ionizing radiation. However, it is difficult to transport and use as a shield, as it is a liquid and provides no structural integrity. There are also studies being conducted that use organic material as protection against radiation. Organic materials also contain significant hydrogen and can be constructed in many ways to cater to specific use cases. For example, single-walled carbon nanotubes could be used for radiation shielding as they are a high-tolerance, structurally sound material, and is also able to withstand extreme environments (Karthik & Shirvram, 2008). According to Karthik & Shirvram (2008), carbon nanotubes can withstand up to 300 MeV in proton radiation.

Thibeault et al. (2015) also support the claim that hydrocarbons are a very effective tool for stopping radiation. Different materials can also be layered on top of each other for optimal radiation insulation. Varga & Horvath (2003) show the different variations of materialistic arrangements using aluminum, PEEK carbon honeycomb, PEEK, and tantalum; they also discuss the effects of those arrangements on shielding and weight.

Active Shielding

Active Shielding is a type of shielding where magnetic fields are produced and used to deflect protons. This type of shielding is compact and can be adjusted to the SPE that a spacecraft will face. Different methods can be used to generate the required electrical field. French (1970) used the plasma radiation shielding method. It is a shield that magnetically pulls electrons to the outer layer and makes the inner wall positively charged, making it into a capacitor structure. The positively charged ions that head towards it (solar flares) will get repelled or deflected if they pass through. The energy that gets through will be Energy (flare) - Energy (capacitor).

Cocks & Watkins (1993) deployed high temperature super-conducting coils (DTHSC) to produce large volume, low-intensity magnetic fields to shield a manned spacecraft against solar flare protons. These use high-temperature superconductors to power the magnetic field instead of using electric and plasma shielding. Active shielding is ideal for manned missions where the safety of the astronauts holds more priority over energy consumption. This is not conventionally used in satellites because it has a relatively large energy consumption and will reduce the satellite's runtime, thereby allowing it to approach its end-of-life much sooner than without active shielding.

Radiation Hardened Electronics & Redundancy

In addition to installing radiation shields outside to protect the spacecraft, individually radiation-hardening the electronic circuits may further prevent the failure of instruments. Radiation Hardening is constructing semiconductors with radiation-insulated materials and using different functionality based on reliability rather than latency. The electronic components go through extensive testing to ensure proper radiation hardening. This, in addition to low demand, makes the electronics lag compared to their normal counterparts (Heyman, 2024). They are also expensive and difficult to design optimally (Fettes, 2024b).

Another method to preserve functionality is redundancy, where multiple parts perform the same function so that when one part is damaged by radiation, another part can take over. According to Chang (2025), "Redundancy is particularly vital as NASA estimates that a significant portion of spacecraft failures, around 80%, stem from power system anomalies." But the addition of backup redundancy items and circuits increases the weight and makes the circuitry more complex, which has an incremental effect on both the cost and time required to produce the satellite carefully. Therefore, redundancy is only practical when an item is readily available and not too costly or heavy (Lisk, 2003).

METHODOLOGY

This paper cross-compares the following materials shown in Table 1, arranged by Name, Density, and Formula:

Material Name	Density (g/cm^3)	Chemical Formula
	Single element	
Aluminum	2.7	Al
Tantalum	16.69	Ta
Titanium	4.5	Ti
Carbon Nanotubes	1.35	C (Graphene)
	Compound Shielding	
Polyethylene	1.0	CH_2
Kevlar	1.44	$C_{14}H_{14}N_2O_4$
Lithium Hydride	0.82	LiH

To account for radiation hardening and separate shielding inside the satellite for different components, a 1mm aluminum layer was used as the base protection in every case. As in a real-world scenario, with multiple layers used together to shield from radiation, we used a 4mm maximum thickness of the desired materials.

The February 1956 Webber SPE with the corresponding differential formula was chosen as the environment in OLTARIS (Singleterry et al., 2010), where m is the mass of the proton and is approximately 938 MeV:

$$\phi(E) = 1 \times 10^7 \left[\frac{E + m}{\sqrt{E(E + 2m)}}\right] exp\ exp \left[\frac{239.1 - \sqrt{E(E+2m)}}{100}\right]$$

The SPE was assumed to occur at 1 AU in free space and had 100 MV rigidity. Different slabs of the above-mentioned materials were created and were put through the simulation on top of the base 1mm aluminum slab. The graphs of Dose vs Depth were obtained from OLTARIS. Costs and weights were obtained separately.

RESULTS & DISCUSSION

Control Satellite

Most scientific satellites and many weather satellites are in a nearly circular, low Earth orbit. Therefore, Low Earth Orbit satellites will be used as the reference model in this paper. The height of the satellite is around 800 km above the surface of the Earth. The dimensions will be 2x3x2 (m). Considering the base aluminum of thickness 1mm and density 2.7 g/cm^3, the weight of the shielding comes out to be 0.864 kg.

According to the 2023-2025 average rates, $1.5 is the cost of aluminum per kg. $2.16 is the production cost to buy aluminum, and the average cost of launch per kilogram of payload is around $18,000 for small and medium launches (CSIS Aerospace Security Project, 2022, with minor processing by Our World in Data). Therefore, the total cost to launch the shielding is estimated to be around $15,552.

The calculated dose received by the electronics vs depth is shown in Figure 1 below:

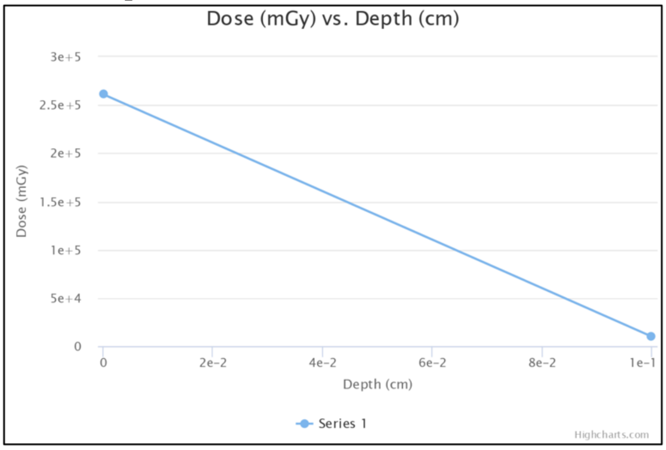

Figure 1: SEQ Figure * ARABIC 1

It is observed that 2.511752×10^5 mGy is absorbed, and 9.7948×10^3 mGy dose is received by the electronics.

Single Elemental Shielding

Aluminum: Aluminum is the most commonly used material in satellites, as its abundance provides cost efficiency and a high strength-to-weight ratio ensures lightweight bodies and structural integrity.

The 3 mm aluminum shield weighs 2.592 kg, with the total structure weighing 3.11 kg. Using the same statistics as earlier, the production cost is $4.66, and the launch cost is $55,987.2. After adding the base cost, the total cost comes out to be $71,543.86

Figure 2 shows the Dose vs Depth obtained from OLTARIS for 3mm Aluminum+1mm base:

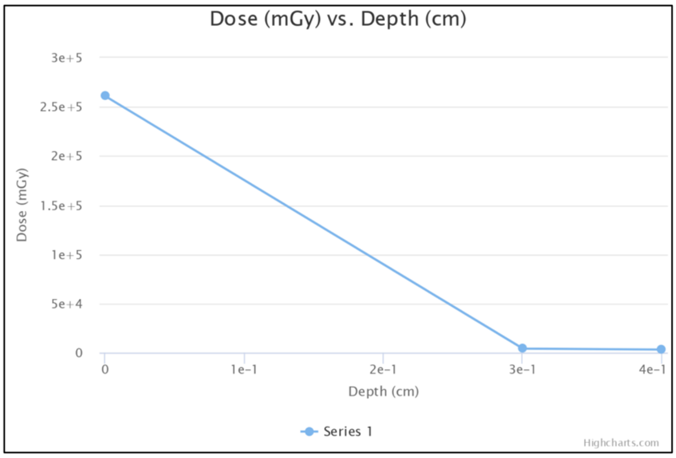

Figure 2

It is observed that a 2.578905×10^5 mGy dose is absorbed and a 3.0795×10^3 mGy dose is received on the electronics. An off-the-shelf electronic circuit can typically take 1×10^4 mGy before starting to malfunction and may have a significant loss in function by 5×10^5 mGy. Therefore, the electronics get 30.795% of their maximum dosage limit. It is also noticed that the base aluminum slab does not reduce the radiation further by the same rate. This tells us about the nature of radiation absorption. There may be two possible theories for this. One says that the secondary radiation emitted might not be absorbed by aluminum properly and might pass through it unaffected. Another theory suggests that materials may block high- and low-energy doses at different rates, with the high-energy ones being blocked more.

Tantalum: Tantalum is an almost chemically inert metal with high strength and a high melting point. It shares similarities with tungsten in shielding capabilities, according to Adlienė et al. (2020), and is less dense and lighter than tungsten, with its density at 16.69 g/cm^3. It also has corrosion resistance. However, it is expensive, with a considerable price tag of $330.31 per kilogram. Hence, it is usually used as a coating for radiation shields.

A 3 mm tantalum shield weighs 16.02 kg, with the total structure weighing 16.8864 kg. The production cost is $5,292.35, and the launch cost is $288,403.2. After adding the base cost, the total cost comes out to be $293,695.55

Figure 3 below shows the Dose vs Depth obtained from OLTARIS for 3mm Tantalum + 1mm base. It is observed that 2.6 × 10^5 mGy dose is absorbed and 9.3332×10^2 mGy dose is received on the electronics. The electronics get 9.333% of their maximum dosage in this configuration.

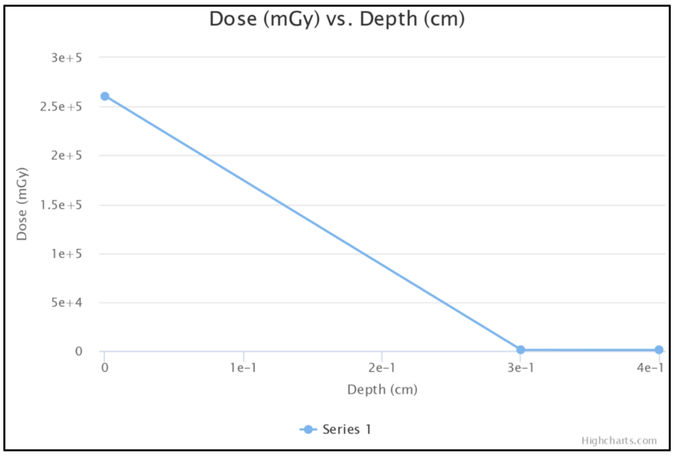

Figure 3

Titanium

Titanium, like aluminum, has a high strength-to-weight ratio, especially at low temperatures. It is a durable material, as it is highly resistant to corrosion, and its properties do not vary significantly over changes in temperature. Titanium also has a low density, which makes it a cost-friendly material to use for space applications.

A 3 mm titanium shield weighs 4.32 kg, with the total structure weighing 5.184 kg. The production cost is $129.6, and the launch cost is $77,760. After adding the base cost, the total cost comes out to be $93,312.

Figure 4 shows the Dose vs Depth obtained from OLTARIS for 3mm titanium + 1mm base. It is observed that a 2.58675 $\times 10^5$ mGy dose is absorbed and a 2.285 $\times 10^3$ mGy dose is received on the electronics. The electronics get 22.85% of their maximum dosage in this configuration.

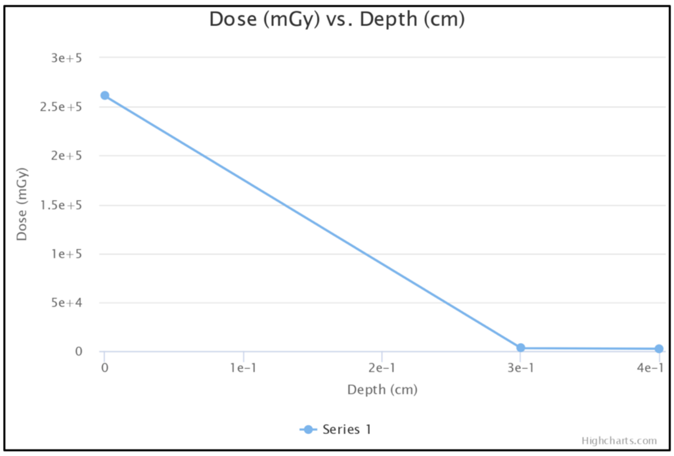

Figure 4

Compound Shielding & Hydrocarbons

Carbon Nanotubes

Carbon nanotubes (CNT) are small tubes constructed out of graphene. Carbon nanotubes are very strong structurally and have tolerance for heat and large quantities of radiation. They can also act as a vessel to store hydrogen to further protect from radiation. A specific type of CNT called a Single Walled NanoTube (SWNT) will be used, as suggested by Karthik & Shirvram (2008), to be the most effective variant to stop radiation. However, carbon nanotubes are very hard to produce in large quantities effectively without breaking up, so it is expensive, with around $600 per kg for a decent multiwalled carbon nanotube. It is, in essence, sheets of graphene on top of each other. So, we have assumed the material to be graphene layered on top till it reaches 3mm thickness.

A 3 mm graphene shield weighs 1.296 kg, with the total structure weighing 2.16 kg. The production cost is $648, and the launch cost is $23,328. After adding the base cost, the total cost comes out to be $38,880 (see Figure 5 below).

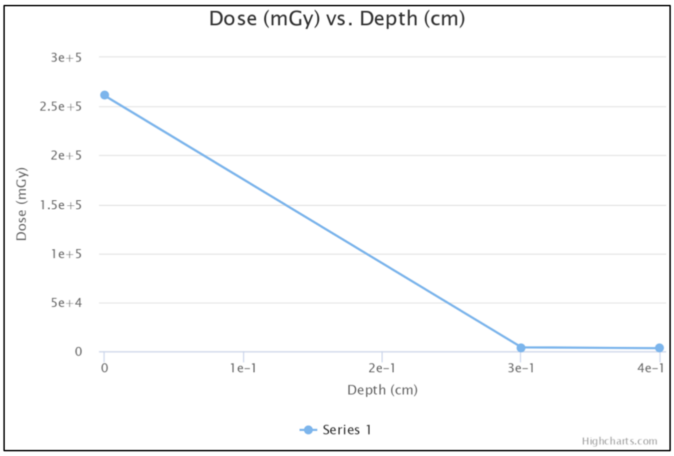

Figure 5

Figure 5 shows the Dose vs Depth obtained from OLTARIS for 3mm SWNT + 1mm base. It is observed that a 2.578815 $\times 10^5$ mGy dose is absorbed and a 3.0785 $\times 10^3$ mGy dose is received on the electronics. The electronics get 30.785% of their maximum dosage in this configuration, which is a very surprising result, as it is only 0.1% better than the base configuration for SPE radiation.

Polyethylene: Polyethylene-based compositions are very common since they have the highest concentration of hydrogen nuclei per cm3. However, polyethylene is unstable above 150-200°C and unstable above 70°C when in contact with a metal (Rojdev et al., 2009).

A 3 mm polyethylene shield weighs 0.96 kg, with the total structure weighing 1.824 kg. The production cost is $123.84, and the launch cost is $17,280. After adding the base cost, the total cost comes out to be $32,832.

Figure 6 shows the Dose vs Depth obtained from OLTARIS for 3mm Polyethylene + 1mm base. It is observed that 2.564127 $\times 10^5$ mGy dose is absorbed and 4.5473×103 mGy dose is received on the electronics. The electronics get 45.473% of their maximum dosage in this configuration.

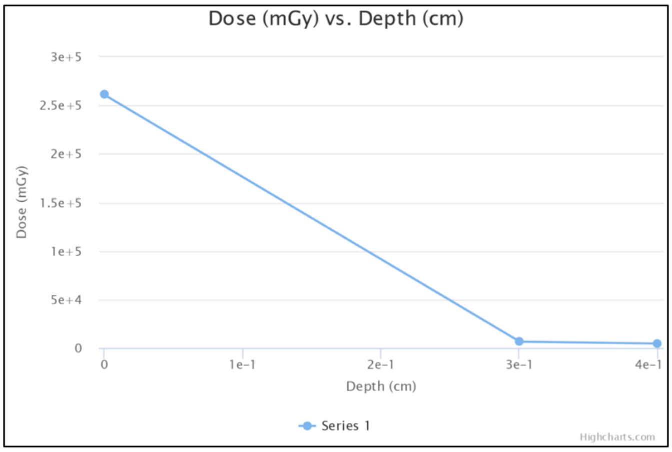

Figure 6

Kevlar

Kevlar is lightweight and strong, able to withstand extreme temperatures, and has high tensile strength. It also has excellent ballistic properties, allowing it to protect the satellite from space debris. It is a very common material to be used for space applications; for instance, it is widely used in the ISS.

A 3 mm Kevlar shield weighs 1.3824 kg, with the total structure weighing 2.2464 kg. The production cost is $467.85, and the launch cost is $24,883.2. After adding the base cost, the total cost comes out to be $40,435.2.

Figure 7 shows the Dose vs Depth obtained from OLTARIS for 3mm Kevlar + 1mm base.

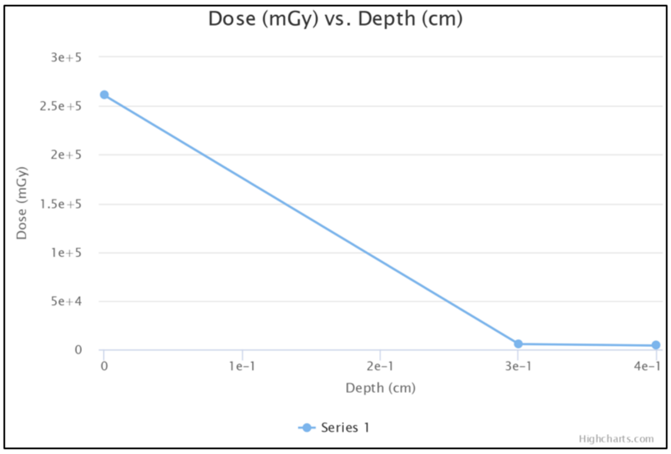

Figure 7

It is observed that 2.56982×10^5 mGy dose is absorbed and a 3.9780×10^3 mGy dose is received on the electronics. The electronics get 39.78% of their maximum dosage in this configuration.

Lithium Hydride: Lithium hydride is a great radiation shielding compound because it consists of 50% hydrogen that can deflect neutron radiation with good efficiency. It is also the lightest material on this list, so it's a very useful material for radiation protection and is often used.

A 3 mm lithium hydride shield weighs 0.7872 kg or 787.2 g, with the total structure weighing only a light 1.6512 kg. The production cost is $1023.36, and the launch cost is $14,169.6. After adding the base cost, the total cost comes out to be $29,721.

Figure 8 shows the Dose vs Depth obtained from OLTARIS for 3mm Lithium hydride + 1mm base.

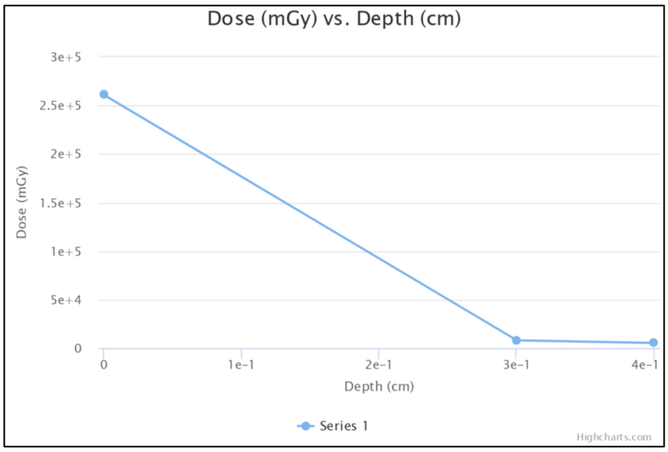

Figure 8

It is observed that a 2.557522×10^5 mGy dose is absorbed and a 5.2078×10^3 mGy dose is received on the electronics. The electronics receive 52.078% of their maximum dosage in this configuration.

Graphical Overview

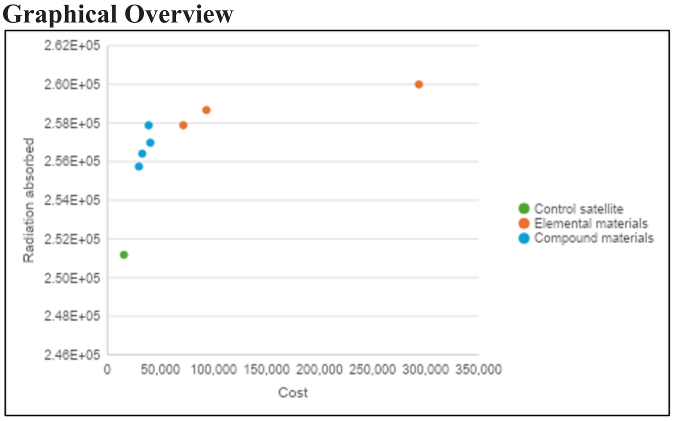

Figure 9: The farther up and left the material is, the better

If we look purely at the shielding aspect and ignore the cost, elemental materials outrank compound materials. Tantalum performs the best, and is followed by titanium. Titanium is followed by CNT and aluminum, which have the same dosage absorption, with aluminum being better by only 19 mGy. These are then followed by Kevlar, polyethylene, and lastly, lithium hydride.

However, in terms of cost, compound materials are cheaper than elemental materials and are similarly priced, with the ranking being lithium hydride, followed by polyethylene, followed by CNT, and finally Kevlar. Meanwhile, elemental materials are very expensive, each being marginally more expensive compared to the last, where aluminum is the cheapest but still more expensive than all compound materials, followed by titanium; after which, by a huge margin, tantalum is the most expensive material.

To better compare both the cost and shielding properties, we can compare the effectiveness of the materials.

$$\text{Effectiveness of the material} = \frac{radiation\ absorbed}{cost}$$

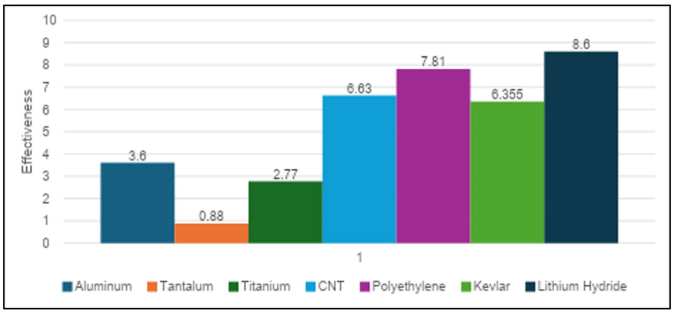

Figure 10: The higher, the better

Observing Figure 10, it can be determined that lithium hydride, with an efficiency of 8.6, is the most efficient in terms of absorption-to-cost ratio, followed by polyethylene with an efficiency of 7.81. Kevlar, with 6.33, and carbon nanotubes, with 6.63, come next with almost equal effectiveness, whereas CNT ranks just a bit higher. It is followed by aluminum with 3.6, titanium with 2.77, and finally, tantalum, being the least efficient, with a 0.83 efficiency.

COUNTER-ARGUMENTS

It can be argued that other methods of protecting satellites from radiation should be used instead of passive shielding to save the weight of the satellite and fuel. The other methods include, but are not limited to, active shielding, radiation hardening, and redundancy. Active shielding provides much better protection from radiation as it generates its own magnetic field to deflect the CME as opposed to absorbing it. However, it consumes a lot of energy, and it should be used for manned missions or missions with a short operating time. It is not recommended for satellites, as it will reduce the duration of the mission significantly. Radiation hardening makes electronic components by using special techniques that are more resistant to radiation than normal ones. However, this method is very slow and difficult, and thus, radiation-hardened electronics are often very behind on technological advancements.

Redundancy is creating extra components that perform the same function as backups in the satellite. This makes it so that when one component is damaged, the other one can take over. It is worth noting that such failsafe are vital in any system. However, there is the disadvantage of added weight, which can increase the cost of the satellite and complex circuitry required for redundancy.

CONCLUSION

From this study, it can be concluded that compound materials are the cheapest and the most efficient, but with enough budget, we can settle for elemental materials, as they are much better at shielding radiation. There is also an interesting observation that the first layer of the shield blocks a majority of the radiation, and then the layers after it. Thus, no matter what they are or how much radiation is imminent, never block the dose that effectively. We can see this in the slope of the figures. Here is another instance of the same effect happening with 3 layers in Figure 11:

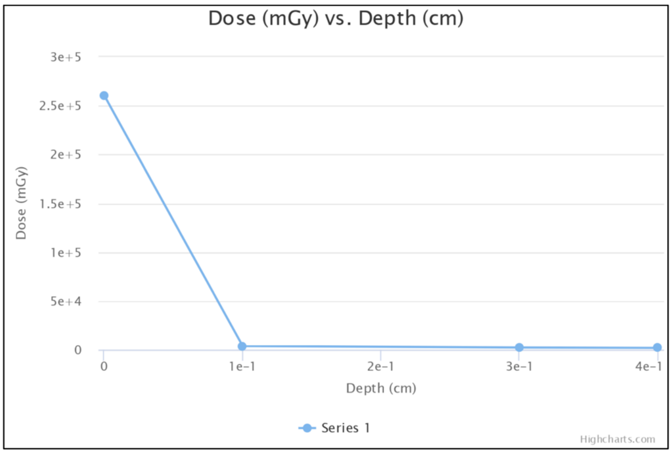

Figure 11

Further research can be done on this effect and how to avoid it. It can be speculated that the reason for this effect is that one type of radiation is being converted into another. For example, proton radiation, when interacting with materials, gets converted into electron radiation. Each radiation needs a different type of material to shield it. Therefore, in conclusion, we should use all types of radiation shielding techniques, like active shielding, redundancy, radiation hardening, etc., to achieve maximum protection of electronics and not rely on one method, and if we do use passive shielding, we should put the best material towards the outside.

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