Radiation Protection

Going to Mars? Better put on a heavy coat.

Space is a very hazardous place. It is a near perfect vacuum and is bathed in radiation produced by the sun and other cosmic sources and some is concentrated in radiation belts to make it particularly dangerous. Spacecraft design has to walk a fine line between being light and having sufficient radiation protection for the personnel and equipment onboard.

Radiation is a problem for human spaceflight as the incoming radiation can strike our cells and cause damage to the internal cell structure and cause DNA mutations. Most of the resulting mutations end in the death of the cell. But some actually cause the cell to mutate into a cell that reproduces itself continually. This results in the formation of a cancerous tumor. To limit the risk to our astronauts, we need to protect them with radiation shielding.

To protect the astronauts, we can use three different methods to minimize their exposure:

Time: Minimize the time the astronauts are exposed to the radiation. This will minimize the dose they receive. This can be done by planning a trip to Mars when the time in space will be the shortest.

Distance: Maximize the distance from the source of radiation. Radiation fields get weaker the further you move from the source. By increasing your distance, you minimize your exposure. For our astronauts, there is not much we can do here because they are receiving mostly background radiation which is present throughout space no matter where you go. Still, if there are radiation belts that the astronauts will encounter, we can plan their trips to maximize the distance from them.

Shielding: If we increase the amount of shielding, we will decrease the radiation exposure. Shielding varies depending on the type of radiation we want to shield against. Below we will discuss the different types of radiation and the shielding that is effective to minimize exposure.

Types of Radiation

Radiation can be grouped into two main groups: Particles and Electromagnetic. The ability to stop particles is directly related to how charged and how massive the particles are. Particle radiation is neutralized as a threat by having it stopped in a material before it gets to the astronauts. The more massive and charged the particles are, the more they interact with material and give off their energy.

Particle Radiation

Alpha particles: These particles are actually helium atoms with the electrons stripped off (helium nuclei). Because they are made up of 2 protons and 2 neutrons, they are relatively massive and charged compared to other particle radiation. Because of this, they are stopped by shielding as little as a single piece of paper. For the astronauts, this radiation will be stopped in the material in the spacecraft, their clothes, or the outer dead layer of their skin. Because of this, alpha radiation is not too much of a concern.

Beta particles: These are actually just electrons. They have a charge but very little mass. They penetrate better than alpha particles, but can still be stopped by a few millimeters of aluminum in our spacecraft structure. One on the main concerns of beta radiation is allowing it to enter our very sensitive and not very well protected eyes. Beta radiation can cause damage to the tissue and retina and so, for very high Beta particle fields, we will need to ensure enough shielding is in place.

Beta+ particles: Beta particles are electrons. Beta+ particles are called **positrons**. Positrons are the anti-particle of electrons. When an electron and a positron come in contact with each other, they annihilate each other and give off normally 2 high energy gamma ray photons. This is radiation that causes more radiation so we need to ensure we keep these to a minimum on our spacecraft.

Neutron radiation: Neutrons have no charge and are of significant enough mass to be real trouble. Neutrons are absorbed by some materials into their nucleus to form a new isotope of the material. Boron and Hafnium are particularly good absorbers. To do this, the neutron has to be slowed down. Otherwise it will just bounce off the nucleus and not be absorbed. Many times, neutron shielding will be made up of layers. First, a layer high in hydrogen atoms (like water or many plastics) are used to slow the neutrons down through collisions. Then an absorbing material is used to suck them up. Water is actually an effective shielding and we should consider designing our spacecraft with water holding tanks that surround the astronaut work and sleep areas.

Cosmic radiation: These are extremely high energy particles that have huge penetrating ability. Earth's magnetosphere acts as a shield for us and most Cosmic radiation doesn't make it to the surface. In space, these particles are a big problem. They require a lot of shielding to reduce their amount and cause a lot of biological damage for the ones that get through. This is going to be difficult in our design as we need a lot of shielding, but we want to minimize weight. Again, surrounding the astronaut living areas with heavy equipment and storage tanks will go a long way to using what is already on the spacecraft as shielding.

Electromagnetic Radiation

Electromagnetic radiation is seen in the form of energy packets that travel through space. They are not actually mass (although, they can sometimes act like a mass) but a package of energy that travels at or near the speed of light. There are forms we are familiar with (like x-rays). X-rays are very penetrating (hence their use in photographing our internals). Most electromagnetic radiation is stopped by heavy materials (high density molecules) like lead, iron, depleted uranium, etc. Unfortunately, these items add considerable weight to the spacecraft. Using lighter materials usually means needing a lot more thickness of the material adding bulk to our spacecraft.

What can we do to protect our astronauts?

Hopefully, you have a little appreciation for some of the engineering problems faced by spacecraft designers. They constantly have to balance weight and safety. We would love to encase our astronauts in 3 feet of lead, but that craft would never get off the ground. Let's look at a quick problem to see how we can start to get a handle on radiation exposure.

Problem: Find a shielding material that will protect our astronauts from exceeding their occupational exposure limit during the 220-day trip to Mars.

Radiation damage to a person is commonly reported in a unit called the **Sievert**. A Sievert is the damage caused by a joule of energy deposited in a kg of the human body. This equivalent damage can be studied and quantified so that we can assess its risks and set allowable limits for people. NASA and other organizations will set their own limits (as will the government) but let's set our own limit. To do this, we will need to see how much radiation dose (damage) we are willing to have our astronauts receive.

There is a model that shows that the risk of fatal cancer rises **5.5%** with every Sievert of damage. The average dose of someone on Earth is 10 micro Sieverts (**10 µSv**) per day. The radiation from the last rover trip to Mars was measured and revealed that the total dose an astronaut would receive during the round trip to Mars was **0.66 Sv**. If we assume our 220-day shortest trip (440-day round trip), that would be an average of **1.5 mSv** (that is 150 times the dose of being on Earth!).

Let's design a shield made of **Tungsten** to bring down the average exposure of the astronauts to those experienced on Earth. To do this, we will use a concept called **half-value layer (HVL)** (sometimes called half-value thickness, or just half thickness). This is the amount of thickness of the material to reduce the radiation making it through the material by half. For typical gamma radiation, Tungsten has a half-thickness of 3.3 mm. So, for every 3.3 mm of Tungsten, we will reduce the radiation by half. Let's use some math to see how thick our layer needs to be.

$$Radiation\ Level_{Final} = Radiation\ Level_{Initial}\ x\ 2^{\left(\frac{thickness}{half-thickness}\right)}$$

Rearranging for thickness gives:

$$thickness = (half\ thickness)\ x\ log_2\left(\frac{R_i}{R_f}\right)$$

plugging in our values:

$$thickness = (3.3\ mm)x\ log_2\left(\frac{1500\mu Sv}{10\mu Sv}\right) = \mathbf{23.9\ mm}$$

So we would need a shield thickness of 23.9 mm of Tungsten to ensure the astronauts would have the same exposure in space that they would have on Earth.

Let's do a quick calculation of the amount of material required. Let's assume that the astronauts will spend the majority of time in a space the size of the Orion Crew Module (5 m diameter by 3 m height). The volume of a shield 23.9 mm thick surrounding this structure would be:

$$Volume = \frac{1}{2}\pi\ length\left(r_{outer}^2 - r_{inner}^2\right) = \frac{1}{2}\pi\ (3m)(5.0239m^2 - 5m^2) = \mathbf{1.13\ m^3}$$

Given that Tungsten is 19.25 g/cm^3, we can calculate the mass of this shield as 21,752 kg or about 48,000 lbs. At $40,000/lb to get material into space, that would be about 2 billion dollars for the shield alone.

Maybe we can come up with another idea.

Hopefully, you have a better appreciation for the types of radiation, their hazards, and methods to utilize shielding to help protect our astronauts. We made a lot of assumptions and there is a lot more factors involved in shielding. But if you are interested, work hard on math and science and you could be part of the team that solves these difficult problems.

