Effects of the lunar environment and radiation on materials and their implications for Lunar Mission 1

Manuel Alparaque II
Nuffield Research Program, Lunar Mission 1, University of Bath, United Kingdom

Abstract

Lunar Mission One intends to leave an archive in the bottom of a borehole after drilling and gathering samples. This archive will contain digital and DNA information and is expected to last for about a billion years. There are some conditions on the moon which helps in the preservation of the archive such as the extremely low temperatures. However, the main danger for the information stored on the archive is radiation. Being exposed to different kinds of radiation through the course of the mission poses a challenge and in order to find a suitable shielding material, this report identifies the different types of radiation the archive will be exposed to and the dangers each type poses to the archive if any. This report also evaluates the suitability of four different possible shielding materials: titanium, aluminium, polyethylene and Kevlar. These materials have been used in the space radiation environment or have undergone tests to ensure their suitability to shield and survive in space conditions. As each material is effective for one type of radiation and relatively ineffective in another, a multi-layer shield is required to ensure maximum safety for the archive. A multi-layer shield composing of Kevlar and titanium is most suitable as they give the archive maximised protection against impacts and seismic activity while being able to shield off radiation effectively.

Introduction

Lunar Mission One's aim is to send a lunar lander to the South Pole of the moon near Shackleton Crater. Once landed, the lander will start to drill below the lunar regolith up to depths of 20-100 metres. By drilling below the surface, lunar rock dating up to 4.5 billion years could be accessed and stored for recovery in the future. [1] After drilling, the spacecraft would place an archive in the form of a time capsule in the borehole. This archive will contain data of life on Earth, DNA samples e.g. a strand of hair as well as private memory boxes which can be purchased and filled with digital data. [2] This archive is aimed to survive up to a billion years and the conditions below the surface of the Lunar South Pole offer an ideal environment for preservation. However, there is a risk of radiation exposure while the spacecraft travels through space and also due to the target geological timescale, minor exposure over a long period of time can cause an accumulation of intensity and potentially damage the archive and its contents. This report will explore radiation exposure from sources such as Galactic Cosmic Rays, Solar Particle Events, Secondary Radiation and radiation from surrounding radioactive lunar rock. Potential materials for will also be assessed for their suitability for the mission. The aim of this report is to suggest a suitable material to be used for shielding the archive considering the dangers it will be exposed to from travelling in space up to surviving in the borehole for a billion years.

Radiation

Radiation is a form of energy that is emitted or transmitted in the form of rays, electromagnetic waves, and/or particles. [5] Ionising radiation can be dangerous because whenever it passes through substances, it can alter their physical and chemical composition in the atomic scale which leaves a significant amount of damage especially if it results in a secondary particle being emitted and causing further damage. There are three primary sources of radiation that the archive will be exposed to during different stages of the mission. Unlike the Earth, the Moon does not have a strong magnetic field and a thick atmosphere. The Earth's magnetic field scatter charged particles from radiation while the thick atmosphere prevents most cosmic ray particles to enter as they are unable to penetrate it.[4] During the launch and travel stages, the archive will most likely be exposed to Galactic Cosmic Rays and radiation from Solar Particle Events, these are the primary sources of radiation that the archive will be exposed to. During the landing, drilling and storage stages, the archive will also be susceptible to Secondary Radiation from the lunar surface itself and radiation from any surrounding radioactive rocks that have been deposited in the lunar surface. Each of these sources emits a different type of radiation consisting of protons and electrons with occasional heavier nuclei. There are a lot of factors which vary from the different radiation, high-energy galactic cosmic rays at low fluxes, occasional intense particle fluxes from solar particle events; these factors also affect how they interact with the lunar regolith, the different energy levels result in varying penetration depths ranging from micrometres to meters [4]. The results of these interactions, mainly primary radiation include heavy-nuclei tracks, spallation reactions and leads to the production of secondary particles. [4] The wide range of factors and effects make finding a suitable shielding material challenging as it should be able to shield from ionising radiation and protect the archive from the different effects caused by interactions in the lunar surface. Another type of radiation that the archive may come in contact with is radiation from the surrounding lunar rock. Radioactive elements such as Potassium, thorium and Uranium have been found to be present on the moon during the Apollo Missions and various other lunar satellites such as Luna, these radioactive elements will be able to release all three types of radiation over time so the shield must withstand alpha, beta and gamma radiation over prolonged periods of time.

Galactic Cosmic Rays

Galactic Cosmic Rays are radiation of high energy that originates outside our solar system but is within our Milky Way Galaxy. GCR's are a type of particle radiation consisting of about 85% protons, 14% helium and 1% HZE particles which are high energy and highly charged ions.[5] HZE particles can be any element present in the periodic table as these particles also originate in space. HZE particles can cause more radiation induced damage, are more ionising and have a greater penetrating power due to its high energy, this makes it very dangerous although these particles are much less abundant than protons and helium particles. GCR's are accelerated nuclei which have no outer electrons and can reach speeds near the speed of light; they are known to be accelerated by the remnants of supernovae such as giant expanding clouds of gas and magnetic fields which remain for thousands of years. Particles are accelerated in the magnetic fields and the motion and collisions of these particles causes some of the particles to gain kinetic energy and eventually build enough speed to escape the supernovae remnant and be emitted as a cosmic ray. GCR's are constantly present in space although there are factors which limit their abundance. The biggest of which is the Sun's magnetic field, during the 11-year cycle of the Sun it has two points called the solar maximum and minima. During the solar minima there is less activity in the sun and less solar flares due to the low magnetic field strength; this causes an increase in GCR flux as magnetic fields can block the charged particles from passing through. On the other hand, during the solar maxima there is a high number of solar flares and other occurrences due to the stronger magnetic field strength, this causes a decrease in GCR flux as the strong magnetic field is preventing some cosmic rays from passing. This is important because the moon has a relatively weak atmosphere and no magnetic field meaning it is completely exposed to Cosmic Rays. Galactic Cosmic Rays will probably have a small or negligible effect on the archive as the heavy-nuclei particles will be stopped within a few centimetres of the lunar surface, the lighter nuclei particles may be able to penetrate a few metres into the lunar surface which makes them more likely to be able to reach the archive although they will be much less ionising than the heavier-nuclei particles.

Solar Particle Events

The sun is essentially a large particle accelerator, and this allows it to cause phenomena such as Coronal Mass Ejections, Solar Flares and Solar Particle Events.. Solar Particle events happen occasionally but generate high fluxes of energetic charged particles composed of protons, electrons and some heavier nuclei over a short period of time. [4] During the Sun's solar minima, the Sun's magnetic field strength is low so events such as Coronal Mass Ejections occur at a lower frequency and more frequently during the solar maxima. Solar flares and CMEs cause explosions in the Sun's surface and generate an interplanetary shock that propagates in space; they also cause a deformity in the Interplanetary Magnetic Fields causing them to extend beyond their current positions. These deformities can cause particles to escape from their acceleration sites and allow them to be accelerated along the IMF until such extent that they are able to escape and emit high energy proton radiation. Like the GCR, the radiation coming from Solar Particle Events will also be stopped a few centimetres into the lunar surface and will probably have a very small chance of affecting the archive.

Secondary Radiation

Secondary Radiation is composed of neutrons and photons. These are emitted when primary radiation interact with the surface of the moon, as radiation ionises the nuclei of particles, they can produce secondary radiation. Neutrons are more dangerous since they are relatively larger then both electrons and a bit larger than protons. Initially, the neutrons are uncharged but when it strikes an atom with enough energy, it may become charged allowing it to interact with the material it is passing through more easily [4] Secondary radiation usually has a lower flux than both sources of primary radiation although they have a higher abundance than Galactic Cosmic Rays and slightly higher than Solar Particle Events.

Radiation from rocks

There is an abundance of radioactive rocks that can be found on the moon. The natural radioactivity comes from radio elements, Uranium, Thorium and Potassium. Studies from the Luna orbiter and the Apollo missions have given us access to samples of lunar rocks and the level of radiation present. The results after investigating the samples gathered has given a composition of: 0.03 to 0.7% of potassium, 0.1 to 5 p.p.m. and 0.4 to 18 p.p.m. of thorium. [7] Although the individual results can vary greatly because radioactive material are not uniformly present in the lunar surface. These naturally radioactive rocks give off alpha, beta and gamma radiation so the material used for shielding must be able to shield against gamma radiation because although being less ionising it is also very penetrating and over the course of the archive's survival in the borehole, the radiation dose may accumulate and cause damage to its contents. Also by being able to shield against gamma radiation it also becomes an effective shield against the less ionising alpha and beta radiation although this is unlikely as the surrounding lunar rock will be enough to shield against these.

Materials

Different materials will be discussed in order to produce a suitable suggestion for Lunar Mission 1 concerning the material to be used for shielding the archive from radiation. Titanium, Aluminium, Polyethylene, Kevlar, are the materials to be evaluated for their suitability to the mission. Aluminium and Polyethylene are already being used in the ISS and other spacecraft so are proven to withstand space radiation over a substantial amount of time. Meanwhile, Titanium and Kevlar are materials undergoing tests whether they would survive the radiation environment in space and if they can be used as radiation shielding.

Titanium

Titanium has different mechanical and physical properties which makes it suitable as a shielding material. Due to the fluctuation of temperatures on the lunar surface, a great amount of stress will be applied on the material. Titanium Dioxide has a low coefficient of thermal expansion and a high melting point which helps it withstand these temperatures. Having a high strength to weight ratio and the possibility of alloys to further strengthen titanium enables it to withstand impacts from micrometeorite showers and seismic activity on the lunar surface. Titanium can also shield against primary radiation and having smaller nuclei helps prevent neutron and nuclear fragments to be emitted as secondary radiation. Titanium will also absorb wavelengths which are larger and slower due to its moderate to large molecular cross section and density; this can be further improved if alloyed with hydrogen to form hydrogen hydride. The values for these properties are shown in the table below. [8]

Figure 1

Property	
Density	4 gcm^{-3}
Porosity	0%
Modulus of Rupture	140MPa
Compressive Strength	680MPa
Poisson’s Ratio	0.27
Fracture Toughness	3.2 $Mpa.m^{-1/2}$
Shear Modulus	90GPa

Modulus of Elasticity	230GPa
Microhardness (HV0.5)	880
Resistivity (25°C)	10^{12} ohm.cm
Resistivity (700°C)	2.5×10^{4} ohm.cm
Dielectric Constant (1MHz)	85
Dissipation factor (1MHz)	5×10^{-4}
Dielectric strength	4 $kVmm^{-1}$
Thermal expansion (RT-1000°C)	9×10^{-6}
Thermal Conductivity (25°C)	11.7 WmK^{-1}

Aluminium

Aluminium alloys have been used in the ISS as a radiation shielding material. It has physical properties which makes it suitable as a shielding material. Although pure aluminium itself has a relatively high atomic number which helps in stopping lower energy gamma and x-ray radiation, alloys can be made to ensure that secondary particles are reduced when radiation interacts with the material. Aluminium is also used for radiation shielding in satellites, being lightweight also makes it more suitable. The stopping power of aluminium against proton radiation and other ionising radiation are shown below. [9]

Figure 2

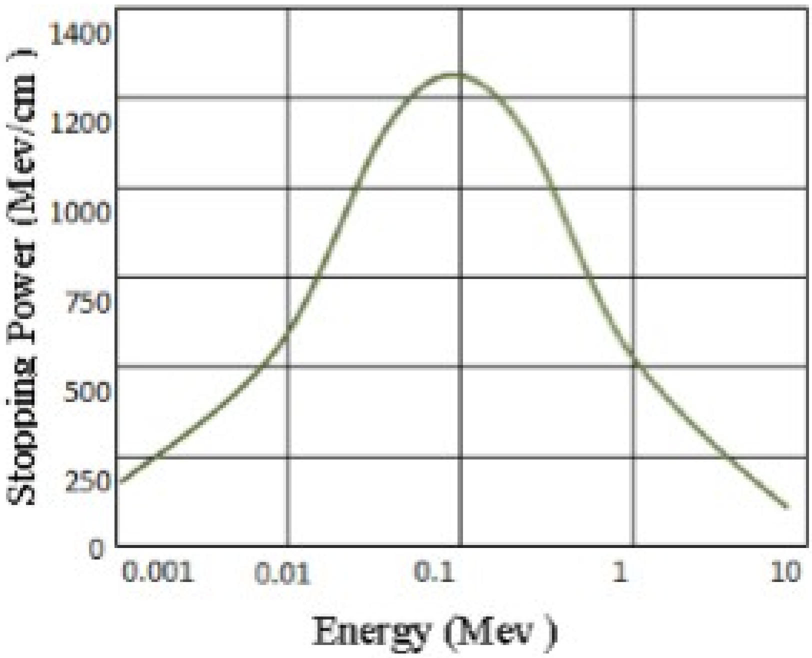
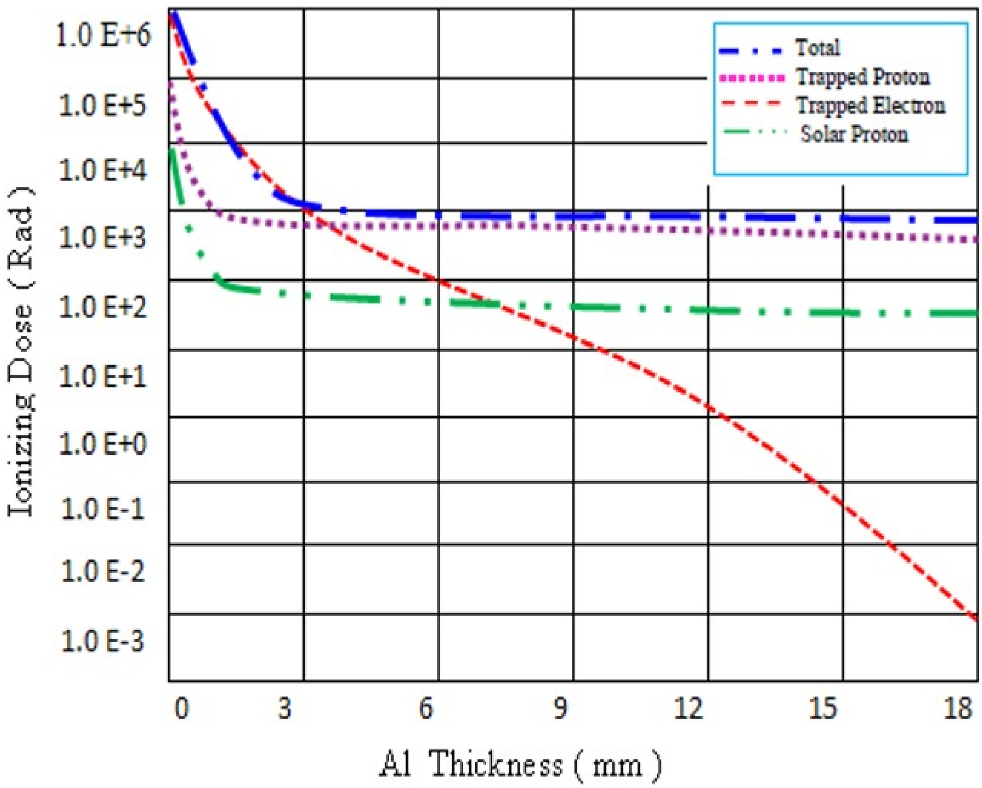


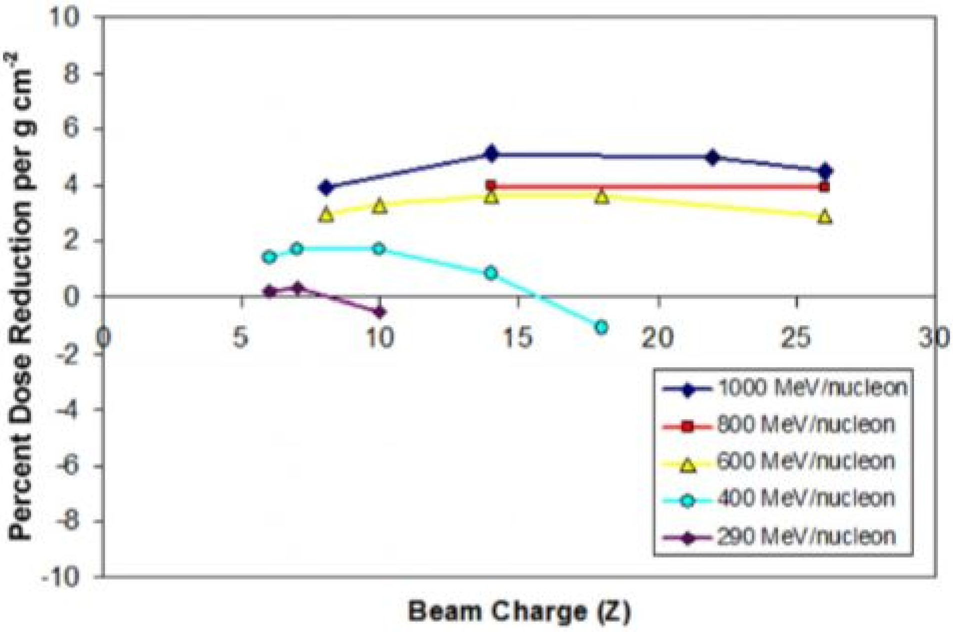
Figure 3



Polyethylene

Polyethylene is a combination of Hydrogen and Carbon. This makes it effective because materials with a lower atomic number are usually more effective against radiation coming from GCRs. Polyethylene has been used widely in the ISS. Its stability, weight, cost and ability to block radiation makes it extremely useful. Although it may not be as effective when stopping radiation such as Gamma radiation because it does not have enough molecular density to overcome the penetrating power of gamma rays. It still has implications for Lunar Mission One because of its properties and use. At a 10 cm thickness of Polyethylene, its percent dose reduction for GCRs could go up to 30% [10]

Figure 4
The data was taken from a 2.83 gcm^{-2} polyethylene target.



Kevlar

Kevlar is one of the newer materials to be tested for suitability in the space environment. Chemically defined as poly para-phenyleneterephthalamide. It has a combination of Nitrogen, Oxygen, Hydrogen and Carbon most of which are effective radiation shielding elements. They are about 80-90% as effective as polyethylene for GCR radiation shielding and due to the mixture of elements with a higher atomic number, they should be more effective against low energy gamma radiation compared to polyethylene. Kevlar is also a more suitable shielding material than Aluminium, having shown better results during the tests. It has undergone different environmental tests to ensure it is suitable for the space environment and known to be used in, bullet proof vests; Kevlar is very durable and will be able to withstand high velocity impacts which may occur from micrometeorite showers and moon quakes. [11]

Discussion & Conclusion

There are a variety of different sources of radiation present in the lunar surface and all emit a different kind of radiation ranging from electromagnetic radiation to particle radiation; this circumstance makes it difficult to only choose one material for shielding as it may be effective against the high energy radiation but be ineffective against the low energy and more penetrating radiation. Considering the aims of Lunar Mission 1, especially the time frame they expect the archive to survive, low energy radiation should not be neglected as a build up of this dose may be just as lethal as a concentrated exposure to high energy radiation. Titanium is overall a useful radiation material although its lack of use in the space environment today makes materials such as aluminium and polyethylene more reliable. Aluminium is suitable for interplanetary space radiation but ineffective to be used in the Lunar environment due to the abundance of secondary particles. Polyethylene Is a very ideal radiation shield against high energy radiation which is important for GCRs and SPEs, but are not ideal as shielding for gamma and x-ray radiation. Kevlar lacks the real-life applications in the space environment but the tests conducted have shown great promise and have proven it to be suitable as a radiation shield. To maximise the effectiveness of the shielding material for the archive, a multilayer shield should be produced to ensure that the shield itself is able to withstand a wide range of radiation types, minimise the production of secondary particles, and to maximise its survivability in the lunar environment. Multi layer shield which involves combinations of Kevlar and titanium or titanium and Polyethylene are reasonable as the Kevlar and polyethylene will be able to shield against any high-energy radiation while titanium is an effective low energy radiation shield. It also helps in preventing secondary radiation to reach the archive and affect it in any way. A multilayer shield maximises the properties of available materials in order to make them the most suitable for this specific mission. Kevlar and Titanium is preferable as their ability to withstand a great amount of damage can help if any unplanned events occur over the period which the archive is set in the borehole.

References

[1] - *Pallab Ghosh (8 December 2014). "UK researchers set out goals for Lunar Mission One". BBC News.Retrieved 12 August 2016*

[2] - *Pallab Ghosh (19 November 2014). "UK 'to lead moon landing' funded by public contributions". BBC News. Retrieved 12 August 2016*

[3] - Dr. David R. Williams (19 April 2016) “Moon Fact Sheet” – NASA. Retrieved 12 August 2016

[4] – Kristina Rojdev (December 2012) “ Long term lunar radiation degradation of potential lunar habitat composite materials.

[5] – David Vaniman, Robert Reedy, Grant Heiken, Gary Olhoeft and Wenell Mendell (26 April 1991) “Lunar Sourcebook”“The Lunar Environment” Chapter 3, page 47-56

[6] -Vainio, R., A. Pönni, M. Battarbee, H.E.J. Koskinen, A. Afanasiev, and T. Laitinen, (2014) “A semi-analytical foreshock model for energetic storm particle events inside 1 AU”, J. Space Weather and Space Climate, 4, AO8, 2014

[7] – Surkov, Iu. A. (1982) “Natural radioactivity of the moon and planets. In: Lunar and Planetary Science Conference

[8] [Figure 1] – AzoM (11 Jan 2012)“Titanium Dioxide – Titania,” http://www.azom.com/details.asp?ArticleID=1179.

[9] [Figure 2 , 3] - Omid Zeynali, Daryoush Masti and Saeed Gandomkar (2012)“Shielding protection of electronic circuits against radiation effects of space high energy particles” “Pelagia Research Library”

[10] [Figure 4] – S. Guetersloh, C. Zeitlin, L. Heilbronn, J. Miller, T. Komiyama, A. Fukumura, Y. Iwata, T. Murakami, M. Bhattacharya (October 2006) “Polyethylene as a radiation shielding standard in simulated cosmic-ray environments” “ Nuclear Instruments and Methods in Physics Research B”, 252, 2006

[11] C. Lobascio, M. Briccarello, R. Destefanis, M. Faraud, G. Gialanella, G. Grossi, V. Guarnieri, L. Manti, M. Pugliese, A. Rusek, P. Scampoli, and M. Durante (2008) “Accelerator-based tests of radiation shielding properties of materials used in human space infrastructures.”

Summary & Acknowledgement

My research was always focused on exploring the different types of radiation present in the lunar surface which could have an effect on the archive. As the project developed, I was able to find four materials which I thought were the most suitable to be used as Shielding material so I evaluated them to then produce a suggested conclusion for Lunar Mission One on materials to be used as shielding for the archive.

I would like to thank: the Nuffield Foundation for giving me the opportunity to undergo in this research project, University of Bath for providing the facilities and coordinating with the researchers throughout the programme, Lunar Mission One for the opportunity to be part of something ambitious and educational and my fellow researchers for making this whole research project worthwhile.