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The future of Moon spacewalks: Next-generation radiation protective spacesuit

Yann VAN ROYEN

Supervisor: Prof. Dr. S. Baatout
Co-supervisor: Dr. B. Baselet

Thesis presented in
fulfillment of the requirements
for the degree of Master of Science
in Space Studies

Leuven, 2019-2020

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Acknowledgements

"No one who achieves success does so without acknowledging the help of others. The wise and confident acknowledge this help with gratitude"

– Alfred North Whitehead

For this master thesis I got the opportunity to carry out a project that might lay the basis for a next-generation spacesuit. While the circumstances were far from optimal during the past few months, with many uncertainties and delays coming forth as a result of the COVID-19 pandemic, I can proudly present this paper in all its glory.

First and foremost, I would like to thank my promotor, and the head of the radiobiology unit at SCK CEN, Prof. Dr. Sarah Baatout not only for offering me the possibility to work in close collaboration with the Belgian Nuclear Research Centre (SCK CEN), but also for her lively wit and keen appreciation of the subject I was assigned to. Whenever Prof. Baatout would join a videocall, a sincere smile was never far away, and progression was quickly made in a heartfelt manner.

Secondly, thanks should be bestowed upon my supervisor, and scientific collaborator at SCK CEN, Dr. Bjorn Baselet. His heart-warming welcome into the research centre on my first day was a great way to take off this internship. Dr. Baselet definitely allowed this paper to be my own work but steered me in the right direction whenever needed. Nevertheless, I am gratefully indebted to his pertinent, yet well-grounded feedback on this thesis. The acquisition of results would furthermore not have been possible without the devotion of Randy Vermeesen, Bsc., to ordering the necessary materials and managing the experiments, such as culturing, colouring and imaging of the cells.

On top of that, I would like to thank all the professors connected to the master program and the external lecturers who were willing to convey their fascination for space to a group of students with such diverse backgrounds. Special thanks should go to the director of the program, Prof. Dr. Christoffel Waelkens of the department of physics and astronomy at KU Leuven. He always put us, the students, and our needs first and has supported us throughout the whole year. He made the program to what it is today, and I am happy that I was able to be a part of it.

On a different note I would like to say thank you to my family and close friends for their ever-growing interest in the subject of this paper and the research behind it – and with ever-growing interest I mean that there is actually one question that I have been grinningly asked many times, namely “So, does this mean you are going to become an astronaut and travel to the Moon?”. The astonishment is marvellous when you look at them with a straight face and go “Yes, of course.”. I can assure you; it is a real icebreaker. Of course, I would not have been able to achieve where I am today without their never-ending support.

This master thesis concludes this year of the advanced master of Space Studies and, with that, my six-year-long study career. This last year would not have been the same without my fellow students, who embarked, just like me, on a journey to the stars and beyond. Of course, it is great to be in contact with other experts in fields related to space, but it is even more amazing to be able to call them my friends. My university career truly is something to look back on with a big smile on my face, even though this last year was unusual in every meaning of the word.

A new life, apart from the perks of being a student, awaits… and I am ready for it!

Leuven, June 2020

Yann Van Royen

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List of abbreviations

Abbreviation	Definition
3D	Three-dimensional
ABS	Acrylonitrile butadiene styrene
AC	Alternating Current
ALARA	As-low-as-reasonably-achievable
AMF	Additive Manufacturing Facility
ARS	Acute Radiation Syndrome
BER	Base Excision Repair
CME	Coronal Mass Ejection
CNT	Carbon Nanotube
CRS	Chronic Radiation Syndrome
DAP	Dose Area Product
DAPI	4',6-dieamidino-2-phenylindole
DC	Direct Current
DEP	Dielectrophoresis
DMEM	Dulbecco's Modified Eagle Medium
DNA	Deoxyribonucleic Acid
DSB	Double strand break
EDTA	Trypsin-ethylenediaminetetraacetic acid
EMU	Extravehicular Mobility Unit
ESA	European Spacr Agency
ESD	Electrostatic Discharge
EVA	Extravehicular activity
GCR	Galactic Cosmic Radiation
Gy	Gray
HDBPE	High-density borated polyehtylene
HDPE	High-density polyethylene
HZE	High charge Z and high energy
ICRP	International Commission on Radiological Protection
ICRU	International Commission on Radiation Units and Measurements
IOM	Institute of Medicine
ISS	International Space Station
LDPE	Low-density polyethylene
LEO	Low Earth Orbit
LET	Linear Energy Transfer
NASA	National Aeronautics and Space Administration
NIST	National Institute of Standards and Technology
PBS	Phosphate-Buffered Saline
PC	Polycarbonate
PET	Positron Emission Tomography
PFA	Paraformaldehyde

PLSS	Primary Life Support System
PTFE	Polytetrafluoroethylene
Q	Quality Factor
R	Roentgen
RBE	Relative Biological Effectiveness
RNA	Ribonucleic Acid
ROS	Reactive Oxygen Species
SAA	South Atlantic Anomaly
SCR	Solar Cosmic Radiation
SEM	Standard error of the mean
SEP	Solar Energetic Particle
SI	International System
SPE	Solar Particle Event
sPUU	Self-healing polyurethane urea
SSB	Single strand break
STR	Space Technology Roadmap
Sv	Sievert
SWME	Spacesuit Water Membrane evaporator
UHMWPE	Ultra-high molecular weight polyethylene
UV	Ultraviolet
WFM	Work Function Matching
xEMU	Exploration Extravehicular Mobility Unit
γH2AX	Phosphorylated histone H2AX

Abstract

Background: The desire of mankind to travel back to the Moon, and eventually Mars, entails that the need for specialised spacesuits has become more pressing than ever. Lunar missions will require astronauts to undertake an average of 50-70 spacewalks during their stay. Mission-related assignments will ask for improved mobility without the loss of protection against factors related to the harsh environment of space. One factor is the omnipresent space radiation, which includes all kinds of ionising radiation types. The sources of this radiation are solar particle events, galactic cosmic rays and particles trapped in the Earth's magnetic field. With future space exploration missions in mind, it is important to comprehend the risks that come with long-term radiation exposure and how shielding may prevent those from happening.

Objective: The aim of this paper is to investigate the radiation protective properties of different polymer-based materials and the potential they might hold for future spacesuit manufacturing.

Methods: Different polymer-based materials (high-density polyethylene (HDPE), polycarbonate (PC), neoprene and polytetrafluoroethylene (PTFE)) were used as shielding against x-rays. Their radiation protective properties were compared to those of both lead and aluminium. Shielding thicknesses from 1 cm up to 5 cm were used for each material. The fraction of x-ray dose that was able to penetrate was measured with dosimeters. Densities and attenuation coefficients of each material were also used to theoretically calculate their shielding capacity. Human primary fibroblasts, as a skin model, were placed behind each layer of shielding and, after irradiation, stained for phosphorylated histone H2AX (γH2AX) to identify double strand breaks as a biological endpoint.

Results: While it has already been shown that lead provides great protection against different radiation types, it was confirmed here once more. The material with the lowest density, neoprene, provided the least protection. The fraction of the dose that was able to penetrate multiple centimetres of PTFE came close the measurements for aluminium. Less γH2AX foci were observed in the nuclei of the cells with PTFE as shielding. Polycarbonate and HDPE also showed a decrease in doses and γH2AX spots with more layers of protection added, albeit less than PTFE.

Besides the radiation protection that polymer-based materials provide, their potential for future use in spacesuit manufacturing is amplified by the fact that these materials are easily available, lightweight, easy to shape and form fewer secondary particles due to their elemental structures. This is touched upon in the comprehensive discussion.

Conclusion: It is clear that one polymer provides better protection against ionising radiation than another. The formation of composites could, on top of that, significantly improve the radiation protection characteristics compared to the pristine material. Further additions to future spacesuits, in the form of dust-repelling mechanics, 3D-printing, recycling, etc… need to be investigated and implemented to allow for sustainable long-term space missions, independent from Earth’s resources, to be undertaken. This paper serves as a proof of concept in order to encourage further research into the differences between many materials and for possible additions to future space suits.

Summary for a general audience

Radiation is all around us nowadays. Nuclear powerplants generate electricity by splitting atoms, radiological examinations in hospitals frequently use x-rays or radiation therapies and industry irradiates, for example, foods and other substances to kill germs. Whereas these are the types we encounter on Earth, radiation in space is a whole different story (and merely one of the factors that makes up the harsh space environment). This radiation is actually a mixture of different kinds of radiation forms that originate from various sources, namely the Sun and high energetic explosions far away from Earth.

Each and every particle that makes up this so-called space radiation has the ability to penetrate matter. Matter includes all everyday objects and, most importantly, organic tissue. Upon penetration, particles interact with the material/tissue and start losing energy. This newly released energy has the ability to affect the molecular integrity of the material/tissue, including that of DNA, and can cause severe health-related problems after high amounts of and/or long-term radiation exposure. It is therefore of great importance that people travelling into space are protected in the best way possible, especially since mankind is on the verge of travelling back to the Moon and possibly Mars. Missions on the surfaces of these celestial bodies will require astronauts to remain there for longer periods of time while performing tasks in their barren environments. Hence shielding against hazardous space radiation is, while preserving mobility, one of the key goals in the field of radiation biology.

Plastic-based materials have become a popular subject within this research field. With their easy availability, low cost, low weight and ability to shape them as you please, the only thing that needs to be established are their radiation protective properties. This study was meant to demonstrate just that. Materials, such as polytetrafluoroethylene (PTFE), which is better known as Teflon®, and neoprene, which is mainly used by divers, were included among others. Dosimeters and human cells were placed behind increasing thicknesses of the different materials. Dosimeters allowed to observe what fraction of the original x-ray dose was able to penetrate the different layers, and the cells showed how much damage was done despite the placement of protective measures.

It appeared that, while not every plastic-based material showed equal radiation protective properties, one seemed to weaken the radiation more than the others: PTFE. Hence, materials that weakened the radiation more can be considered to have better x-ray shielding qualities. Following this, less damage was observed in the DNA of the cells that were protected by these materials, and in particular PTFE. It is, however, not possible to simulate the whole complex mixture that makes up space radiation here on Earth. Nonetheless, each study brings us a step closer to better preservation of astronaut health.

Nevertheless, plastic-based materials offer the opportunity to be recycled, allow the incorporation of other elements to create more resistant composites and can be more secure by the addition of technologies that provide an improved lifetime of such materials. The items as discussed in this paper hold great opportunities for the future of spacesuit manufacturing, but further research is recommended to increase the knowledge on this subject.

Ground Control to Major Tom
Ground Control to Major Tom
Take your protein pills and put your helmet on
Ground Control to Major Tom `
Commencing countdown, engines on
Check ignition and may God's love be with you

David Bowie: Space Oddity

1 Introduction

Human exploration into deep space has been a dream of mankind for centuries. It is safe to say that this dream is no longer science fiction. We are at the dawn of travelling further into space than ever before. Since 1961, hundreds of humans have embarked on a space mission. Some had the opportunity to walk on the surface of the Moon, some were tasked with the maintenance of satellites with the help of the space shuttle, while others are to this day conducting science experiments on the International Space Station (ISS). Every last one of these so-called *envoys of mankind* has experienced the harsh environmental factors, including microgravity and radiation exposure, associated with space travel. Research on the consequences related to the health of astronauts and the performance of the human body in such an environment has been ongoing since day one of human space travel. This research has allowed scientists to comprehend what needs to be done in order to fix health-related problems and work towards the possibility of preventing them.

Prevention is key in order to be able to protect astronauts aboard the ISS and human explorers that might travel into deep space within the coming years/decades. Each destination, whether we are talking about the Moon or Mars, offers different challenges and opportunities. Nevertheless, the main risks associated to space exploration programmes can be summarised as follows[1]:

1. Physiological problems caused by microgravity or reduced gravity: These are being studied during long-term missions on the ISS and Earth-bound Bed Rest studies. The risks associated to microgravity, such as bone loss, formation of kidney stones, reduction of muscle mass, immune system dysfunctions, etc… are well characterised, and countermeasures, such as compulsory daily workouts in order to preserve skeletal muscle mass, are already available.[2] Long-term missions outside of Low Earth Orbit (LEO) have, however, been executed scarcely. Knowledge on the effects of deep space missions is therefore minimal.

2. Psychological and related medical problems caused by isolation and poor psychosocial adaptation: In order to simulate these, ground platforms, such as the Concordia base in Antarctica and the Mars500 experiments, are used to better understand the impact of the neurobehavioral changes associated with isolation.
   On top of that, longer missions, and thus longer isolation periods, ask for the capability to handle sickness or accidents by oneself. This problem of autonomous medical care relies heavily on the development of portable medical equipment and telemedicine.[2]
3. Acute and late risks caused by exposure to complex space radiation: Space radiation consists mainly of protons and heavy ions (compared to x-, gamma, beta and alfa rays on Earth). Acute radiation syndrome can usually be associated with solar particle events (SPE) due to inadequate shielding. Late radiation morbidity is, on the other hand, linked to chronic exposure to galactic cosmic radiation (GCR). Textbooks generally mention three means in order to reduce exposure, namely: increasing the distance from the source, reducing exposure time and shielding. The isotropic nature of cosmic radiation rules out increasing the distance. Plans for exploration and colonisation entail the necessity of an increased period of time in space, rather than a reduction. The only feasible countermeasure that remains, at this point in time, is thus increased shielding.[2]

While it is necessary to take all the risks in account, the main focus of this paper will be on radiation exposure during space travel. In order to know how to protect ourselves from space radiation and prevent the effects from deteriorating our health, it is important to understand what space radiation exactly includes and to what extent astronauts are exposed to this invisible danger.

2 Literature review

2.1 Radiation in all shapes and sizes

2.1.1 Galactic cosmic radiation vs. solar cosmic radiation

Every last one of us, whether we are on the surface of the Earth or out in space within our solar system, is exposed to some kind of ionising radiation. This radiation is made up of two types, namely galactic cosmic radiation (GCR) and solar cosmic radiation (SCR). GCR originates from outside the solar system, while SCR is produced by the Sun. The SCR consists of two subtypes, namely highly energetic solar particles and a constant flow of low energy particles released through the solar winds. The GCR, on its turn, consists of 98% baryonic matter and 2% electrons. The baryonic matter can be divided in hydrogen nuclei or protons (85%), helium cores or alpha particles (14%), and a small fraction of heavier nuclei or high charge Z and high Energy (HZE) particles (1%). The latter are considered to be a grave danger for living beings out in space and especially for long-term missions at high altitudes or high inclinations and missions extending beyond the protection provided by the atmosphere and magnetic field of the Earth. This is because the HZE particles, though they are less abundant, possess a high ionising and penetration power.[3]

GCR can thus be considered to be a confluence of nuclei of atoms whose electrons have been stripped away. The particles exist within giant clouds and magnetic fields of supernova remnants and gain energy and are accelerated due to interactions within these fields. Some will reach a velocity, which is nearly the speed of light, that allows them to escape the remnant and become GCR.[4,5] Upon entering our solar system, the GCR has to overcome disturbances in the magnetic field due to the solar winds. It has been shown that the GCR flux is inversely proportional to solar activity, resulting in a trend that can be spotted throughout the solar cycle. The GCR flux will thus reach a maximum or minimum at minimal or maximal solar activity respectively (Figure 1). This phenomenon is called the Forbush effect. The magnetic field of the Earth serves as a shield which protects the planet and its habitants from the GCR to the extent that only high energy particles will reach low inclination orbits. Orbits with higher inclinations are less shielded due to the shape of the magnetic field and are therefore also accessible by lower energy particles. At the poles, or the polar cusps, all particles are able to impinge in the direction of the magnetic field axes.[6]

All conditions and phenomena on the Sun, in the solar wind, in near-Earth space and in our upper atmosphere that can potentially affect ground- and space-based technology and humans are considered to be part of space weather. These phenomena include changes in the interplanetary magnetic field, coronal mass ejections (CME), changes in solar wind and disturbances of the Earth's magnetic field. Space weather is thus closely related to the aforementioned solar cycle. This eleven-year cycle is characterised by the solar activity, which is linked to increases and decreases in the number of sunspots seen on the surface. More solar particle events (SPE) and CMEs are seen during solar maximum periods, leading to increased levels of radiation in our solar system. Despite being able to predict periods of solar minimum/maximum, it is not (yet) possible to predict single events, such as solar flares, SPEs and CMEs.[4]

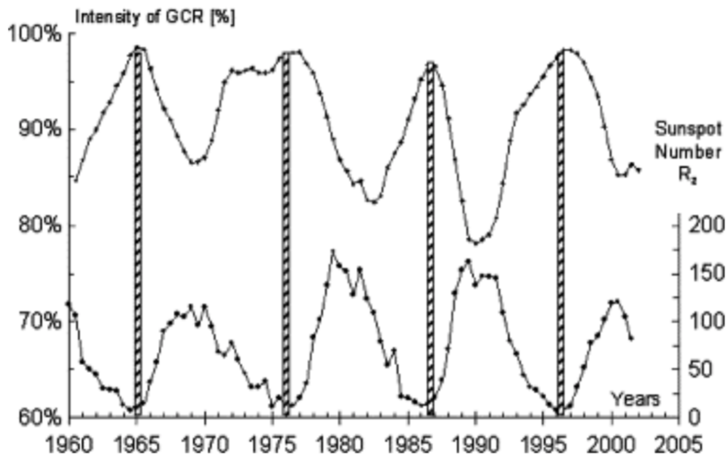

Figure 1. The Forbush effect. *Changes in intensity of the galactic cosmic radiation (Climax neutron monitor) (%) and in sunspot number (R_Z) for the period of 1960-2002 are depicted here. A high number of sunspots resembles higher solar activity. Data shows that the intensity of the galactic cosmic radiation is inversely proportional to solar activity. GCR, galactic cosmic radiation; R_z, Zürich number. Figure copied from Alania et al.*[6]

2.1.2 Ionising radiation vs. non-ionising radiation

Based on the energy of radiation, one can distinguish ionising and non-ionising radiation. High energy radiation, or ionising radiation, has the ability to ionise atoms/molecules by removing an electron from its orbit. These incident photons leave a positively charged atom behind. Particles associated to ionising radiation can be divided into three different groups according to their source, namely cosmic ray particles, solar flare particles and particles trapped in the Van Allen belts.

Examples are: α-particles (He cores), β-particles (electrons/positrons with high velocity), γ-rays, x-rays and galactic cosmic rays.[7,8] Non-ionising radiation does, on the other hand, not have enough energy to ionise atoms. Examples of this kind of radiation are radio- and microwaves, infrared and visible light and ultraviolet (UV) radiation. Both types are capable of damaging living and non-living systems/materials. However, it is easier to protect against non-ionising radiation, while ionising radiation remains a major challenge to hold back. Protection against non-ionising radiation can be acquired by shielding, whereas ionising radiation can then cause additional damage through the formation of secondary particles within the material it penetrates.[8,9]

2.1.3 Terminology of ionising radiation dose

The amount of energy absorbed by a medium, whether this is the human body, a particular tissue or an organ, is called the radiation dose. The amount of absorbed radiation and impact on biological pathways is quantified by various terms:

> Linear Energy Transfer (LET) of charged particles in a medium is defined by the International Commission on Radiation Units and Measurements (ICRU) as the average amount of energy per unit track length imparted to a medium by ionising radiation of a specified energy when penetrating a short distance.[7,10] It describes the action of radiation into matter. A high LET is known for attenuating radiation more quickly, making shielding more effective and preventing deep penetration at the same time. However, higher concentrations of deposited energy can on their turn cause more severe damage to any structures, for example microscopic ones, near the track of the particles. While the International System (SI) unit for LET is the newton, it is usually expressed in units of keV/µm (thousand electron volts per micrometre).
>
> Relative biological effectiveness (RBE) represents the ratio of doses required by two different radiations to produce the same magnitude of the same biological effect. Both the biological endpoint and LET of the particular radiation influence the RBE. The RBE increases with an increase in LET to about 100keV/µm, at which point the average separation between ionising events is close to the diameter of the DNA double helix, and then decreases with further increase in LET.

The SI unit of absorbed dose of ionising radiation is Gray (Gy). It is defined as the absorption of one joule of radiation energy per kilogram of matter. Two older units are the rad (radiation absorbed dose), a unit of absorbed dose of ionising radiation, and the roentgen (R). One Gy is equal to 100 rads and the effect of one rad and one R on dry air is approximately the same.[7]

Several properties of radiation need to be taken into account when measuring or quantifying radiation. For example, the magnitude of the source of radioactivity, the energy of the radiation and the amount of radiation energy absorbed may differ. These properties determine the nature of the radiation itself, making it clear that equal doses of different kinds of radiation are not equally damaging. Alpha particles exert, for example, more damage, by depositing their energy thousands of times more effectively than beta particles or gamma rays do for a given absorbed dose. The radiation dose is therefore expressed as 'dose equivalent', in order to account for the difference. The unit of dose equivalent is the sievert (Sv). This unit is equal to the absorbed dose multiplied by a radiation weighting factor (previously known as the Quality Factor (Q)). An example is the difference between x-rays and alpha particles. These particles cause 20 times the damage of a similar dose of x-rays, resulting in a Q of 20.[5]

Effective dose is a calculated value, also measured in Sv, that takes three factors in account, namely (I) the absorbed dose to all organs of the body, (II) the relative harm level of the radiation, and (III) the sensitivities of each organ to radiation, as not all organs are equally radioresistant. Examples of radiosensitive organs are the gonads, bone marrow regions and blood forming organs.

2.2 Amount of ionising radiation exposure in space

The amount of ionising radiation that is received by humans and the effects it can have on health can be established by taking three main factors into account, namely:

- Altitude above the Earth: Upon leaving the surface of the Earth, the Earth's magnetic field becomes weaker when higher altitudes are reached. This implies less protection against ionising particles and that spacecrafts will pass through the trapped radiation belts more often. When travelling beyond the magnetic field, for example for deep space missions, the protection disappears completely.

- Solar cycle: As mentioned before, the eleven-year cycle of the Sun is characterised by periods with numerous sunspots, which results in a dramatic increase in the number and intensity of solar flares. While the cycle can narrowly be predicted, single events remain a challenge to foretell.
- Susceptibility of the individual: While this remains an area of active investigation, researchers have observed that not every person is as susceptible to the damaging effects of space radiation.[5] The radiosensitivity of an individual has shown to change with age and health status, and to be related to gender. Genetic factors, however, are thought to take most credit for the observed variation in radiation sensitivity.[11]

The effects of space radiation are negligible on the surface of the Earth thanks to the protection from the atmosphere and magnetic field. From the average dose of 3.6 mSv of background radiation received per year, cosmic radiation contributes for an average of 0.39 mSv to the total. However, the background radiation coming from cosmic rays increases with altitude (0.3 mSv per year for sea-level areas up to 1.0 mSv per year for higher-altitude cities). This is a small dose. International standards, as proposed by the International Commission on Radiological Protection (ICRP), limit the effective dose of ionising radiation at 1 mSv per year averaged over five years for public exposure and 20 mSv annually, or in special circumstances up to 50 mSv in a single year, for radiation workers.[12]

However, once the complete protection of the two Earthly features is left behind and a LEO is reached, radiation doses up to approximately 20 mSv are received per month, depending on the orbital parameters.[13] Another source of radiation also comes into play at these altitudes, namely the Van Allen belts. These belts exist of two regions, the inner (1000 - 12000 km) and the outer (13000 – 40000 km) belt, in which charged particles are trapped due to the magnetic field of the Earth (Figure 2a). On top of that, the offset and tilt of the magnetic axis make it possible for part of the radiation belts to penetrate deeper. The inner proton radiation belt can, for example, reach down to lower than 400 km above the Earth's surface. This phenomenon is called the South Atlantic Anomaly (SAA) (Figure 2b) and accounts for up to 90% of the total radiation exposure in LEO. Not to forget, the secondary radiation that can arise from interactions between cosmic radiation and the spacecraft itself, which was mentioned before, should be taken into account from these altitudes onwards.[14]

The total amount of radiation that astronauts receive will thus depend upon the activity of the Sun, the location of the astronaut compared to planetary magnetic fields, and the protection by the spacecraft. Astronauts aboard the ISS are typically exposed to 200 – 400 mSv on an annual basis. On the other hand, the average dose-equivalent rate on one of the Space Shuttle missions was 3.9 μSv per hour. The highest rate was measured when the Shuttle passed through the SAA at 96 μSv per hour.[5]

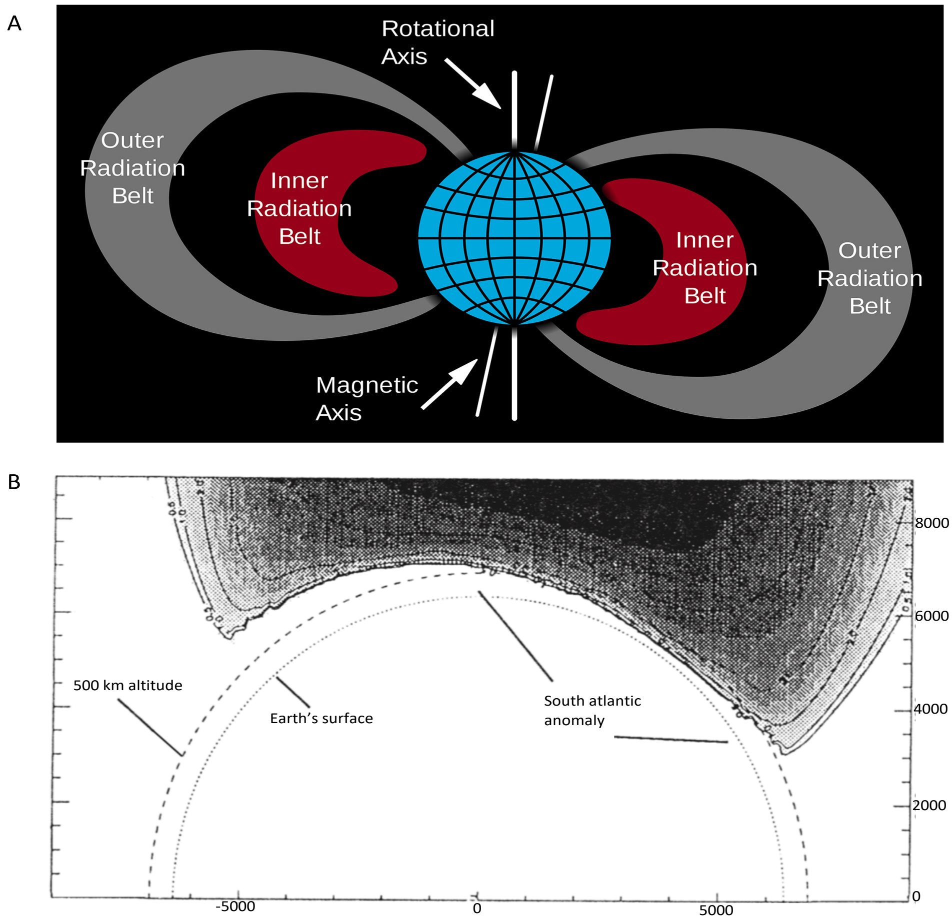

__Figure 2. Van Allen radiation belts. A.__ 2D schematic display of the radiation belts, showing the two-zone structure with an inner (red) and outer (grey) radiation belt. Offset and tilt of the magnetic axis allows a deeper penetration into the Earth's atmosphere. Figure copied from Li and Hudson, 2019.[15] ***B.*** *The area where the Earth's inner radiation belt comes closest to the Earth's surface is called the South Atlantic Anomaly. It dips down to an altitude of 200 kilometres. Figure adapted from the International Astronautical Federation (IAF).*

Travelling even further away from Earth, two celestial bodies of major interest, namely the Moon and Mars, are encountered. Both lack the presence of a global magnetic field. However, scientists of the National Aeronautics and Space Administration (NASA) have discovered, during the Lunar Prospector mission, that some areas of the Moon actually harbour a weak magnetic field. These locations could be the best candidate sites for future Lunar bases. While Mars has similar magnetic fields, these will not significantly change the exposure level and magnitude of radiation that reach the surface of both the Moon and Mars. Both celestial bodies are therefore not shielded from SPEs, and the GCR can freely bombard the surfaces.[5,16] Both the Moon and Mars do, on top of that, not have dense atmospheres. While the Moon genuinely lacks an atmosphere, Mars has an extremely thin one composed primarily of carbon dioxide.[17] Although the atmosphere of Mars may have been thicker in a distant past, the current radiation levels at the surface are approximately one hundred times higher than on Earth.[3,5]

The seven successful Lunar landings are shown in Table 1 in order to give an idea of what amount of radiation astronauts were exposed to during the renowned Apollo missions. The received doses were small because no major SPEs occurred during these missions and the duration of the Lunar surface missions were relatively short. A calculation for the amount of radiation exposure for a six-month journey to Mars can easily be made with available data. An astronaut would be exposed to approximately 300 mSv for a one-way-trip or 600 mSv for the round-trip. Of course, the planets need to be aligned to make the journey back to Earth possible. This would take about 18 months, during which the crew would be stuck on the surface of the red planet. The crew would be exposed to an additional 400 mSv, resulting in a total of roughly 1,000 mSv. While uncertainties still exist with respect to health risks, this dose represents more than 75% of the total NASA astronaut career limit, which ranges from 800-1200 mSV.[18]

Table 1. Radiation exposure of astronauts during different Apollo missions.

Mission	Total Duration	Average Radiation Dose
Apollo 11	08 days, 03 hrs, 13 mins	1.8 mGy
Apollo 12	10 days, 04 hrs, 31 mins	5.8 mGy
Apollo 14	09 days, 00 hrs, 01 mins	11.4 mGy
Apollo 15	10 days, 01 hr, 11 mins	3 mGy
Apollo 16	11 days, 01 hr, 51 mins	5.1 mGy
Apollo 17	12 days, 13 hrs, 51, mins	5.5 mGy

Table adapted from Johnston et al., 1975.[19]

2.3 Radiation damage in living organisms

2.3.1 Attacking biological molecules

The ability of ionising radiation to penetrate and interact with habitats, spacecrafts, equipment, spacesuits, and even astronauts themselves, allows the interaction of space radiation with living organisms. These interactions, which happen along charged particle tracks with biological molecules such as deoxyribonucleic acid (DNA), which is the blueprint of life stored in the cells of every organism, and ribonucleic acid (RNA), can unsurprisingly lead to harmful consequences to the health of crewmembers in the form of cancer and non-cancer effects. The effects can be divided in direct interactions and indirect interactions with DNA/RNA. The damage caused by direct radiation interactions is directly proportional to the radiation dose, as the energy is absorbed by the DNA/RNA. Damage as a result of indirect radiation interactions is, on the other hand, related to the production of reactive oxygen species (ROS).[5,20] A clear overview of the radiobiological chain of events within biological cells is depicted in Figure 3. The complexity and clustering of radiation-induced DNA lesions are the most important features to take into account.[21]

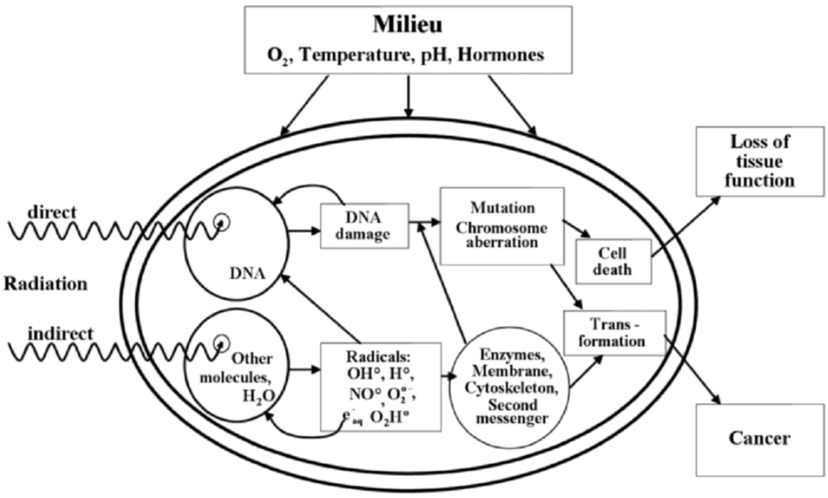

Figure 3. Direct and indirect interaction pathways of ionising radiation in a biological cell. *Radiation damage to biological key substances, such as proteins, RNA, and DNA, can follow two possible ways in a cell. Energy can directly be absorbed (direct radiation effect), or radicals (indirect radiation effect) can be formed, for example through radiolysis of cellular water molecules. Figure copied from Clément and Slenzka, 2006.*[3]

As mentioned before, the speed of HZE particles in GCR makes them essentially electron-free and they tend to decelerate on a linear track due to Coulombic interactions with matter. HZE ions thus have a very high LET compared to X- and gamma rays, beta-particles and high energy neutrons. A high LET, which is thus linked to heavier ions and alpha particles, is also called *densely ionising radiation*. The particles deposit a large amount of their energy along linear tracks and the remaining energy is deposited uniformly by secondary electrons (Figure 4b). Low-LET particles, or *sparsely ionising radiation*, deposit their energy more uniformly (Figure 4a). Examples of DNA lesions are single strand breaks (SSB) and double strand breaks (DSB). The most problematic type are DSBs, which are induced by both low- and high-LET radiation. However, the complexity of damage varies with LET. If the assumption is made that a simple DSB is made of one break on each strand of the DNA and a complex DSB has at least one additional break between the two strands, then roughly 80% of high-LET induced DSBs are complex against only 20% for low-LET.[20]

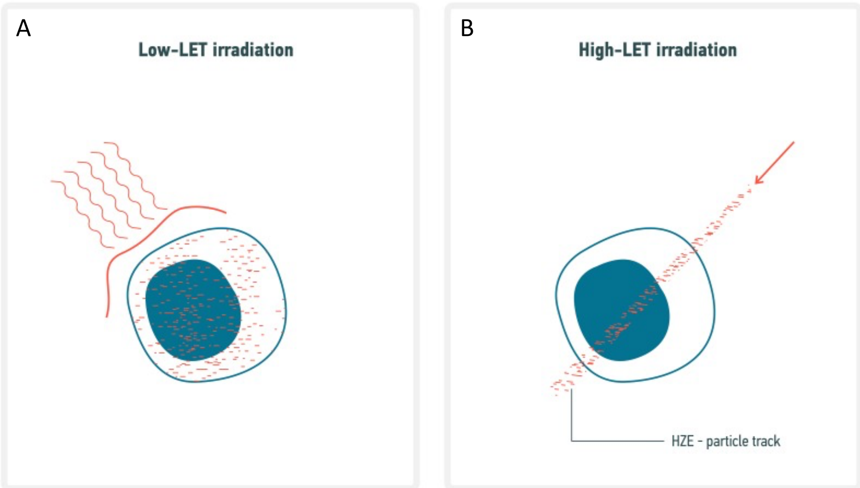

Figure 4. DNA damage induced by low- and high-LET radiation. *A large amount of the energy of high charge Z and high Energy particles is deposited along linear tracks. Remaining energy is deposited uniformly by secondary electrons. This is also called densely ionising radiation. Low-LET energy is deposited uniformly and is referred to as sparsely ionising radiation. LET, Linear Energy Transfer; HZE, high charge Z and high Energy particle. Figure copied from Cortese et al., 2018.*[20]

2.3.2 Repair and consequences

Evolution has ensured a certain level of protection within all organisms against endogenous and exogenous mutagens, of which ionising radiation exposure is an example. Multiple mechanisms for DNA repair and protection have developed. Examples of defence mechanisms are (I) the production of antioxidants that neutralise ROS[22], (II) DNA repair in the form of (a) base excision repair (BER), which corrects small base lesions as a result of deamination, oxidation or methylation[23], (b) mismatch repair for single-strand modifications, which is a highly conserved biological pathway that plays a key role in maintaining genomic stability through high specificity recombination[24], (c) non-homologous end-joining, which promotes the joining of DNA ends by recruiting a loading protein among others[25], and (d) homologous recombination for double strand breaks, which is a high-fidelity metabolic process that repairs complex DNA damages[26], (III) elimination of damaged cells through apoptosis if DNA repair failed, and (IV) proliferative arrest and replicative senescence.[20]

These defence systems constantly monitor our DNA to make sure it stays intact. However, these mechanisms are not failproof. If ionising radiation is able to change the number or order of nucleotides within a DNA molecule, the information stored within the DNA becomes altered and can cause significant problems in the structure and function of cells. Every error in a DNA molecule can be passed on to the resulting daughter cells and even when the translation into RNA occurs. The ribosomes, where translation happens, read the DNA and assemble the RNA accordingly, even if a nucleotide is missing. Protein synthesis carries on and amino acids are assembled into a protein structure which is different than the original structure. The consequences of a malformed protein could be extreme. Once the genetic information has been changed, the expression of the genetic information may also be changed. Radiation is an example of a stimulus that has the ability to influence genes, such as cancer genes, in their functionality (to turn on and off).

2.3.3 Health risks

A distinction can be made for the actual risks to the health of astronauts. First of all, there is the Acute Radiation Syndrome (ARS). The ARS is deterministic and is recognised by a sequence of symptoms that take place shortly after the reception of a high radiation dose, namely well above one Sv, in a short amount of time. The symptoms depend on the radiation dose, radiation type and individual radiation sensitivity. Examples of the consequences, with respect to the aforementioned parameters, are as follows:

- Nausea, vomiting and malaise,
- Depression of bone-marrow function, better known as the hematopoietic syndrome,
- Fluid losses, haemorrhage and diarrhoea as symptoms of the gastrointestinal syndrome,
- Loss of intestinal mucosa,
- Life-threatening sepsis that causes injury to tissues and organs, and
- Deterioration of consciousness resulting in coma and death, better known as the neurovascular syndrome.

Besides the ARS, delayed effects can occur from the accumulation of radiation doses that are not high enough to cause acute effects. An example is the chronic radiation syndrome (CRS). This syndrome results from long-term exposures to doses of around two to four Sv per year. Once again, the effects depend on the accumulated dose that was received and include:

- Cancer,
- Cataract,
- Non-malignant skin damage,
- Death of non-regenerative cells or tissues,
- Decreased fertility or infertility,
- Genetic damage, and
- Suppression of immune reactions.

Symptoms that may be encountered are sleep and appetite disturbances, easily fatigued, loss of concentration and impaired memory, mood changes, headaches, and bone pain. NASA has furthermore defined the four significant health risks in their Human Research Roadmap, part of the Human Research Program, which include carcinogenesis, acute and late central nervous system risks, chronic and degenerative tissue risks and acute radiation risks.

In order to better map the biological changes during spaceflight, experiments with model organisms are usually sent to the ISS where they will grow in space as part of a flight experiment. At the same time, an identical experiment is conducted on Earth under normal conditions and will serve as a ground control. Careful analysis and comparison of both experiments allow to better understand the changes of biological systems during spaceflight. These model organisms are used because both their behaviour and physiology, as well as their entire genomes are known. However, flight experiments require careful designing, a lot of time of the researchers, and, of course, a lot of funding. Many studies are therefore conducted in ground-based research centres, which allow a variety of parameters to be tested. As a result, researchers can decide which would be the best to focus on for a spaceflight experiment.

Intermezzo: space analogues on Earth

Additional data on human health in space conditions is acquired from space analogues on Earth for human studies. Examples are the well-known Bed Rest Studies, the MARS 500 mission, and stations in the Arctic region. Bed Rest Studies are meant to develop new countermeasures that prevent as much as possible the deleterious effects of simulated and real microgravity. The current countermeasures have proven to be insufficient at times. There are three centres where Bed Rest Studies can be done, namely the German Institute of Aerospace Medicine (Cologne), the French MEDES Centre (Toulouse) and the *Zentrum für Muskel- und Knochenforschung* institute (Berlin). The setting for these studies, used by the European Space Agency (ESA), is as follows: the head of the so-called *pillownauts* is tilted down (-6°) in order to simulate a number of space flight changes, such as body fluid shifts, muscle alteration and bone resorption. By doing this, the short-, mid- and long-term effects of bed rest can be investigated, and tests can be conducted. Examples are:

- Exercise regimes: from total immobilisation to frequent, heavy exercise, implementing the broad spectrum of exercise forms,
- Mechanical impact and strain: from total immobilisation to frequent, significant impact, implementing different frequency regimes and forms of impact,
- Pharmacological manipulation: implementation of pharmacological compounds with different targets and in different activity scenario's,
- Nutritional manipulation: manipulation of food components with known impact of certain mechanisms: salt levels (fluid balance and distribution), calcium intake, proteins, and total overall calorie intake.

The MARS 500 mission was a psychosocial isolation experiment conducted between 2007 and 2011 by Russia, ESA and China, in preparation for an unspecified future manned spaceflight to Mars. During these years, three different crews of volunteers lived and worked in a mock-up spacecraft. The final stage of the experiment was intended to simulate a 520-day manned mission. This experiment helped to plan such an interplanetary mission. The aim was to yield valuable psychological and medical data on the effects of the planned long-term space mission. Planning of diagnostics, forecast and treatment of medical support, the use of telemedicine technologies, and monitoring of each participant were all part of the scientific objectives. The crew undertook cardiac, immersion and hypoxic experiments and studies of the gastrointestinal tract. These data, together with the psychological burdens, allowed to predict a number of effects of a long-term space mission on the human body.

The stations in the Antarctic region give the highest fidelity of 'real life' analogues for future Lunar and Martian habitats. The inland Antarctic environment can be compared to space due to its naturally hostile environment, its monotonous landscape and the absence of vegetation. The habitat is comparable, since people live in a confined environment for the entire mission (same food, air, water, germs…). On top of that, there is only a limited resupply of food. The mission is comparable when it comes to workload, mission duration, emergency protocols, telemedicine (limited medical support), and isolation for multiple months. Last but not least, the social situation is almost the same. The crew is international and have complementary competences, there is only restricted communication with the outside, everyone needs to be involved in housekeeping and a high level of solidarity is needed.

These space analogues, while being indispensable in the research towards assuring health in space, are not able to test all the aspects related to radiation risks, protection and prevention. It is in fact not possible to simulate the whole complex mix of radiation types that make up the space radiation environment here on Earth and it is, on top of that, not allowed to irradiate healthy people in the name of science. A lot of uncertainty therefore exists when it comes to the risks that space radiation entails. The need for specific experiments is pressing, as humankind is on the verge of travelling further into the ever-growing void than ever before.

2.4 Ways to mitigate the risks of space radiation

2.4.1 Monitoring and countermeasures

Mitigation of and protection against space radiation are crucial in ensuring a better astronaut safety, as radiation has the ability of penetrating spacecrafts, spacesuits and helmets. The first step in tackling the radiation problem is the constant monitoring of received doses in the different compartments of spacecrafts like, for example, the ISS. This allows furthermore the direct detection of potential breaches in the shielding. The assessment of the radiation load on astronauts has been of major interest since the beginning of spaceflight missions.[27,28] Both passive integrating devices and active real time radiation monitors have been put in use over the past decades. The development of instruments and the discussion and comparison of space radiation-related data have known a great increase during the ISS era. The systems aboard this spacecraft can be divided into two categories, namely (I) the operational radiation monitoring devices, which consist of area monitors, and personal dosimeters, and (II) the science-driven experiments.

The operational radiation monitoring allows (I) assessment of doses and to keep records of previous and ongoing missions, (II) determination of organ and tissue doses which can be used for normalising radiation transport calculations, and (III) to estimate in (near) real-time the dose rates for purposes of immediate dose management and/or practicing the as-low-as-reasonably-achievable (ALARA)-principle.[29]

A second step is the employment of actual countermeasures that can be taken in order to mitigate radiation exposure. The measures that are taken nowadays can be divided in three categories[4]:

- Operational countermeasures are put into place to simply limit astronaut exposure. Shortening overall mission duration (3-6 months on ISS), reducing the time spent on extra-vehicular activities (EVA) and planning missions during periods of reduced solar activity are the most common examples. However, future long-term missions will both take longer and expose astronauts to even more damaging types of radiation, increasing the need for better shielding and mitigation strategies.
- Structures that can serve as shields to protect astronauts from radiation are part of the engineering countermeasures. Different types and levels of radiation ask for different materials and thicknesses in order to be stopped. Highly penetrating ionising radiation can, for example, pass through aluminium, while it is stopped by thicker materials such as cement. The main problem associated with space radiation shielding are the interactions that lead to secondary particles, as mentioned earlier. On top of that, shielding does not provide complete protection against space radiation and existing shielding usually makes spacecrafts heavy and therefore expensive to launch. New technologies, such as the development of electrostatic, plasma and magnetic shielding, are thus being investigated for their protective properties. Besides spacecraft shielding, the spacesuits, worn both in- and outside of spacecrafts, offer additional shielding of the crew and radiation sensitive organs in particular.
- Two groups of drugs, that have the potential to reduce effects of ionising radiation, make up the dietary countermeasures and are (I) nutrients that prevent radiation damage from happening and (II) supplements that are able to facilitate recovery from radiation damage.

Other ways to reduce health risks as a result of space radiation have already been proposed for future deep space travels (Figure 5). A first approach includes the medical selection of radioresistant individuals. Evidence of *in vitro* adaptive response studies has shown a promising range of adaptive responses to radiation exposure among different individuals.[30] These responses may be driven by various rates of DNA damage accumulation and repair. However, the results of such studies are currently not (yet) taken into consideration for the selection process of candidates for spaceflights, as regulations don't impose them as obligatory requirements. An alternative intervention is the administration of geroprotectors. These pharmacological agents protect the consumer by decreasing the rate of aging and thus extending the lifespan. This counteracts the ionising radiation effects that cause accelerated aging at the cellular level as well as in the body. A more ambitious approach is the idea of hypostasis, hypothermia and biobanking, otherwise known as *hibernation*. The interest in this idea found its origin with insects and lower animals that are able to freeze themselves during winter season and spontaneously thaw in spring and with mammals, such as bears, that hibernate during winter. This so-called hypostatic state requires a decrease in metabolic rate and a slowdown of all vital bodily processes, with the ability to recover subsequently. Experimental work on laboratory animals has in fact shown that such state leads to increased resistance to the influence of extreme factors. However, years of extensive research are necessary before such interventions can be applied in humans. Enhancing radioresistance in humans with the aid of gene therapy is another promising strategy. Three main gene enhancements are being thoroughly researched nowadays, and include (I) the overexpression of antioxidants that protect against ROS produced by water radiolysis as a result of ionising radiation exposure, (II) the overexpression of DNA repair genes that can offer enhanced protection against mutagens or increase genome stability and (III) the expression of radioprotective transgenes by delivering and expressing them in humans. A last proposed approach employs therapeutic modalities in regenerative medicine that facilitate the elimination and substitution of endogenous cells damaged by cosmic radiation. Two strategies have been presented. The first one consists of random elimination and substitution of biological systems, independent of the level of damage acquired by irradiation. The aim is to eliminate and replace cells, tissues and organs that may have sustained enough damage to put them at risk for carcinogenesis. Targeted and radiation-responsive elimination and substitution of cells, on the other hand, consists of engineering cells and organs to undergo apoptosis in a targeted fashion in response to contracted irradiation damage. The level of apoptosis is in accordance with either the self-detected levels of irradiation they are exposed to or the self-detected amount of irradiation damage that they acquire.[20]

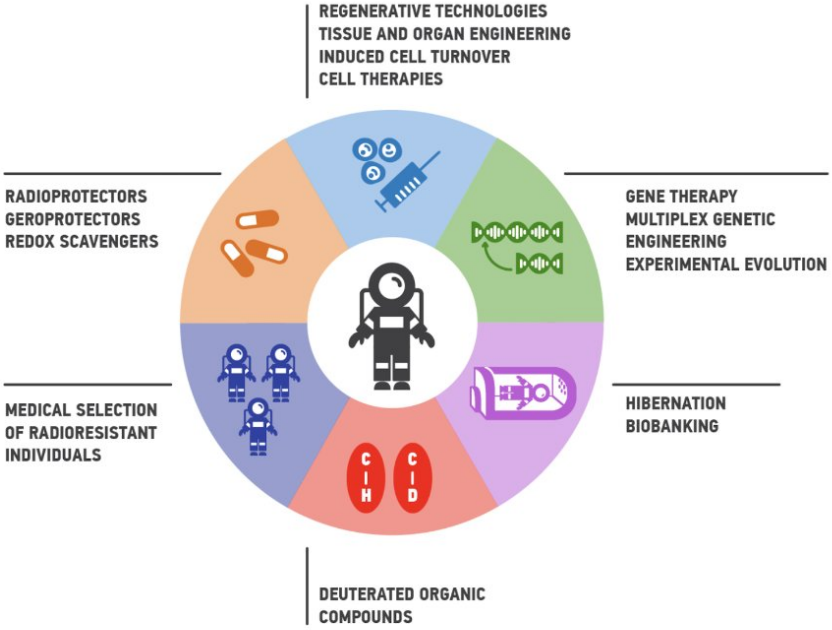

Figure 5. Proposed ways to reduce health risks from space radiation during future deep space travels. *Figure copied from Cortese et al., 2018.*[20]

2.4.2 Spacecraft and habitat shielding in detail

Long duration space missions, both in LEO and deep space, are planned in the near future. Human-on-board missions, as well as remote controlled missions, require proper radiation shielding to protect crew and electronics. Understanding space radiation environments is therefore a first step in order to provide proper shielding. A second step is realising that each environment brings its own difficulties and requires different shielding measures.

LEO

As mentioned before, spacecrafts in LEO are protected by the Earth's magnetic field and atmosphere, but still have to endure damage from penetrating GCR particles and the Van Allen belts. Spacecrafts, such as the Space Shuttles and the ISS, are thus located in a place where the quantity and energy of radiation is lower. Active and passive radiation detectors are meant to map radiation doses in all modules. In order to maintain astronaut exposures according to the ALARA-principle, mitigations, such as hydrogen-rich polyethylene shielding, are used aboard the ISS to protect the most frequently occupied locations, which include the sleeping quarters and kitchen areas.[31]

It has been proven that the amount of required shielding is dependent on age, gender, and other factors. An estimate has been made with a 95% confidence interval for the number of days a human can be inside a spacecraft with walls of 20g/cm^2 aluminium, which is considered as the average applied shielding. The estimate established that it takes around 120 days before the astronaut will reach the radiation limit allowed by NASA.[32] Besides actual spacecraft shielding, different kinds of garments and prototypes are being tested within the space station. An example is a water-filled garment that has a good shielding potential and comfort level. The water on board the ISS can be used to fill the garment and be recycled afterwards.[33] Another example is the AstroRad personal protective vest. This garment is characterised by its selective protection of radiation sensitive organs by variable shielding thicknesses to complement the body's own shielding. Vests like these are tested within LEO before being implemented for deep space missions.

Moon and Mars

The harsh radiation environment of the Moon and Mars will require very thick shields in order to prevent primary cosmic rays from penetrating into habitation modules. The metal of spacecrafts and insulating layers, for example made out of Lunar water or rock, will therefore be necessary in order to achieve a proper amount of shielding. Mission proposals for travels to the Moon are a popular item nowadays. The radiation exposure on its surface is about 300-400 times that of Earth and gives a great view of the Earth's early history, as the Moon has no magnetosphere nor an atmosphere. Missions to and on the Moon will serve as a springboard and testing ground before the deep space missions to Mars will become a reality. A first step is the setup of a 'Moon village' where humans and robots are able to work together on mining operations, astronomy and other projects. While the general architecture has been decided, uncertainty remains on how the base will protect future spacefarers and which suits will be the most convenient for such an environment.

Mars is the next step. This planet, which is the most similar to Earth, was once much warmer and full of water. It is believed that this planet will help us understand whether life existed elsewhere in the universe beyond our Blue Planet. While radiation levels rise to 1000 times that of Earth, it has one percent atmosphere and thus may potentially harbour a habitable environment. However, a lot of research on radiation protection, as well as other fields such as the possibility of hibernation, new propulsion techniques, etc… is highly necessary before a trip to Mars can be undertaken.

2.4.3 Spacesuits: miniature spaceships shaped like a human body

As mentioned in the previous section, research is being conducted on a wide variety of garments and vests that are being worn inside the ISS. With the help of dosimeters under, between and on top these vests, researchers are able to detect what amount of ionising radiation is stopped. These garments hold a lot of possibilities for long space travels in the future. The other, probably best known, suits that are used in space are the ones dedicated to EVAs. Two different EVA spacesuits are used by the crew members aboard the ISS. One is the American Extravehicular Mobility Unit (EMU) (introduced in 1981) and the other is the Russian Orlan spacesuit (in use since 1977). The two suits are very similar when it comes to functionality. They are designed to allow an astronaut to perform operations in the vacuum of space but are not made for use on the surface of a celestial body. The biggest difference is how they are put on. While the EMU is a modular suit, with the torso, legs, arms and helmet being separate pieces, the Orlan exists of a single component which is entered from the rear. These suits are considered to be small, self-contained spacecrafts that have the ability to support life for as long as seven to eight hours. In order to do so, these suits not only block parts of the radiation, but also maintain the breathing atmosphere at correct pressure and gas composition to prevent hypoxia and decompression sickness from occurring. Life-support systems are needed to back up the metabolic workload and gas cooling systems improve the heat-removal of the suit.[34] Both suits therefore have an aluminium hard upper torso that protects against radiation and micrometeoroid impacts, a urethane-coated nylon pressure bladder that holds in pressure, ortho-fabric such as Kevlar, a restraint layer that can be sized and sewn according to the individual astronaut's fit, aluminised mylar skin that insulates and protects against extreme temperatures and a polycarbonate helmet. Wearers of both suits are required to wear a liquid-cooling and ventilation undergarment (Figure 6).[35] However, scheduling EVAs during benign environmental conditions, together with monitoring and responding to a change in conditions in real-time, remain the most effective dose-reduction strategies.

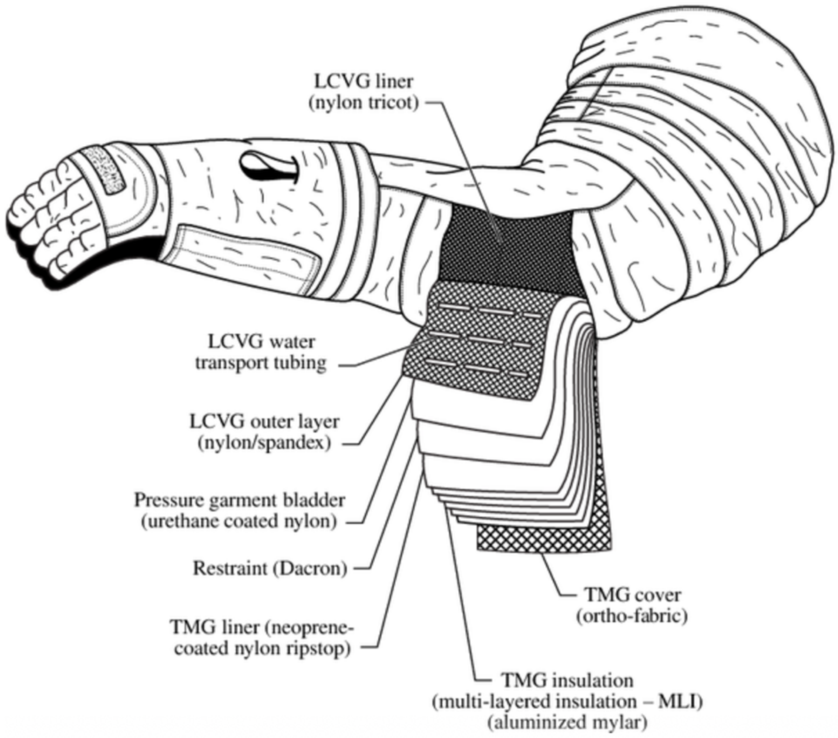

Figure 6. Fabric material layup used for the arms and legs of the Extravehicular Mobility Unit. *The inner liquid-cooling and ventilation garment covers the torso and limbs. It supports small water-transport tubes for regulating the body temperature. The suit further consists of a urethane-coated nylon pressure bladder that holds in pressure, ortho-fabric such as Kevlar, a restraint layer that can be sized and sewn according to the individual astronaut's fit, and aluminised mylar skin that insulates and protects against extreme temperatures. LCVG, liquid cooling and ventilation garment; TMG, thermal micrometeoroid garment. Figure copied from Cucinotta et al.*[35]

Before the implementation of the popular EMU suits, a wide variety of spacesuits had been used on previous missions. The first flights into space, as part of the Mercury program, required suits that were only worn inside the spacecraft. The suits were unpressurised, and their mere purpose was to serve as a backup for possible spacecraft cabin pressure loss. The first spacewalks were part of the second space program, namely Project Gemini. These suits did not contain their own life support systems. The astronaut was connected to the spacecraft by a tether and breathed oxygen through it. Spacesuits for the Apollo program needed to support spacewalks on the surface of the Moon. Since the astronauts needed to walk away from their Lunar lander, boots were fabricated that could withstand the rocky ground, and a life support system was installed. The well-known orange spacesuits were the ones worn during launch and landing of the space shuttle. Since these could only be worn inside, astronauts wore heavy white spacesuits when going on spacewalks. These white EVA suits have been advancing over the years to eventually result in the current EMU suits used on the ISS.

A better view of what the future may hold was created at the end of 2019 when NASA introduced its new spacesuit that will be worn on the Artemis missions. These Exploration EMUs (xEMU) are meant to support the astronaut on EVAs outside the ISS and the Lunar Gateway, and also in much more complex tasks that need to be undertaken on the surface of the Moon. The Phase I design will be tested on the ISS in mid-2023. The upper torso is made of machined aluminium and has a rear-entry hatch like the Russian Orlan suit. The helmet is redesigned with better downward visibility and a microphone and speaker system are built in. Infographics displaying life support parameters, procedures and reference material will, on top of that, be able to be projected for missions far from Earth. Two major changes have been made to the primary life support system (PLSS). The new design will have a constantly renewable absorber that consists of a pair of chemical beds containing amine. One of these beds absorbs CO_2 and the other one desorbs to vacuum. The beds swap functions periodically so that one will continue to remove CO_2 for the duration of the EVA. The PLSS of the xEMU also avoids the need for a separate water supply. The water from the cooling garment is directly evaporated into space through a permeable membrane, which is called a spacesuit water membrane evaporator (SWME; pronounced as 'swimmy'). The SWME has already had many hours of testing and while the tiny pores of the old PLSS were sensitive to water impurities, the SWME is not. If the required manufacturing quality can be achieved, the SWME will serve as a reliable cooler that works in vacuum and under the conditions of Mars.[36] Although safety remains the number one concern, the Artemis spacefarers will be nimbler than ever as a lower-torso assembly will be foreseen within the Phase II surface suits. Lunar legs and an environmental protection garment, to protect the wearer from micrometeoroids, dust and thermal extremities, are also part of the Phase II design. Further research into bio-inspired coatings or self-cleaning gecko hairs, is being conducted in order to be able to automatically repel dust from the suits.

While we are still far away from going for a stroll between the craters on the surface of the Moon ourselves, it is clear that we are closer than ever. The new Moonwalkers should and will be able to walk, skip, bend over and kneel, but as Amy Ross, the xEMU pressure garment subsystem lead at Johnson Space Centre said: "Putting a shell on a human and asking him to move like a human is a big challenge. We're probably never going to be able to do backward handsprings."

3 Objectives

The aim of this project is twofold and exists of a biologic- and dosimetry-related part. (I) Cells will be irradiated with x-rays over corresponding exposure times and within a defined energy range, with the intent of verifying the quantity of biological damage in the form of DSBs in the DNA. The cells will be protected by increasing thicknesses of different materials in order to check for their radiation protective properties. (II) Dosimetry will be conducted to supervise the amount of radiation that is attenuated by the layers of each material. Comparing both studies will give a great idea of the penetration strength of radiation and the effects it has on a molecular level. This paper can be considered as a proof of concept to establish the practical potential of these experiments and the ability of different materials in obstructing ionising radiation. It allows to proof the difference in radiation protection provided by a variety of materials. Other aspects, such as availability, cost and shaping possibilities are, on top of that, taken into account with the choice of materials. Spacesuits do, however, not only have to withstand the threats of space radiation. Support of the user's movement and protection against dust abrasion and thermal changes are merely some examples of other dangers in the phenomenally hostile environment of space. Looking into all these aspects allows a proper analysis which will uncover the most appropriate material/technology choices for future spacesuits and spacecraft/habitat protection.

4 Materials and methods

4.1 Characterisation and culturing of cells

Human primary fibroblasts from a 38-year-old white female donor were grown in Dulbecco's Modified Eagle Medium (DMEM) and cultured at 37°C and 5% CO_2 (Thermo Fisher Scientific). Passaging was done by using 0.05% Trypsin-ethylenediaminetetraacetic acid (EDTA) and cells were split at 80-90% confluence. Cultured fibroblasts were seeded at a concentration of 10000 cells per well on 8-well chamber Labteks. A total of 36 Labteks were prepared one day before the irradiation experiment and were incubated overnight at 37°C for adherence.

4.2 Irradiation

Irradiation was based on the ISO 4037 standard. The X-ray beam code of H-250 corresponds to an effective energy of 211 keV. The actual source was an Xstrahl 320 kV tube I=12 mA. Both cells and dosimeters were irradiated at >95% confluence. Measurements were performed in an environment with a pressure of 1010 hPa, a temperature of 21°C and a relative humidity of 30%.

4.2.1 Cells

Cells were irradiated at a dose rate of 1 Gy for 112 seconds with six different amounts of protection by different materials. The source was located at a distance of 50 cm and cells were irradiated with 1 Gy dose area product (DAP) between 13331 and 13672 μGym^2. The protective materials that were used as shielding were neoprene, high-density polyethylene (HDPE), Polycarbonate (PC), polytetrafluoroethylene (PTFE), lead and aluminium (Table 2). Each layer of protective material had a thickness of 10 mm. One Labtek was not covered by a layer of protection, the second was protected by one layer of material, the third had two layers of protective material as cover, and so forth, until the five layers of protection were reached. The six blocks were put together under the beam each time, so that a total of six irradiation rounds needed to be run per protective material. Maximal γH2AX response was pinpointed at 30 minutes after x-ray exposure.

Table 2. Materials used as shielding.

Material	HDPE	PTFE	PC	Neoprene	Lead	Aluminium
Vendor	Sigma-Aldrich	Sigma-Aldrich	Sigma-Aldrich	www.rubbermagazijn.be	In-house	In-house
Size	10 x 150 x 150 mm	10 x 150 x 150 mm	10 x 150 x 150 mm	5 x 150 x 150 mm	1 x 15 x 15 cm	1 x 15 x 15 cm
Density	0.9928 g/cm^3	2.3627 g/cm^3	1.20 g/cm^3	0.17 g/cm^3	11.34 g/cm^3	2.7 g/cm^3
Properties	Strong intermolecular forces Ultimate tensile strength Withstand higher temperatures Resistant to many solvents	Chemical inert Slippery (organisms and dust cannot get grip) Good flexibility at temperatures above -79.15 °C	Durable High impact-resistance Highly transparent Can undergo large deformations without cracking or breaking	Aging and moisture resistant Weatherproof Flexible Resilient Insulating Extensive chemical resistance	Malleability Ductility High resistance to corrosion	Can serve as a good reflector of visible light Malleability Ductility Excellent thermal and electrical conductor

HDPE, High-density polyethylene; PTFE, polytetrafluoroethylene; PC, polycarbonate

4.2.2 Dosimetry

Measurement of the effective dose was done with the use of InLight dosimeters. Dosimeters were irradiated with a dose rate of 0.3 Gy for 34 seconds. The X-ray source was located at 50 cm distance and the dosimeters were irradiated with 0.3 Gy DAP between 3971 and 4177 µGym^2. Dosimeters were also protected by the same number of layers of the aforementioned materials. Each of the used dosimeters consists of four active elements with carbon-doped aluminium oxide that are placed behind different filters in the enclosure. These filters are used to establish the energy of the incident radiation, so that the dosimeter will react in a tissue-equivalent manner to multiple radiation types, such as beta, x- and gamma rays. Technical specifications are given in Table 3. For every layer of protection, one dosimeter was placed behind the shielding and compared to a dosimeter exposed to the naked beam.

Table 3. Technical specifications of the InLight dosimeter.

Size	7.5 cm high, 1 cm thick, 18 g
Minimally detectable dose	50 µSv
Measuring range	50 µSv up to 10 Sv
X-rays and gamma energy range	12 keV up to 6 MeV
Beta energy range	700 keV up to 2.3 MeV

4.3 DNA double strand break characterisation

After returning the cells to the incubator post-irradiation, they were stained for phosphorylated histone H2AX (γH2AX) to identify DSBs.[37] Cells were fixed by adding 2% paraformaldehyde (PFA), permeabilised through incubation with 0.25% Triton X-100 in Phosphate-Buffered Saline (PBS) and blocked by incubating in 1% normal goat serum (Thermo Fisher) in Tris-NaCl (Perkin Elmer), in order to be probed with primary anti-γH2AX (1/300; Merck-Millipore #05-636). Working in dark conditions was essential from this point on. After thoroughly washing the cells, they were incubated with secondary Alexa Fluor 488 goat anti-mouse (1/300; Life technologies) antibodies (1 h, 37°C). Cells were mounted by adding a drop of Prolong Diamond containing 4',6-dieamidino-2-phenylindole (DAPI) to each well and leaving them to harden overnight at 4°C.[38] The slides were visualised by using an Eclipse Ti microscope (NIKON) equipped with a 20 x Plan Fluor objective. Four fields (z-stack of 12 planes axially separated by 0.9 µm) were captured per replicate. Analysis of the images was done with the Cellblocks toolbox[39] on the open-source platform FIJI.[40] Each nucleus was able to be analysed by using Gaussian filtering and identification of region of interest based on the DAPI signal. The analysis of each pixel size and intensity emitted from the Alexa 488 fluorochromes along with their overlap within the nucleus allowed the automatic determination of the foci number per nucleus with the use of a predefined threshold algorithm in combination with multiscale Laplacian filtering. Outliers were removed after spot analysis. To note: a problem with the antifade mountant caused some pictures to have an increased level of background, allowing too many spots to be counted. Statistical data is shown as means ± standard error of the mean (SEM).

4.4 Analytical calculation of x-ray dose fractions after shielding

The shielding abilities were analytically computed by use of calculations of x-ray mass attenuation coefficients of the National Institute of Standards and Technology (NIST) database (https://www.nist.gov/pml/x-ray-mass-attenuation-coefficients). The attenuation (µ/ρ) coefficients are dependent on the elemental composition of the material and the energy spectrum of the used x-rays (0.2 MeV). The coefficients of neoprene and polycarbonate were calculated by the weight fraction of each element, as these were not available in the table of compounds in the NIST database. A summary of used coefficients is given in Table 4. The actual equation is as follows:

$$F_{(after\ shielding)} = e^{\left(-\left(\frac{\mu}{\rho}\right) x\ \rho\ \mathrm{x}\ \mathrm{d}\right)}$$

With $F_{(after\ shielding)}$: fraction of dose after shielding

μ/ρ: attenuation coefficient from NIST database (cm^2/g)

ρ: density of material (g/cm^3)

d: thickness of shielding material (cm)

Table 4. Attenuation coefficients of the different shielding materials.

Material	Attenuation coefficients (cm^2/g)
HDPE	0,1402
PTFE	0,1189
PC*	0,1297
Neoprene*	0,13121
Lead	0,985
Aluminium	0,1223

**calculated by the sum of the elemental attenuation coefficients by their weight factors.*

HDPE, High-density polyethylene; PTFE, polytetrafluoroethylene; PC, polycarbonate.

5 Experimental results and discussion

5.1 Dosimetry results

5.1.1 Experimental dosimetry

Whereas the protective properties of lead and aluminium against x-ray radiation have been extensively proven, the ones for the included polymer-based materials are still being researched. The graph in Figure 7 (based on Addendum I) depicts the experimental percentage of the original dose that penetrated increased layers of protective materials. The equations in Table 5 show the percentage of decay as a function of the layers of material. The exponential equations were fitted through the different measurements and most observed variations, except for lead and neoprene, can be explained by the model's input, since $R^2 > 0.92$.

Table 5. Experimental functions with associated coefficients of determination.

Material	Exponential function	R^2
Neoprene	$y = 100e^{-0.022x}$	0.7582
HDPE	$y = 100e^{-0.115x}$	0.928
PC	$y = 100e^{-0.114x}$	0.9592
PTFE	$y = 100e^{-0.209x}$	0.9549
Aluminium	$y = 100e^{-0.263x}$	0.9759
Lead	$y = 100e^{-1.63x}$	-0.08

The coefficient of determination (R^2) values are the proportions of the variance in the dependent variable that is predictable from the independent variable. HDPE, High-density polyethylene; PTFE, polytetrafluoroethylene; PC, polycarbonate.

Experimental data of the shielding capability of lead shows that after one layer, or 1 cm of the material, 0.26% of the original dose is able to penetrate. Results like these were expected because of the high density and atomic number of lead. However, lead is not effective against all types of radiation. It is mainly able to attenuate electromagnetic radiation, such as gamma and x-rays, but the occurrence of bremsstrahlung when high energy electrons collide with the material is potentially more dangerous to biological tissue than the original radiation. On top of that, lead is not particularly able to effectively absorb neutron radiation. Lead is used as radiation protection in applications ranging from x-ray imaging and Positron Emission Tomography (PET) rooms to nuclear reactors.

The use of lead during space missions is mainly hindered by the weight of the material, which makes it impossible to get high amounts up to the ISS or Moon. One layer of aluminium is penetrated by 76.43% of the original dose. The addition of four layers allowed, on the other hand, only 27.24% of the radiation to go through. Material shielding with aluminium is the primary method for radiation protection of spacecraft and equipment structures due to its high strength to mass ratio. Significant attenuation of x-rays is possible with a couple of centimetres of the material, as shown, and beta particles can even be absorbed by a few millimetres. Nevertheless, high energy protons and cosmic ray ions in space raise a concern for human spaceflight. Materials with high hydrogen contents, such as the ones included in this project, are thought to be able to reduce primary and secondary radiation to a greater extent than metals.[9] The values of the penetrated doses through PTFE are 87.61% for 1 cm and 36.06% for 5 cm of the original dose. The experimental exponential decay of the x-ray dose through PTFE, while showing higher values, followed a relatively similar path as that from aluminium. These radiation protective properties, together with potentially reduced formation of secondaries after particle irradiation, and with the fact that other characteristics of PTFE improve in vacuum, such as tensile strength, elongation and impact values, show that this material may bear a great potential for the use in future space missions.

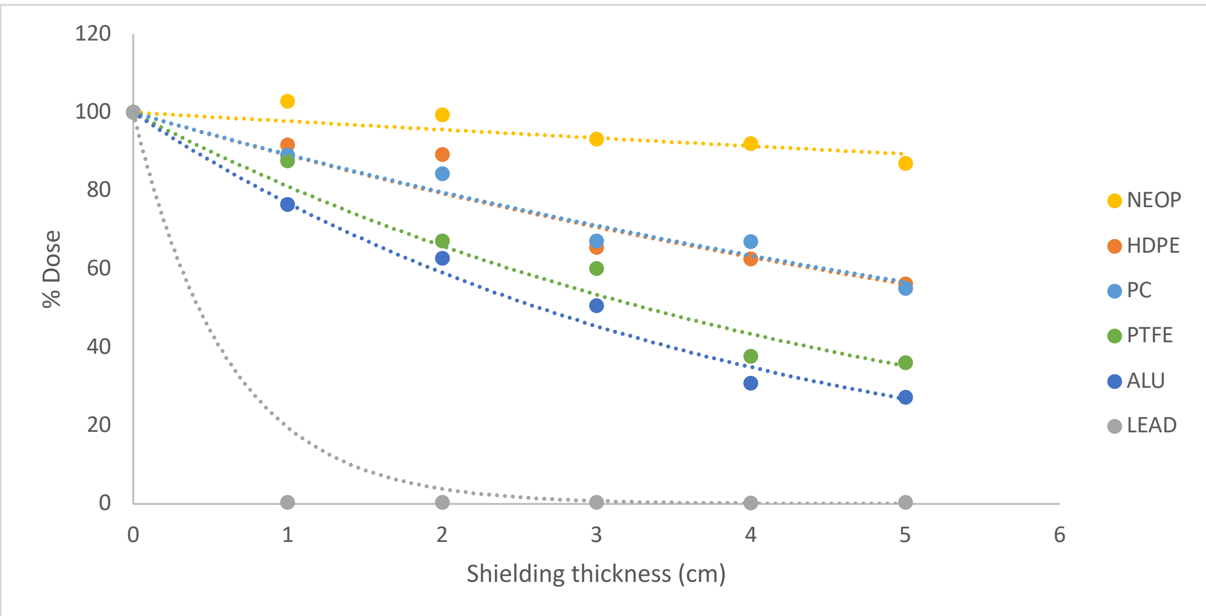

Figure 7. Radiation attenuation by increasing shielding thickness. *Lead showed an immense decrease in penetrated radiation dose after 1 cm of shielding. Neoprene showed the least amount of attenuation, while HDPE and polycarbonate followed a similar decay in dose. The known attenuation effect of aluminium was observed, and the shielding ability of PTFE was almost able to keep up with it. NEOP, neoprene; HDPE, high-density polyethylene; PC, polycarbonate; PTFE, polytetrafluoroethylene; ALU, aluminium.*

The decay of the dose through HDPE, with 91.74% after one and 56.22% after five, ran parallel with that of PC, for which after one layer 89.09% and after five layers 54.96% of the original dose came through. Whereas 5 cm of these two materials was not able to attenuate more than 50% of the original dose, it might be a smart idea to test for other radiation types that make up the so-called space radiation. Both materials have a high hydrogen count that, once again, could lead to a better protection against particle radiation with reduced formation secondary particles. More than the original dose, namely 2.77% more, was able to go through 1 cm of neoprene. This rise could be explained by the scattering of x-rays, which could be considered to be noise, or by the formation of secondaries after the rays interact with the neoprene. With more layers added, the dose percentage that penetrated the material was 99.40% for 2 cm down to 86.92% for 5 cm. The density of neoprene was significantly lower than the other materials used in this study, and results show that the protective characteristics of neoprene are the lowest as well.

Further research on the actual radiation protection characteristics of these, and similar, materials is recommended. Examples of similar materials that are worth testing, include the multiple variations of polyethylene, such as ultra-high molecular weight polyethylene (UHMWPE) and low-density polyethylene (LDPE). Better knowledge on the formation of secondary particles and protection against other types of radiation is necessary to protect astronauts from venturing in the harsh environment of space.

5.1.2 Experimental dosimetry vs. theoretical computation

A comparison of the experimental results with the analytical calculation of the shielding (Figure 8, Addendum II), based on the attenuation coefficient of each compound, showed some differences. Whereas the distribution of penetrated dose was comparable to the experimental results, each calculation, except for neoprene, showed lower values of penetrated dose after 5 cm of shielding. Differences vary, but maxima of 10% dissimilarity between the theoretical and experimental results were observed.

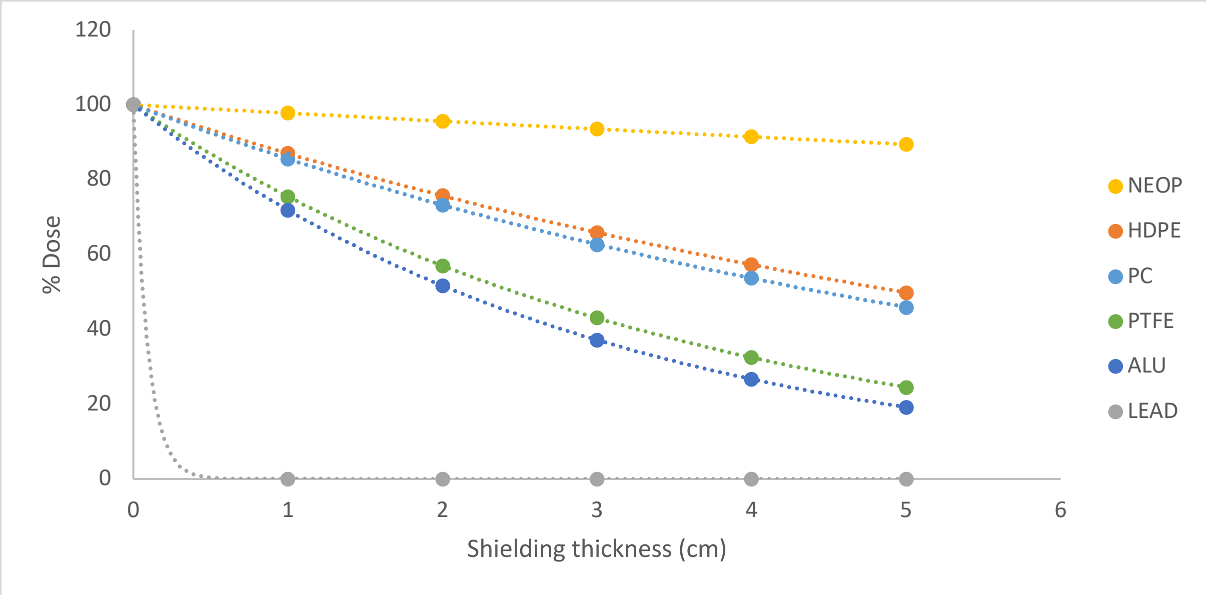

Figure 8. Theoretical attenuation of radiation for each shielding material. *Calculations were made with the use of the densities and known attenuation coefficients of the included materials. Similar trends were seen for HDPE and polycarbonate, and PTFE and aluminium. Calculations for the lowest density material, neoprene, showed the highest amounts of penetrating doses. Only a minimal fraction of the original dose was able to penetrate even one layer of lead. NEOP, neoprene; HDPE, high-density polyethylene; PC, polycarbonate; PTFE, polytetrafluoroethylene; ALU, aluminium.*

Moreover, a comparison of the attenuation coefficients from the theoretical calculation and experimental observation was made (Table 6) and showed that most experimental observed values were lower than their theoretical counterparts. However, the attenuation coefficient of neoprene during the experiment was equal to 0.131, which was exactly the same as its theoretical value. Lead, on the other hand, showed an experimental value of 0.144 for its attenuation coefficient, whereas the theoretical value is 0.985. The best possible explanation here is that the calculated exponential fit of the experiments focused only on part of the measurements, also leading to a low R^2-value. As shown in Figure 7, this fit did not cover most of the measured values.

Table 6. Comparison of theoretical and experimental attenuation coefficients.

	Theoretical attenuation coefficient	Experimental attenuation coefficient
Neoprene	0.131	0.131
HDPE	0.140	0.116
PC	0.130	0.095
PTFE	0.119	0.089
Aluminium	0.122	0.097
Lead	0.985	0.144

HDPE, high-density polyethylene; PC, polycarbonate; PTFE, polytetrafluoroethylene.

A discrepancy between experimental and theoretical values is rarely non-existent. Equations, such as the one used here, usually assume perfect or near-perfect conditions. Experimental values, on the other hand, depict what is actually measured with the possibility of deviations due to the precision of machinery, human intervention, sample flaws etc… In general, it reflects how the universe actually is. Of course, the main goal is for the theoretical prediction to match experimental results. However, a proof of concept, like this study, is meant to set off further research in a field, such as for example that of dosimetry. The acquisition of more data will allow to get statistically significant results, rather than a few tests. Studies like these are a first step in the right direction and encourage other researchers to get started. The setup is easily replicable and expendable, which is necessary for a more thorough understanding on the subject.

5.2 Irradiation of human primary fibroblast

5.2.1 Visualising DNA double strand break damage

H2AX is a variant of the H2A histone. When DNA undergoes damage in the form of a DSB, H2AX is phosphorylated as part of the responding signalling cascade that is meant to repair the break. This phosphorylation is called γH2AX and foci will form in DSB areas. Whereas H2AX phosphorylation promotes DSB repair, γH2AX foci should be regarded as a marker for DSB damage. Figure 9 shows the number of γH2AX spots as means $\pm$ SEM for irradiation of the 8-well chamber Labteks per material per layer, after removal of outliers (Addendum III). As shown, control cells showed 5.45 DSBs on average, which was then used as the baseline. This high background damage (Figure 10A) was probably due to damage incurred before irradiation. That is because γH2AX foci originate in a body's own physiological process as well, namely during replication fork slippage. A difference can be made between radiation induced foci and physiological ones after additional staining for tumour suppressor p53-binding protein 1, since this protein is not visible in physiological γH2AX foci. This was, however, not added in this study.

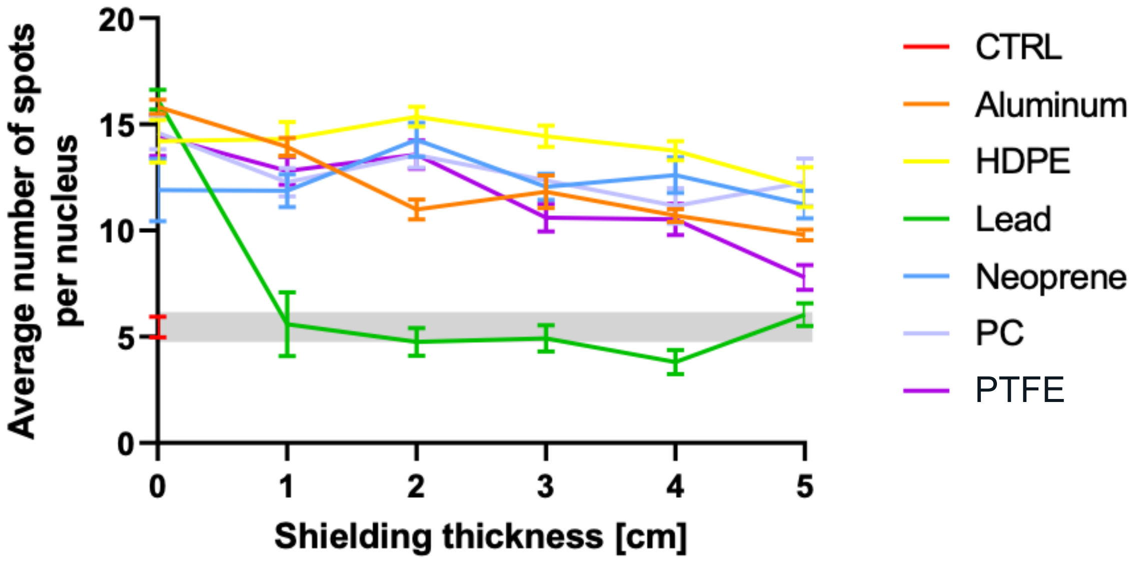

Figure 9. The number of γH2AX foci, resembling double strand breaks, at increasing shielding thicknesses. *A decrease of almost a third of the γH2AX spots was observed after protection with one layer of lead. However, an increase of foci was seen after five layers. PTFE showed a lasting decline of foci for increasing number of protective layers. While aluminium did show a decrease in spots, it almost stagnated after three layers. HDPE showed small drops in foci for every additional layer of shielding, whereas the number of spots after shielding with polycarbonate and neoprene were scattered around the same values. HDPE, high-density polyethylene; PC, polycarbonate; PTFE, polytetrafluoroethylene.*

Without any protection, between 11 and 17 spots were observed per nucleus. Data shows that for lead, even after one layer of protection (Figure 10C), almost a third less γH2AX foci observations were made compared to when there was no presence of a protective layer (Figure 10B). A rise in DSBs was seen behind 5cm of lead. It is unknown whether this is due to scattering, formation of secondary particles or more background noise, but observations during future research should be done with care in order to track down the occurrence of similar increases. The most interesting results were seen for the protection with PTFE. An increase of foci with two layers of PTFE protection was followed by a solid decrease towards almost half of the original amount with 5 cm of shielding. Decreases in γH2AX spots in the nuclei were furthermore observed after increasing layers of protective materials in the form of aluminium and HDPE. Increasing the layers of neoprene and PC showed fluctuations in the number of DSBs but they did, however, not lower them sufficiently.

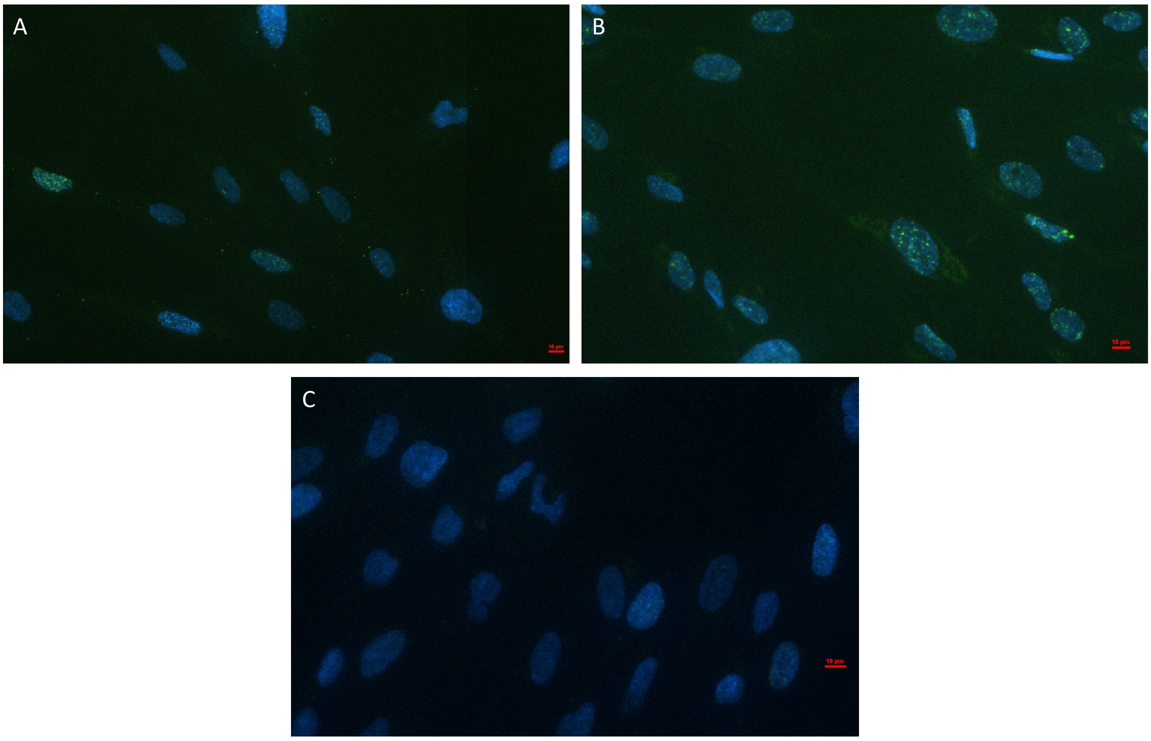

__Figure 10. γH2AX foci as seen under a microscope.__ Human primary fibroblasts were used for this experiment. __A.__ Control cells show a high background that was later used as baseline. __B.__ Increase in γH2AX foci after irradiation of cells. __C.__ 1 cm of lead ensures a decrease in visible spots.

This proof of concept shows that polymers hold great potential in future protection of biological materials against space radiation. Whereas one material seems to protect DNA better than the other, expanding the pool of possibilities is recommended.

5.2.2 Biological results vs. dosimetry

The three materials (lead, PTFE and aluminium) that will be discussed here showed either promising results or differences between dosimetry and the biological assays. Whereas HDPE was able to both decrease the penetrated dose and withhold DSBs from happening, this material, together with Neoprene and PC, did not show any major contingencies between the biological and dosimetry side of the story.

Even though lead, with its high density and atomic number, was able to stop 99.74% of the original dose after one layer of shielding, the nuclei with H2AX phosphorylation still showed an average of around five DSBs. This trend continued after increasing the shielding thickness. This showed that even a small dose that penetrated the shielding had the ability to induce DSBs in the DNA of the cells. A major decrease in dose was seen after increased shielding with PTFE after both theoretical computation and experimental measurements. The number of DSBs in the DNA also decreased relatively strong by adding more layers of the material.

This means that PTFE is able to not only reduce the dose significantly, but also to protect biological material from being damaged. Whereas Aluminium was second-best, both theoretically and experimentally, in decreasing the penetrated dose, more γH2AX foci were observed in the nuclei of the cells. Once again, the problem of secondary radiation may lie at the bottom of this slight increase in DNA damage.

Major discrepancies were seen when comparing the attenuation coefficients of the dosimetry with the ones from the biological assay (Table 7). Obtaining these values for the biological assay was done in the same way as for the experimental dosimetry. However, the baseline acquired from the control cells was subtracted from the original values in order to get a baseline at zero. Whereas Lead showed better attenuation after the irradiation of cells, with 0.472, compared to 0.144 for the dosimetry experiment, other materials even showed lower values than the ones from the dosimetry.

Table 7. Comparison of dosimetry with biological assay.

	Theoretical attenuation coefficient	Experimental attenuation coefficient	Biological assay attenuation coefficient
Neoprene	0.131	0.131	0.055
HDPE	0.140	0.116	0.016
PC	0.130	0.095	0.057
PTFE	0.119	0.089	0.065
Aluminium	0.122	0.097	0.052
Lead	0.985	0.144	0.472

HDPE, high-density polyethylene; PC, polycarbonate; PTFE, polytetrafluoroethylene.

It is important to note that radiosensitivity depends on cell type, cell cycle and radiation type. The sensitivity of cell types and dependence on radiation type have already been mentioned, but it is necessary to consider cell conditions in the cultured cell population in *in vitro* experiments as well. That is because the amount of DNA in a cell nucleus changes depending on the part of the cell cycle. Cells in the Gap 2 phase contain, for example, double the amount of DNA compared to the Gap 1 phase. The higher the amount of DNA that is exposed, the higher the probability that DSBs will appear. This was, however, not taken into account during this proof of concept.

6 Comprehensive discussion

6.1 Material choice and shaping

While the new xEMU designs have shown a monumental evolution in spacesuit technology, questions still remain on the use of materials and possibility to adapt/improve suits on site, far away from Earth. The materials chosen for this research, except for lead and aluminium, were plastic-based. Their radioprotective properties were the main reason for this choice and have been proven in this study for, for example, PTFE. Plastics, however, offer multiple other opportunities which are key for future spacesuit designs. After all, a new dimension to polymer processing was given through the emergence of advanced digital manufacturing technologies. With just one processing step, this technology allows to produce sustainable lightweight constructions and complex multifunctional material systems. A great example is the rise of additive manufacturing, commonly known as three-dimensional (3D) printing. Virtually designed 3D objects can be transformed via digital slicing into real 3D objects by adding layers on top of each other.[41] Extensive research has been conducted on the 3D printing characteristics of plastics such as HDPE[41], PC[42] and PTFE[43] and has without a doubt piqued the interest of the space sector. An Additive Manufacturing Facility (AMF) has even been activated in 2016 on the ISS. It allows to print with over 20 different materials, which makes it incredibly adaptable for future mission design and support. However, it mainly prints with HDPE, PC and acrylonitrile butadiene styrene (ABS), as these are approved materials for ISS operations.[44] The ability to print objects far from the surface of the Earth has ushered humankind in a new era of manufacturing.

This technology could furthermore have an immense impact on spacesuit and habitat research. Take, for example, a 3D printed spacesuit. A first requisite would be the measurements of the wearer, which would mean that each part is printed for one person individually. With hundreds of possible measurements, a 3D printed suit would be able to be assembled in a modular manner that allows easy maintenance of each component without losing the ability to integrate and regulate refrigerant underwear, on-board computers that monitor health parameters in real-time and send alerts in case of malfunctions. The easy shaping of lightweight plastic-based materials is perfect for precise organ protection. Radiosensitive organs, such as the breast region, gonads, bone marrow regions and blood forming organs, need better protection and thus thicker material.

Tools, necessary to carry out any task, can be foreseen as well, in order to guarantee optimal autonomy. This way of manufacturing even allows parts to be easily repaired and, on top of that, be recycled. Tests with recycled HDPE even showed higher values for stress at yield, stress at break and strain at yield compared to pristine material. On top of that, no major differences have been shown between recycled and reference HDPE during tensile testing of printed specimens and printed samples of recycled HDPE did not fracture during tensile testing.[45] 3D printing thus allows to print, test, destroy and reprint material as many times as needed. It is, however, important to keep in mind that by shielding the space radiation, the materials themselves can become radioactive. This depends on the dose and quality of the radiation and is probably neglectable on short-term. Nevertheless, while the potential of recycling the material is indispensable for a remote place like the Lunar surface, infinite recycling needed for long-term missions will remain a challenge that needs to be tackled.

When wondering about the possibilities of 3D printing, it is impossible to leave the vision of a Lunar base out of the picture. The idea of living on the Moon is not novel. It could pave the way for Lunar mining, assessment of health impacts of the environment on living organisms and refuelling stations for spacecrafts in the mindset of interplanetary travel. It will, however, not come cheap. Since it is not feasible to send up a rocket every time you need something, it is necessary to fall back on other technologies, such as 3D printing. One potential input material could be Lunar regolith, of which many properties and mechanics have been characterised.[46] Three other promising processes have been established to manufacture items necessary for a sustainable Lunar base (Figure 11). However, not every structure can be 3D printed and the Moon environment, with its lack of atmosphere, presence of Lunar dust, Moonquakes and extreme temperatures, definitely holds surprises for whoever will embark next on a *voyage dans la lune*[I].

[I] Directed by Georges Méliès, 1902. *Le Voyage dans la Lune* (*A Trip to the Moon*) depicts a group of astronomers who travel to the Moon where they experience a number of unexpected events.

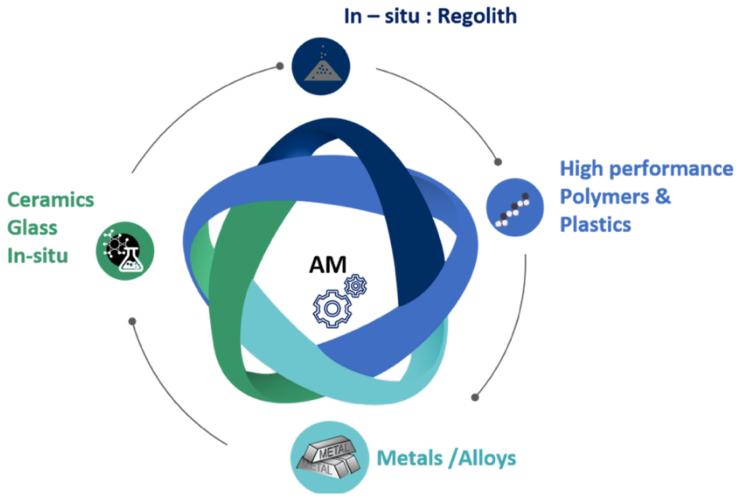

Figure 11. In-situ and on-demand created structures will become the standard for future planetary settlements. *Sustainable long-term presence in space will require astronauts to be independent from Earth's resources as much as possible. The most feasible way of doing this would be 3D printing nowadays. The four aspects resemble the necessities for accomplishing the dream of living on the Moon. AM, Additive Manufacturing. Figure copied from ESA.*[47]

6.2 Possible additions to assure better protection

6.2.1 Environmental tolerance

When considering the possibilities for future spacesuit models, thoughts immediately venture towards the Artemis program, which plans to return astronauts to the Lunar surface by 2024, and the dream of travelling to Mars. Take for example the years of research and work that have gone into the phase II design of the xEMU suits which are built to be worn during EVAs on the Moon, as mentioned before. However, besides providing better movability, visibility and health monitoring, new models should provide better environmental toleration compared to their predecessors. Whereas suits during the Apollo missions have been shown to rapidly degrade by incoming Lunar dust, new models should be able to withstand the damaging effects of dust adhesion. Although the Apollo missions comprised only a small number of EVAs on the Lunar surface, dust was inadvertently transferred into the habitable volume of the Lunar module, and any further exposure of the suits to dust would have significantly increased health risks to the astronauts from, for example, radiation exposure (Figure 12). However, the plans for a Lunar outpost will require longer and rigorous EVAs by astronauts. NASA's 2015 Space Technology Roadmap (STR) identified that future spacesuit systems should be able to maintain full functionality during (I) exposure to dusty environments of the Lunar, and other dusty planetary, surfaces, for a minimum of 100 EVAs or 800 hours of use, and (II) EVA performances without the need for specialised servicing, maintenance, or ground support, for a minimum of 100 EVAs or 800 hours of use.[48]

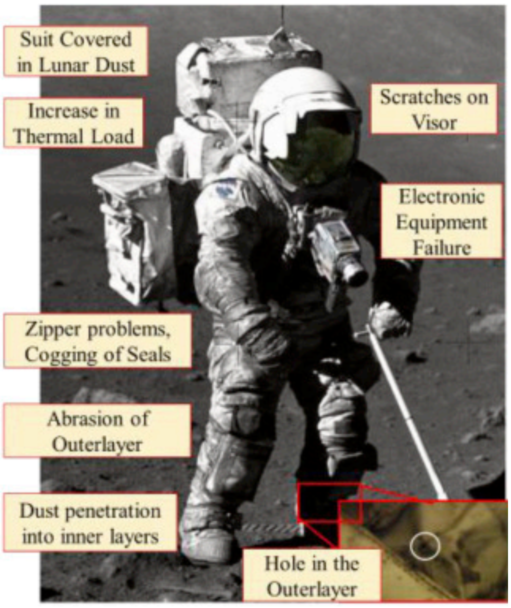

Figure 12. Dust abrasion creating spacesuit wear on the surface of the Moon during the Apollo missions. *Figure adapted from Manyapu et al.*[48]

These endeavours thus require dust mitigation/protection technologies for spacesuits and possibly other EVA systems. Multiple state-of-the-art active (A) [which require power, gases, vibrations or other means to keep vital surfaces clean] and passive (P) [which do not require an external stimulus and involve modification of the chemistry or texture of external surfaces][49] dust mitigation technologies have already been proposed and include, but are not limited to:

- Brushing (A) – a self-cleaning brush that mechanically removes dust from surfaces. Brushes can be operated mechanically using power or be temperature activated through shape memory alloys.[50]
- Electrostatic removal (A) – methods that use direct current (DC) electric fields to remove dust from surfaces.[51,52]
- High-velocity gas jets (A) – able to blow dust particles from surfaces.
- Electrodynamic removal (A) – electrodes, embedded in the surface, with varying high voltage signals. These are applied to lift and transport dust off of the surface.[52]
- Superhydrophobic coatings (P) – materials/fabrics that have a very high contact angle can lower the adhesion of water-based contaminants. This does not allow capillary forces to take hold.[53]
- Lotus leaf coatings (P) – limitation of Van der Waals force of adhesion by microscopic nanostructures
- Electrostatic Discharge (ESD) coatings/film (P) – coatings that are statically dissipative are less likely to accumulate charge and hence dust in dry environments.[52]

While application of these technologies seems promising for future spacesuit manufacturing, the majority of the techniques has only been demonstrated for use on rigid surfaces such as solar panels and glass structures.[54] However, the application of such technologies on spacesuits remains a challenge due to the complexity of the designs, which require a flexible structure of soft areas, irregular contours and Teflon coatings, that counter the integration of the technologies. Research in this field is therefore in full swing, as the dusty surfaces of the Moon and Mars will have to be conquered with these next-generation technologies.

Two promising mitigations have already been proposed and are thoroughly being tested at the time of writing this paper. One of these is an active system that utilises parallel conductive yarns made of carbon nanotube (CNT) flexible fibres embedded into the outer layer of a spacesuit. A travelling wave of electric field is formed around the surface of the suit by energising the CNT yarns with a multi-phase alternating current (AC) voltage signal. This signal is fittingly called the 'cleaning signal'. Charged and uncharged dust particles are repelled through electrostatic and dielectrophoretic forces. Dielectrophoresis (DEP) is the physical mechanism of exerting a force on a dielectric particle when it is subjected to a non-uniform electric field. A benefit of this phenomenon is that this force does not require the particle to be charged. Research has indicated that three-phase single frequency AC voltages yield the optimal compromise between dust cleaning efficacy and implementation on the fabric of the spacesuit. The aim of this system is twofold. It allows to prevent the accumulation of dust particles on the suit and repels the particles that have already adhered to the suit's surface. In practice, the CNT fibres could be integrated into the outer layer of the spacesuit, in order to minimise the risk of absorption of CNT particulates by the skin. As suits undergo repeated motions that flex, bend, or twist, the materials have to meet some requirements, and the CNT fibres tick all the boxes. They possess in fact (I) a high flexibility that allows to conform to the irregular contours of a suit, (II) a great mechanical strength which ensures a high fatigue resistance, (III) a low density in order to minimise the mass, and (IV) abrasion resistance that allows them to withstand degradation by the abrasive dust particles.[48] The second, passive, possibility is the Work Function Matching (WFM) coating. This method, developed by NASA, lowers dust adhesion to surfaces by the application of a coating that has a work function that matches the dust as closely as possible. Although multiple charging mechanisms are at work in the Lunar environment, this method is based on triboelectric-charging as this is thought to be the most important anthropogenic charging mechanism.

During triboelectric-charging, electrons are transferred from a material that easily loses its electrons (low work function) to a material that holds tightly onto its electrons (high work function). This phenomenon is thus minimised when the work function of both materials is similar. A dust resistant coating applied to the thermal control surface could therefore repel any incoming dust.[55] While these are merely two examples of possible mitigations, their future potential seems favourable for the next-generation spacesuit. The performance of the aforementioned methods can even be augmented by adding them together (Figure 13). Both have proven to be compatible with the traditional spacesuit manufacturing process.

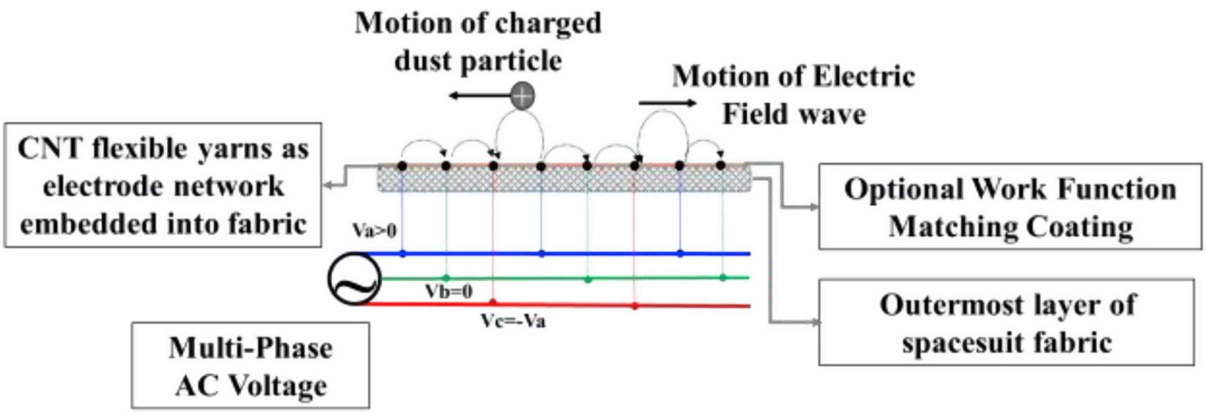

Figure 13. Operating principle of a Work Function Matching coating with carbon nanotube fibres exerting electrical fields. *The passive Work Function Matching coating lowers the dust adhesion through triboelectric-charging and lowering the work function of the outer layer of a spacesuit. The carbon nanotube fibres are embedded in the outer layer. The yarns are energised which forms a travelling wave of electric field. Charged and uncharged dust particles are repelled through electrostatic and dielectrophoretic forces. CNT, carbon nanotube; AC, alternating current. Figure copied from Manyapu et al.* [48]

As this paper deals with the next-generation spacesuit, futuristic technologies are also worth looking into. Such technologies are not planned to be used in the field by tomorrow, but rather in 10 to 20 years. One example includes a futuristic 'second skin' as the outer layer of a suit. Researchers have been able to come up with a self-healing polyurethane urea elastomer (sPUU). The aim of this 'self-healing skin' is to rapidly heal *in situ* damage to a spacesuit, in order to minimise any threats to the human body. During testing, a 1 cm by 2 mm cut was made on the surface of the material. The cut was not visible anymore after one hour and was completely healed in 12 hours (at room temperature).

Although such technologies bear immense potential for future wellbeing of astronauts, it seems incomprehensible at this moment in time, or to quote Arthur C. Clarke's third law[II]: "Any sufficiently advanced technology is indistinguishable from magic".

6.2.2 Composite materials

By recapitulating the structure of radiation in deep space and LEO, it is possible to introduce the problem of secondary neutrons. It was mentioned that deep space radiation is a mix of GCR and SPEs, and that the Van Allen belts are able to trap protons and electrons in LEO. However, neutrons have also been encountered on the ISS and on the surface of celestial bodies. They are produced by nuclear interactions of GCR and trapped protons with elements in the walls and the interior of a spacecraft[56]. Furthermore, as the Moon lacks both atmosphere and magnetic field, the Lunar surface is directly exposed to GCR and solar energetic particles (SEP), allowing them to interact with Lunar material, which in its turn results in secondary radiation in the shape of neutrons and gamma rays[57]. It has been shown that these neutrons contribute significantly to the total radiation dose received by astronauts. Effective additional shielding is thus required. The key players are materials with low atomic numbers, for example paraffin, water and polyethylene, as they have the ability to slow down fast neutrons, and those with high neutron absorption cross sections that can absorb thermal neutrons. However, low cost, mechanical strength, stability and easy handling are factors that have to be taken into consideration in addition to neutron attenuation properties.

One of those key players, namely HDPE, was tested in this proof-of-concept-study. In addition to proving its radiation shielding ability, the ease of shaping the material was also shown. However, could it be possible to improve its radiation shielding properties for use in neutron and gamma fields? Of course! Multiple investigations have already been performed on the construction of protective materials containing nanoparticles. One example is the fabrication of high-density borated polyethylene (HDBPE).[58,59] Boron is incorporated in polyethylene as boron carbide (B_4C). Borated composites are denser, more crystalline, and thermally more stable than neat polyethylene. The low atomic number properties of HDPE together with the high neutron absorption cross section of boron improve the effectiveness in neutron shielding vastly.

[II] Arthur C. Clarke was a British science fiction writer who formulated three phrases, better known as Clarke's three laws.

A composite formulation that contains 10% of boron content has been shown to be optimal. The fast neutron dose rate was reduced by 63.6% and, due to highest achievable balance of hydrogen and boron contents, the highest mass removal cross section was reached.[59] Nevertheless, effective attenuation for fast neutron beams requires thicker shields. Studies on such composites are therefore promising for future Lunar and/or Martian settlements but leave the options for spacesuits to be desired.

6.3 Additional considerations for travelling into deep space

6.3.1 Bone loss in space

Prolonged stays in microgravity have shown to result in calcium, vitamin D, and vitamin K deficiencies, increases in urinary calcium excretion and serum calcium levels, and decreases in intestinal calcium absorption and levels of serum parathyroid hormone and calcitriol. In short, weightlessness during space flight causes an increase in bone resorption together with a decrease in bone formation, hence bone loss. Data on skeletal unloading aboard the ISS has shown a 0.5 – 2% decrease in bone mass per month (6 – 24% per year). The knowledge on the effects of radiation on bone is, on the other hand, relatively limited. Nevertheless, it has been shown that radiation exposure has the ability to damage both osteoblast precursors and local vasculature. Data on the effects of radiation to skeletal tissue mainly originate from medical radiation environments. General treatment regimens for e.g. pelvic tumours include thirty 1.8 Gy doses over six weeks. This results in a total dose of 54 Gy administered to the tumour. The normal skeletal tissue surrounding the tumour, such as femoral neck, sacrum and acetabular rim, can receive up to half of each fraction, which totals in 27 Gy.[60] Even though an increase in long-term survivorship is being recorded, the incidence of long-term side effects, such as fractures at irradiated sites, are becoming a new concern.

Nutrition, exercise and medicine are three key elements that promote bone strength in order to prevent fractures. These elements have been implemented for the crew on the ISS and improvements are being tested. Meals are nutritionally balanced and include foods rich in calcium and vitamin D. Physical exercise increases bone load and trains the muscles. Effective exercise programs are therefore setup for the crew aboard ISS and are required to be executed responsibly. Last but not least, bisphosphonates are taken, as it increases bone mass and decreases the occurrence of bone fracture.

Although these countermeasures are already in play and have proven their efficacy, longer residency in space could still influence bone mass significantly. This could in its turn thwart actions that need to be fulfilled within a spacecraft or on the Lunar/Martian surface. Nevertheless, there is one clever piece of technology that could both supply resistance for an in-space exercise and help astronauts to walk and lift things when needed, namely: the exoskeleton. While "robotics is playing a key role aboard the ISS and will continue to be critical as we move toward human exploration of deep space", as said by Michael Gazarik, previous director of NASA's Space Technology Program, the concept of a powered suit that allows superhuman strength (cf. Iron Man[III]) is not the goal. The exoskeleton technology is, however, meant to someday help astronauts to stay healthier in space by maintaining bone density and muscle strength. A great example is NASA's X1 robotic exoskeleton (Figure 14), which is worn over the legs with a harness that reaches up the back and around the shoulders. The X1 has four motorised joints at the hips and knees, and six passive ones that allow sidestepping, turning, and flexing of the feet. The device is able to measure, record and stream back data. This allows better feedback by doctors on the impact of the crew's exercise regimen. One mode allows the supply of resistance against leg movement as an in-space exercise, while the reverse mode could provide a power boost to astronauts while they work on the surface of celestial bodies. As technology matures, the device could be coupled with a spacesuit in order to ensure additional force for surface exploration, allowing astronauts to walk in a reduced gravity environment. The potential of the X1 will in the near future be improved by the addition of more active joints to other areas such as the ankle.[61]

[III] Created by Stan Lee, Marvel Comics' fictional superhero and alter ego of Anthony Edward "Tony" Stark, possesses a powered armour that gives him superhuman strength among other things.

***Figure 14. The X1 robotic exoskeleton manufactured by the National Aeronautics and Space Administration.** The main goal of the exoskeleton is to someday help astronauts to stay healthier in space by maintaining bone density and muscle strength by allowing the supply of resistance against leg movement as an in-space exercise. On top of that, the suit could provide a power boost to astronauts with activities on planetary surfaces. Figure copied from NASA.*

6.3.2 Difference between the sexes

"An all-female mission tends to be something that NASA has avoided in assignments because it seems like a stunt," said Margeret Weitekamp, curator at the National Air and Space Museum. This turned out to be true, as the first all-female spacewalk outside the ISS, on October 18, 2019, was publicised globally. Even Donald Trump, the president of the United States, congratulated them and stated that "this is the first time for a woman outside of the space station". Well, actually, the first woman that walked in space was the cosmonaut Svetlana Savitskaya in 1984. This all-female spacewalk was just the first time that there were two women outside at the same time. Nevertheless, in the past 58 years of spaceflight, only 11% (63 individuals) of the humans that have been launched into orbit, were women. A total of 129 NASA astronauts have flown to the ISS, of which 26 were women (approximately 20%). Although NASA recruited and flew only all-male crews for decades until 1978 and the early spacesuits were specially designed for male wearers, a female astronaut crew could be an intelligent choice for interplanetary missions.

While the sample size of female astronauts on a long-duration spaceflight is relatively modest, the previous statement is not meant to raise any eyebrows. On the contrary, it is based on four elements:

- Differences in size: Women tend to be smaller than men. Although thoughts immediately go towards the lower body weight, and thus the lower costs associated to fuel for the launch and manoeuvres, this is just a small part of the benefits of a smaller size. Amount of food, oxygen, and other resources, necessary to keep humans alive, are also reduced. Females expend almost less than half the calories of their male counterparts for similar levels of activity and men require 15% to 25% more calories a day. Even less waste (carbon dioxide and other bodily excretions) is produced in smaller people, which requires fewer systems designed to recycle and remove it. While these differences might be negligible for short-duration trips, the contrast for longer space missions would be substantial.
- Interdependencies between physiological and physical areas: While women have only recently started flying to space, preliminary sex-based disparities have already been discovered. Whereas women seem to be more affected by space motion sickness and urinary tract infections, men experience diminished hearing and kidney stones quicker. One significant difference is the fact that men are prone to vision deterioration in space, while women don't experience this as often. It has been reported, however, that women are more susceptible to radiation-induced cancers, such as breast and lung cancer. They are, however, considered to be more radiation resistant overall, due to increased amounts of body fat compared to men. [62,63]
- Psychological traits suited for long-duration missions: Considerations beyond the physical/physiological, for example the psychological consequences in the intense and monotonous environment of space, need to be taken into account as well. Scientists are able to observe teams during Earth analogues, such as polar expeditions, to identify psychological factors that might ensure the success or failure of long-term missions. Observations have shown that men usually do well in short-term missions with one clear goal, while women are more interpersonally sensitive, which is required for habitation-type circumstances.[64]
- Repopulation: While this may seem more science-fiction than anything else discussed in this paper, it is something that definitely comes to mind when talking about spaceflights on an interplanetary level. There would be no reason to send men, as their contributions can be collected and cryopreserved during the travel. This approach is obvious when looking at costs and the increase of genetic diversity of the parental pool.

The currently available data suggest multiple sex-based differences. Whereas these data are merely preliminary at this point in time, they will become important components for the anticipated personalised medicine approach in the future. Of course, the ISS has already delivered us a solid platform with many people flying in and out, but the need for more studies in general and studies where women are involved remains.

Besides the improvements that these data bring to the rise of personalised medicine, it also involves the need for spacesuit modifications. In the past, NASA spacesuits were designed specifically for the individual wearer. However, in 1978, when women were able to join the astronaut ranks, fit became especially challenging. The differences between the bodies of men and women thus became an important factor and the range in size of components increased so that suits could fit women of 1.52 metres up to men of 1.93 metres. However, unexpected challenges, such as limited range of motion of shoulders, posed an issue for both men and women. It took trial and error, but the upcoming xEMU suits are equipped with a host of new features and have more of a custom fit, since it is the goal to put men and women on the Moon. However, is one type of equipment able to protect both men and women equally? Full-body 3D scans of astronauts holding various poses is the first step in providing each person the most comfort and best fit. Next up, 3D printing could allow to shape materials, for example the ones used in this study, as one desires. For example, women are more susceptible to radiation-induced breast cancer, as mentioned before. The logical response in spacesuit research should be the possibility of reinforced shielding of the breast area. Other parts of the body, such as the hips, gonads and kidneys, would benefit from better protection as well. On top of that, the decrease in bodily excretions, such as carbon dioxide, in women allows necessary systems to work at a slower pace which increases their lifespan. Every individual has a different size. Although personalised suits will increase the manufacturing costs, they seem to be the obvious choice for interplanetary spaceflights with extended exposure to radiation among other things. In the end, protection of the crew is, and always will be, the biggest concern.

6.3.3 Solar Energetic Particles

Although the uncertainty around SEP event predictions was touched upon earlier, it is worthwhile to highlight the consequences for longer space missions on the surfaces of celestial bodies. SEPs are created either during a flare close to the Sun (impulsive SEPs) or in interplanetary space by CME shocks (gradual SEPs). The energetic particles exist of protons with an energy range of 10 – 100 MeV up to 20 GeV, electrons of just a few MeV and alpha particles. The frequency of SEP events is proportional to sunspot activity and peaks when sunspot activity is highest. The phase of the solar cycle does, on the other hand, not determine the intensity of an SEP event. Some of the strongest measured solar events have happened when there was a reduced number of sunspots.[65] The particles generated by these events are accelerated and, while most particles travel not much faster than the shock that produced them, the fastest ones travel near the speed of light, which means they take only tens of minutes to arrive. The flux can thus increase with 2 – 6 orders in energetic magnitude for hours or days and the protons with the highest energy even have the capability of penetrating a spacesuit effortlessly. Without the protection of an atmosphere, like on the Moon or Mars, an astronaut, who is working on the surface or in vulnerable parts of a spacecraft, is doomed. The perspectives for advanced warnings on those most energetic particles are, however, not very promising. It is not possible to observe an event, downlink the data, contact the crew on a far-away celestial body and allow them to have enough time to move to a more heavily shielded place. Within the time of the Apollo missions, one large event occurred. The event luckily occurred in August 1972, between the Apollo 16 and Apollo 17 missions, and did therefore not affect any astronauts.[66] Predictions on the slower particles are, on the other hand, auspicious and have become a very active field in the field of space weather sciences. In the past, observatories based their information on real-time observations. However, in order to ensure the protection of astronauts, one needs to be able to predict the actual generation of events. That’s why, nowadays, data on previous SEP events are stored in a database, reviewed and extrapolated in order to possibly predict new ones. As these events have the capability of severely affecting the health of an astronaut, it is not hard to see the value of those predictions for prolonged spaceflights.

6.4 Where are we now?

In 1962, John F. Kennedy charismatically stated that "we choose to go to the Moon"[IV]. One could say that, at this point in time, we are choosing to go back to its dusty, crater-filled surface. However, the Moon is merely an intermediate station with the real endpoint being Mars. Visionaries believe that a stroll on the surface of the Red Planet is within reach and are putting all their efforts into making it possible. However, two questions immediately come to mind: "Was humankind ready to venture to space 58 years ago?" and "Is humankind ready to go back now?".

Astronauts aboard the ISS are continuously monitored nowadays. This has immensely increased our knowledge on life sciences in space and has allowed to improve the wellbeing of individual astronauts. Technology has been a critical player in this. One example is the study that allowed the collection of health data from twins, from whom one spent 340 days aboard the ISS, while his identical twin remained on Earth. The intent of the study was to monitor the twins, Scott and Mark Kelly, before, during and after the mission to find biological differences caused by the space environment compared to a baseline on Earth.[67] This mission can be looked at from different angles. A first approach is from a utilitarian's point of view. In this case, the mission and its results outweigh the uncertainty of what one human would go through by spending a year in space, as they are for the benefit of the wide public. Utilitarianism strives towards the greatest degree of happiness for the largest amount of people. Nobody could have predicted what Scott's body would go through on short- and long-term, but it was known that the data would seriously increase the knowledge on physiological changes in space. On the other hand, the question could be asked whether it is ethically acceptable to send a human on such a mission? The risks were unknown, the effects of the risks were unprecedented, so who are we to decide that someone should embark on a mission with this level of uncertainty? It is of utmost importance that the need to acquire significant results will never overtake the protection of the wellbeing of research subjects, which are in this case the astronauts themselves. This is the part where the *Ethics* of space travel and exploration come into play. Although technological advances have made it possible to send humans further than ever before, to monitor their health in real time, and to gather data that was never deemed possible, the question remains of how far we can go as humans?

[IV] The 'Address at Rice University on the Nation's Space effort' was a speech delivered by United States President John F. Kennedy.

Is there any justification in sending people on a retour flight to Mars, packed with dosimeters, just to see how much radiation they would have to undergo? Is it justifiable for astronauts to undertake EVAs and make them risk their lives in order to repair a piece of machinery? More and more questions arise with the evolution of technology and it has been difficult to come up with unilateral answers.

The Institute of Medicine (IOM) has developed a set of ethical principles[68] that are meant to guide in the decision making on health standards for long duration and exploration missions for which existing health standards cannot fully be met. Although the merits and shortcomings of major single ethical theories have been debated deliberately through history, it is advisable to apply mid-level principles rather than focussing on the theory from which they were derived. An approach like this has already proven to be successful in situations where individuals with diverse commitments make efforts to find common ground on how to approach ethical issues. The main goal of the ethical framework should be deciding if a long-term space mission's value is worth the potential risk to the astronauts performing it. The composed principles should be applied in the development and implementation of health standards regarding long duration and exploration spaceflights:

- Avoid harm by preventing harm, exercising caution, and removing or mitigating harms that occur, by exhausting all feasible measures to minimise the risks encountered by the astronauts.
- Provide benefits from both a scientific and technological point of view to current and future beneficiaries, such as astronauts and members of society.
- Seek a favourable and acceptable balance between risk of harm and potential for benefit by systematically assessing the uncertainties attached to each.
- Respect autonomy by allowing individual astronauts to make voluntary decisions regarding participation in proposed missions, as they have the right to self-determination.
- Ensure fair processes and provide equality of opportunity for mission participation and crew selection. Burdens and benefits need to be distributed fairly.
- Recognise fidelity and the individual sacrifices made for the benefit of society. Honour societal obligations in return, by offering health care and protection for astronauts during missions and over the course of their lifetimes.

There are however many unknowns and the principles are there to guide us through them. For example, while this paper is mainly focused on the radiation environment in space, the effects on the human body and how this radiation could be shielded, this factor rarely acts individually. Spaceflight factors that act over extended periods of time, such as radiation, microgravity and isolation-related ones, have been proven to interact and entail combined influences. Various methods are in play to disentangle the complex interplay of these aspects. The interaction between two or more factors can be (I) additive, in which the effect of agents in combination produces a total effect the same as the sum of the individual effects, (II) synergistic, where a system is sensitised to one agent by another, (III) antagonistic, where one agent reduces the sensitivity to another, and (IV) independent, which means that both agents act on their own.[3] Nevertheless, the determination on how every aspect behaves relative to one another in practice is yet to be discovered.

7 Conclusion

As expected, thicker/more layers of protection ensure better ionising radiation shielding. In particular, PTFE showed great shielding and biological protection against x-ray beams. Lead also showed its immense ability in attenuating the radiation and the results concerning the other materials gave a better insight in the relation of elemental structure and density to their shielding abilities. There are, however, many aspects that influence the radiation protective properties of a material. Examples are the density, molecular weight and the formation of secondary particles after collision with radiation particles. Nevertheless, synthetic polymers are promising compounds in the quest for better radiation protection of future astronauts. The artistic view of a next-generation spacesuit, as shown in Figure 15, might not be as science-fiction as what most people had hoped for/expected.

Whereas the look of the outer layer might resemble that of current suits, it is what it is made of that is important. A suit like this is achievable to be manufactured and, more so, promising for the following reasons:

1. Polymers can be 3D printed. Separate pieces allow easier movement and can be recycled or repaired one at a time. It also allows to shape the suit for each astronaut individually.
2. An incorporated exoskeleton could serve as a support for longer adventures on the surface of celestial bodies and as a training mechanism for regaining muscle mass.
3. An outer layer, for example out of PTFE, could cover the whole suit. Incorporation of a Work Function Matching coating and nanotubes could serve as dust mitigation systems, which could be replaced by a self-healing skin coating in the future.
4. As women are smaller, produce less waste and are physically better suited for space travel, the future spacefarers could well be female.
5. The necessary pressure, multiple layered suits and PLSS systems will remain conserved, but adjusted as technology advances.
6. Real-time monitors and other monitoring/communication improvements could allow astronauts to get rid of unnecessary apparel, like the popular snoopy caps.

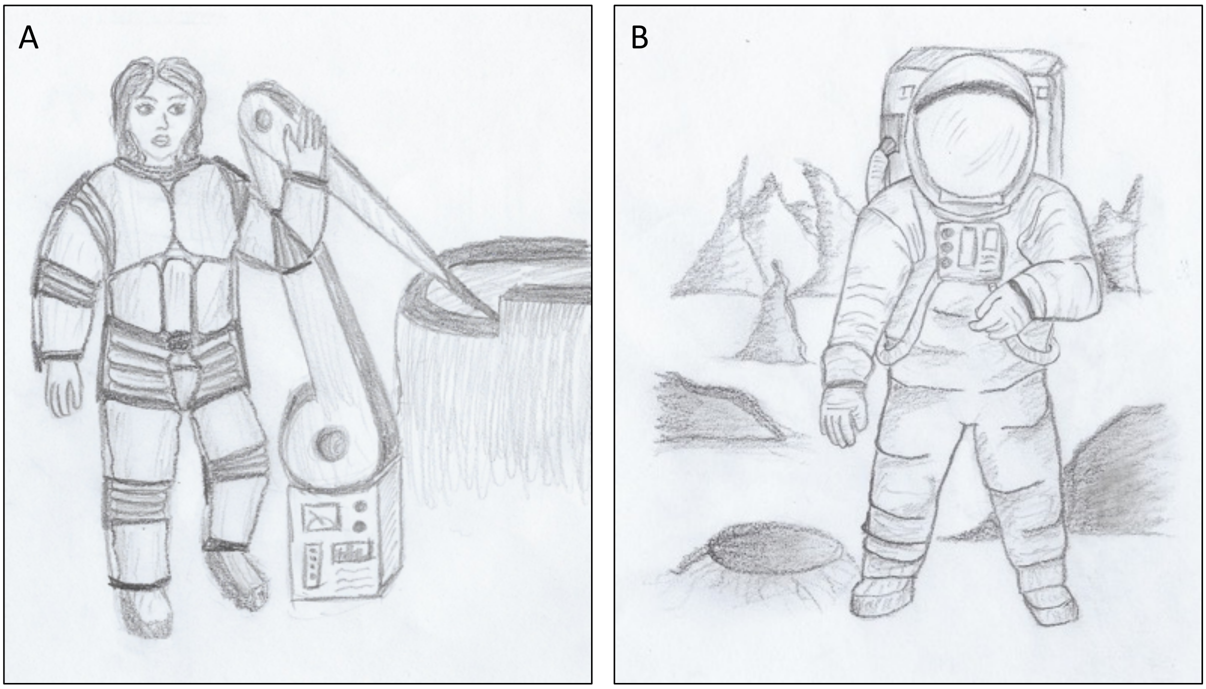

Figure 15. Artistic view of a next-generation spacesuit: before addition of the outer layer (A) and after full assembly (B). A. *A suit that consists of separate 3D printed pieces allows easier movement of the joints and to recycle/remake a piece when necessary. An incorporated exoskeleton (lines beside the arms and legs) will support the astronaut in everyday tasks on the surface of celestial bodies. A woman occupies the suit, as women are considered a better fit for long-term space missions. The addition of the 3D printer shows what an impact this technology will have on both housing and manufacturing on remote places in space.* ***B.*** *An outer layer of a strong resistant will be covering the whole 3D printed suit. Beside better mobility, wider vision is enabled by an advanced helmet design. Dust mitigation systems, in the form of coatings, incorporated nanotubes or both, could improve the lifetime of this layer. As shown, the suits will still be worn in multiple layers, pressure should still be applied inside the suit and a renewed primary life support system will be worn during adventures on the Lunar surface. Technological improvements ensure better monitoring of the astronaut in real time.*

Advances are being made in the field of individual radiation shielding. Nevertheless, further research into different potential materials, compounds and composites is encouraged. It is important to not only look at the shielding ability, but also at the weight, cost, shaping possibilities and availability. We are on the verge of the greatest missions that mankind has ever embarked on. However, one thing is for sure: travelling into deep space will never be as easy as *take your protein pill and put your helmet on*[V].

[V] David Bowie – Space Oddity

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I. Addendum

Experimental results dosimetry:

	Percentage of original dose (%)					
Layer amount (cm)	ALU	HDPE	LEAD	NEOP	PC	PTFE
0	100	100	100	100	100	100
1	76.43178	91.74394	0.254888	102.7671	89.09436	87.60594
2	62.76538	89.27373	0.267475	99.40002	84.31442	67.09847
3	50.59054	65.44957	0.280062	93.10334	67.18344	60.0214
4	30.76907	62.52937	0.201393	92.03659	66.8782	37.65104
5	27.2384	56.21696	0.280062	86.9168	54.95511	36.05878

II. Addendum

Theoretical results dosimetry:

	Percentage of original dose (%)					
Layer amount (cm)	ALU	HDPE	LEAD	NEOP	PC	PTFE
0	100	100	100	100	100	100
1	71.87728	87.00622	0.001409	97.79412	85.58672	75.50849
2	51.66343	75.70083	1.99E-08	95.63691	73.25087	57.01533
3	37.13427	65.86443	2.8E-13	93.52727	62.69302	43.05141
4	26.6911	57.30615	3.94E-18	91.46418	53.65691	32.50748
5	19.18484	49.85992	5.56E-23	89.44659	45.92319	24.5459

III. Addendum

Number of γH2AX foci in the nuclei of cells with shielding of following materials. Empty cells depict removed outliers due to a problem with the antifade mountant. Each row shows a layer of protection starting at zero. The average number of γH2AX foci in the nuclei of the control cells was 5.45 and was used as baseline.

Layer	Aluminium							
0			14.69	16.31	15.99	16.00	16.88	15.05
1	16.33	13.50	14.19	14.42	12.66	12.52	13.81	14.14
2	11.94	8.92	8.92	12.08	11.54	11.37	10.98	12.12
3	13.03	12.16	12.91	12.91	6.51	12.68	12.26	12.21
4	11.38	10.62	11.48	10.32	9.96	10.55	9.41	11.98
5	10.36	9.97	8.36	10.18	10.16	10.06	8.96	10.25

Layer	HDPE							
0		11.87	16.77			14.19	14.00	
1	11.82	10.96	13.35	17.15	14.42	14.33	14.97	17.42
2	15.08	17.21	15.28	15.00	12.77	15.17	15.60	16.75
3	12.67	13.99	15.17	15.56	16.16	12.09	14.89	14.97
4	15.25	13.57	13.56	15.29	15.10	12.23	12.47	12.57
5	13.55	13.73	6.69	13.04	15.27	12.56	10.20	11.31

Layer	Lead							
0	13.64	16.82	17.68	17.19	16.34	16.86	14.84	15.95
1	15.63	6.07	4.80	3.82	3.60	1.67	4.38	4.79
2	4.99	3.69	5.13	5.83	2.73	3.40	8.58	3.76
3	2.13	3.84	4.83	5.78		5.88	7.30	4.69
4	2.76	2.92		2.76	4.29		6.31	3.82
5	3.35	6.19	7.48	4.69	6.43	8.07	6.66	5.47

Layer	Neoprene							
0	9.89	16.29	8.57	8.83	11.51			16.37
1	12.93	7.39	12.64	13.41	11.38	10.22	14.05	13.04
2	14.70	15.93	16.87	12.63	16.11	9.76	14.17	14.04
3	13.34	10.09	10.51	11.70	12.35	15.61	11.18	11.68
4	8.99	14.86	14.46	11.89	15.39	11.00	13.87	10.41
5	10.86		9.62	13.37	9.93	9.69	11.27	13.81

Layer	PC							
0	16.47	16.88	15.78	13.80	16.61	13.36	13.35	10.61
1	10.87	10.24	13.98	9.99	11.47	14.53	14.41	12.69
2	13.81	14.27	16.28	11.72	13.16	14.94	13.38	10.90
3								
4	11.43		9.35			10.57		13.32
5	12.75		9.20	7.09	14.74	14.20	13.31	14.60

Layer	PTFE							
0	10.35	14.57	13.61	11.92	18.84	14.03	14.88	17.56
1	12.46	12.89	14.05	14.82	9.04	14.10	13.62	11.54
2	11.63	16.68	13.37	13.16	10.68	14.33	15.24	13.53
3	9.75	10.94	11.27	11.06	13.81	7.19	10.80	9.98
4	9.45	13.05	10.47	8.90	7.23	11.61	10.20	13.34
5	9.44	5.43		8.58	6.77	9.43	6.64	8.29