Chapter

Regolith and Radiation: The Cosmic Battle

Yulia Akisheva, Yves Gourinat, Nicolas Foray and Aidan Cowley

Abstract

This chapter discusses regolith utilization in habitat construction mainly from the point of view of radiation protection of humans on missions of long duration. It also considers other key properties such as structural robustness, thermal insulation, and micrometeoroid protection that all have to be considered in parallel when proposing regolith-based solutions. The biological hazards of radiation exposure on the Moon are presented and put in the context of lunar exploration-type missions and current astronaut career dose limits. These factors guide the research in radiation protection done with lunar regolith simulants, which are used in research and development activities on Earth due to the reduced accessibility of returned lunar samples. The ways in which regolith can be used in construction influence its protective properties. Areal density, which plays a key role in the radiation shielding capacity of a given material, can be optimized through different regolith processing techniques. At the same time, density will also affect other important properties of the construction, e.g. thermal insulation. A comprehensive picture of regolith utilization in habitat walls is drawn for the reader to understand the main aspects that are considered in habitat design and construction while maintaining the main focus on radiation protection.

Keywords: habitat construction, lunar regolith, regolith simulants, ionizing radiation, space radiobiology, radiation protection

1. Introduction

Living on the lunar surface will undoubtedly be a psycho-physical, technological and economical challenge. The main source of protection and support for astronauts will be their habitat. Its construction and design has to offer a counter measure against every stressor exposed onto the crew. While a habitat may be perceived as something static and frozen in the cold of lunar vacuum, it will in fact, in itself become the place of an active battlefield—the battle between radiation and matter, where the health and well-being of the people inside is at stake.

This chapter discusses the utilization of regolith in habitats. Regolith is a local source available in abundance on the lunar surface, which can be relatively easily accessed and collected. Its utilization enables a more sustainable exploration and future settlement. It also reduces the cost of a mission dramatically. However, regolith is a complex material with unique properties that result from space weathering (temperature extremes under vacuum, radiation exposure, micrometeoroid impacts), and the techniques of its utilization and associated technologies are under development and improvement across the global space community. To complicate things further, there is a limited amount of returned lunar samples. In order to satisfy the needs in experimentation, testing and prototyping with regolith, diverse simulants are used. Simulants are specifically designed to resemble the lunar soil in its chemical, mechanical, and thermal properties. Depending on the application, some simulants are perfect replacements of regolith for research and development activities.

The main case under consideration here is regolith for radiation protection of humans. When radiation interacts with matter, it deposits a part of its energy in the target material, produces fragments of nuclei and other secondary emissions. It is important to know how effective regolith is in terms of radiation absorption or attenuation on the one hand, and what kind of secondary particles it will produce on the other. The fact that the radiation environment on the Moon is a diverse mix of particles with different energies and charges makes it complicated to optimize the utilization of regolith for dose reduction. The notion of doses is used to estimate exposure and associated risks. It is always advised to keep the risks and doses to the absolute minimum that is technologically achievable and ethically acceptable. When seeking to reduce doses in space radiation protection, we consider both the doses from primary particles and secondary emissions. In both cases regolith will act as a passive shield, and its constituent molecules will interact with radiations in their unique ways which depend on the mutual chemistry of the projectile-target pair, charge and energy of the incident particle.

As regolith will be the main construction material, it will largely define the thermo-mechanical properties of the habitat wall. It is important to look at the different protective properties in parallel and not dissociate their studies too much. For example, density is crucial for both radiation protection and thermal insulation. A holistic approach to habitat building is discussed here, while keeping the main focus on radioprotection.

The rest of the chapter will introduce lunar habitats, regolith and radiation as the main actors of the cosmic battle. Then, it will outline the problem statement underlining the particular challenges associated with habitat construction on the Moon, regolith utilization, and radiation protection. To fight the problems, the existing armor will be presented. In-situ resource utilization (ISRU) technologies, regolith simulants, and radioprotection techniques will be outlined and discussed. Any good soldier is always on the lookout for more troubles and better solutions. In the context of the cosmic battle it means to be on the lookout for improving ISRU technologies, bettering regolith simulants, and investigating the use and properties of new materials that can either be brought from Earth or made in-situ. A generic conclusion summarizes the main points regarding regolith utilization in habitat construction, mainly from the point of view of radiation protection of astronauts.

1.1 Habitats for long-term exploration

Continuous human presence and surface exploration of the Moon sets an overarching requirement on the lunar habitat that it must sustain human life for several long-term missions and withstand a harsh environment. In other words, the habitat becomes a fortress under a continuous and variable siege of the cosmic and solar radiation, extreme temperatures, and micrometeoroid bombings.

On top of robustness, the habitat must present a comfortable alternative to living on Earth. Working on the Moon for extended periods of time will be extremely challenging, stressful and may even become alienating and daunting. The least that can be done to counteract the psychological burden and physical exhaustion is that the well-being and comfort of astronauts becomes another top-level requirement in habitat construction.

Since the very first steps on the Moon, humanity has been envisioning a long-term presence or even a permanent settlement there. In the most recent years, the global space community focuses primarily on the cislunar space the access to which will enable frequent missions to the surface, ultimately making preparations for the Moon Village [1]. The global exploration roadmap suggests that such efforts should be made in a sustainable way [2]. This leads to the choice of using local materials in habitat construction, and in fact, maximizing their utilization both in hardware and life support.

The most straightforward way to use regolith is to cover a primary structure with it. The primary structure may be brought from Earth, e.g. inflatable or origami-inspired unfolding structure, a metallic cylinder, or even a repurposed part of a spacecraft. **Figure 1** illustrates an artistic view of what such regolith-covered habitats and storage facilities could look like. The authors interpret the image as a capture of the evolution in maturity of ISRU-technology on the Moon. It could be argued that the very first habitats will resemble the one encircled and marked by letter A (in red) since regolith seems to be either loosely piled on top of the structure or compressed and reinforced with dense tiles, which could be produced either through sintering or 3D-printing. Such an approach is feasible at the early stages of exploration. Increasing in complexity, the habitat/storage unit of type B seems to be entirely produced by additive manufacturing. The dark color could be an indicator of another material present in the mixture, e.g. a binder. The surface seems to be rough, possibly owning to the chosen 3D-printing technique which had not yet been thoroughly explored in lunar conditions. Habitat C seems to use more regolith in the material mixture, and it is also produced by additive manufacturing. The triangular and conical shapes observed on the outer layer (both in types B and C) can present a significant advantage in thermal properties of the wall due to partial shadowing—this could help withstand the harsh temperature of the lunar day, which reaches up to 120°C at the equator where the solar heat flux reaches 1300 W/m^2. Finally, the image depicts how the multilayer technology can be utilized with regolith, as the underlying shelter is being covered with another layer of regolith-rich material, seemingly by 3D-printing.

Another straightforward way to benefit from regolith protection is to seek shelter underground. Lava tubes have long been studied as an alternative to living on the Moon, e.g. [3–5]. They extend meters underground and offer a natural

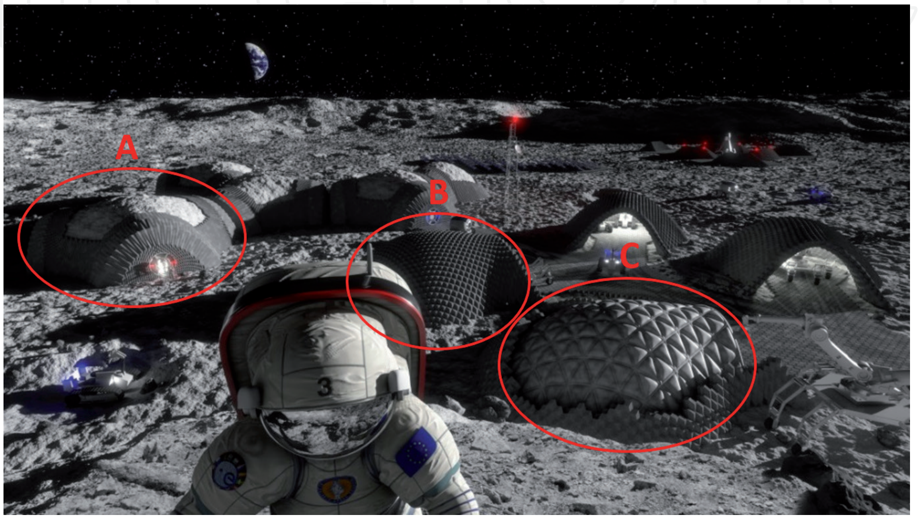

Figure 1.
Solar sintered moonbase, credit: RegoLight Consortium, visualization: LIQUIFER Systems Group.

protection from radiation and micrometeoroids. Most commonly, it is considered that a habitable structure would either be inflated or mounted inside a lava tube. Although it may seem rather convenient and even poetic for the first settlements on the Moon to use the equivalent of caves on Earth, and despite the fact that lava tubes can provide substantial radiation protection (see Section 3.3), this solution has some important limitations which will be outlined in Section 2.1. A surface habitat is considered as the main option for living on the Moon in this chapter.

1.2 Regolith

Committing to a sustainable long-term exploration implies one key material choice—regolith. Abundant on the surface, it will serve as the main force to fight back the cosmic oppressors on the Moon. Regolith, or the lunar soil, will make up the bulk of habitat walls and thus, will act as a shield against incoming radiation particles, heat, and meteoroid projectiles.

Regolith collectively refers to the megaregolith crust consisting of boulders, large particles, grains and powder, or dust. Lunar observations and sample return from the Apollo and Luna missions have resulted in an extensive knowledge of the bulk regolith properties and deciphering some of the history of lunar geology.

Regolith is a complex material. It consists of a mixture of crystalline rock fragments, minerals, breccias, agglutinates, and glasses [6]. Chemical composition of the lunar soil has been thoroughly studied. For radiation protection, it is the most important property as the mutual chemistry of the radiation-matter pair will define the nature of their interactions, and the results in secondary emissions and doses. Two types of regolith are distinguished: mare and highlands, and both are mixes of metallic oxides, dominated by silicon dioxide up to 42–45% in weight [7]. The composition then varies slightly, namely highlands regolith contains more aluminum oxide than the mare type (approximately 25% and 13% respectively [7]). Mare regions contain high levels of titanium dioxide—between 2% and 10% versus the average of 0.5% in highlands soils [7]. It is approximated that the top 30 cm consist of the lunar dust—particles smaller than 100 μm in size with the bulk density of 1.5 g/cm^3 [8]. These loose grains are accessible for collection and utilization in habitat construction. On the Moon, this will make up the majority of ISRU activities.

Currently, the global space sector is investing into its capacity-building related to ISRU technologies [9]. Regolith utilization ranges in ideas from piling-up to sintering, binding with adhesives and 3D-printing. In order to investigate the properties and behavior of raw materials as well as processed products (e.g. regolith bricks), numerical simulations and experiments are carried out. Simulations mainly concern the thermo-mechanical behavior of bulky solids, e.g. how regolith flows and what thermal insulation properties it has. Experiments are usually set up to verify predictions and observe behavior. Humanity currently possesses 382 kg (Apollo program) [10] and 321 g (Luna missions) [8] of lunar regolith from sample return missions, which manifest the greatness of the pioneering efforts in space exploration beyond the Low Earth Orbit (LEO). However, these resources cannot nearly satisfy the global scientific interest and technological demonstration needs in preparation of a lunar outpost. The solution is to simulate the material using its earthly counterparts.

Regolith simulants are like siblings—arguably originating from similar material but having different characteristics. This is due to the fact that simulants are often made to serve different scientific and technical purposes. Literature classifies simulants according to their most prominent properties [11–13]. As such, some are best at simulating mechanical behavior of the lunar soil, and others are almost the exact copies in chemical composition as the returned samples. Continuing the sibling analogy, the differences among regolith simulants may be compared to the different talents that siblings have, which often result from parental investment and resource allocation to activities that nourish those talents.

The first step in working with regolith consists in choosing the appropriate regolith simulant. The main objectives of a habitat are to sustain human life and well-being. Protection from radiation becomes the key player in early habitat planning and regolith simulant considerations as it is one of the main oppressors in the lunar environment. Like under any attack, the forces of resistance must be pulled together. In radioprotective terms, passive shielding is a technique of protection when a material stands in-between a radiation source and the target. The forces of resistance are then the material's nature, or its chemical composition, and areal density. The choice of a passive shield will be based on the most probable radiation-matter interactions, and material optimization will seek to reduce the negative effects of radiation exposure on human health. The interactions between radiation particles and materials produce a diverse variety of results, ranging from energy deposition to nuclear fragmentation and DNA break-down, to mention some. The uniqueness of each interaction originates from the incoming particle's energy, charge and mass. Therefore, the specific radiation environment on the Moon presents a particular challenge to be considered in habitat construction.

1.3 Radiation environment

There are two distinct families of radiation particles: primary and secondary. Primary particles originate from the Sun, our galaxy and distant galaxies [14]. They are high-energy charged particles, mostly protons that move at speeds close to that of light. The diverse mix of ionizing radiation in space, ranging from X-rays to heavy ions with energies up to TeV makes it an extremely challenging environment for radiation protection of humans [14]. When primaries interact with matter, such as the lunar surface, a habitat, or Earth's atmosphere, secondary emissions are produced. The nature and properties of secondary particles depend on the type of interaction that occurred. On the Moon, we can distinguish two branches of secondary emissions: the ones that will occur in the habitat and the lunar neutron albedo.

1.3.1 Galactic cosmic rays (GCR)

Collectively, the particles that make up cosmic radiation are called Galactic Cosmic Rays (GCR). They are baryons (mainly hydrogen protons (83%) and alpha particles, as well as helium (14%) and heavy (1%) nuclei [14]) and electrons that travel in space and are present everywhere. A substantial part of GCR seems to originate from supernova remnants [15, 16] and GCR are believed to be accelerated from outside the Solar System by neutron stars, black holes and supernovae shocks [17]. The mechanism guiding particle acceleration was first proposed by Fermi who explained the energy transfer from magnetized clouds to individual particles [18]. The Fermi I mechanism, also called the diffusive shock acceleration, applied to a strong shock such as from a supernova explosion predicts a power law particle spectrum which has been observed [18].

The magnitude of the GCR spectrum as observed on Earth, and in the rest of the Solar System is correlated with the solar cycle. When the Sun is most active, the enhanced solar magnetic field causes GCR particles to lose some of their energy, and the lower energy particles are affected the most. As such, the fluence of particles of a few GeV/u drops by up to 20% [14]. GCR models account for this relationship with help of the solar modulation parameter [19, 20]. Such models reconstruct the flux of particles mainly from observations, and the most widely used model is the Badhwar-O'Neill (BON) [21]—BON2014 model. Recently, an improved version has been released, BON2020 which reduces model errors largely owning to revised methods of using the solar modulation potential and calibrating free parameters in the local interstellar spectrum for all GCR ions [22].

1.3.2 Solar particle events (SPEs)

The Sun continuously emits particles which make up the solar wind. These are mostly low-energy protons and electrons which are stopped by thin shielding and are thus normally not considered a threat to human space exploration [14]. However during the periods of high activity, the Sun's ejected protons can be accelerated by the chock of a coronal mass ejection or during a solar flare to very high energies. When the energies and flux of the accelerated particles reach high values and extend over a certain period of time, they are registered as Solar Particle Events (SPEs).

SPEs contain mostly protons; include helium ions as well as some highly charged and energetic (HZE) ions. The flux of protons above 30 MeV can exceed 10^{10} cm^{-2} in several hours or days and particles above 50 MeV can penetrate spacesuits and spacecraft [14].

Although SPEs are related to the solar activity and cycle, their appearance remains rather unpredictable [23–25], especially far into the future as exploration-type missions are typically planned. SPEs differ in the prevalent proton energies and particle flux. Some SPEs have been observed and recorded, and data from those events are typically used for radiation protection in space. In 2018, NASA published a report [23] recommending to use the October 1989 series of events as a reference design case for missions beyond LEO, based on SPE storm shelter requirements provided in [26].

1.3.3 Secondary emissions

When primary radiation enters a habitat wall, it reacts with the target molecules and produces secondary emissions. Depending on the nature and energy of the primary-target pair of agents, the produced results will differ from knocked-off electrons to nuclear spallation and formation of ions, neutrons, pions, muons, etc. The most commonly present secondary particles in metallic space vehicles and habitats will be protons of slightly reduced yet still very high energies (when compared to primary protons), neutrons, helium nuclei [27], X and γ rays, and metallic ions of low energies [28]. Some of the secondary emissions (e.g. neutrons) can travel longer in the human body than the primary incoming particle, thus potentially being more harmful. Therefore, secondary emissions must be specifically considered in habitat construction and counter-acted upon, namely in the choice of supplementary materials.

1.3.4 Lunar neutron albedo

Interactions between the primary particles and the lunar soil cause the formation of lunar radiation albedo. It consists mainly of neutrons that are formed from the constant GCR bombardment of regolith and which shoot upwards from the surface. It has been estimated that the neutron albedo can contribute up to 20% of the effective dose on the Moon [17]. Therefore, any human activity on the surface has to take the lunar neutron albedo into account.

2. Problem statement: the battlefield

2.1 Engineering problems: the main aspects to consider

Four main groups of engineering problems have to be considered in habitat construction on the Moon: robustness, feasibility, sustainability and human factors.

Robustness is concerned with the habitat's resistance to structural, thermal and vibro-acoustic loads, meteoroid shocks, and radiation protection. As any house, a habitat has to bear all the loads, some of them present continuously such as the static structural loads, and others appearing occasionally as for example the vibrations from a nearby launch. Meteoroid population around the Moon follows a power law size distribution with small impactors dominating the representation. Traveling at speeds of 3–70 km/s [29], most micrometeoroids are 30–150 μm in size [30]. It has been found that micrometeoroids generally leave impacts of the same order of magnitude as their own sizes [31]. The accumulation of impact craters over time will result in a local density change of the outer shell of the habitat which may affect the mechanical resistance, thermal insulation and radiation protection effectiveness of the structure. Areal density is the most important feature in radioprotective effectiveness of a chosen material. Since all of the main structural stressors will affect the different protective properties of the structure to a greater or lesser extent, they should be considered in parallel when sizing the habitat.

Feasibility considers the technological readiness of the techniques implied in construction as well as cost and power effectiveness of the proposed methods. The mean Technological Readiness Level (TRL) of ISRU technologies reported in the 2021 *In-Situ Resource Utilization Gap Assessment Report* [9] is 3 and the highest TRL is 6 (out of 9). However, these are reported for various uses of regolith to support the human and robotic exploration of the Moon. The TRL of regolith utilization for habitat construction is hard to estimate as only small-scale prototypes of building blocks and techniques have been demonstrated with technologies plausible for lunar utilization [9, 32]. To choose among available ISRU technologies, cost effectiveness and power budget will have to be considered.

Sustainability guides the choice of materials, technologies and techniques in order to ensure a power budget-effective and scalable development and operations of the systems. Maximizing the utilization of local resources is key in achieving sustainable development on the Moon. Regolith will be the main material not only to build but also to operate and maintain facilities. For radiation protection, the degradation of the protective shell over time has to be considered and supported with timely counter-measures. The most important aspect to consider is maintaining the areal density in habitat walls over the years, possibly decades, of exploration.

Human factors regroup such aspects as the crew's mobility, well-being and safety. Surface exploration and accessibility as well as emergency shelters and escape routes have to be considered. Mundane questions such as storage become strategic engineering decisions as storing certain products can locally enhance radiation protection. The choice of the main carrying materials will be mainly guided by their mechanical properties; however the esthetic appreciation is an important factor in habitat design and should not be neglected as supplementary materials will also affect the radioprotective properties of the habitat. An important element among human factors is the visual reference system. Windows are essential in ordinary life, and observations demonstrate how the presence of windows improves human well-being [33, 34]. The fact that astronauts spend a lot of their free time in the Cupola of the International Space Station (ISS) is a clear manifest to that [35].

From a structural point of view, windows are essentially holes that, strictly engineeringly speaking, the structure would be better off without. A window stimulates local concentration of stresses which typically lead to the need of reinforcement. Radiation on the Moon adds another layer to the question of windows: what materials should be used, and how they will affect the radioprotective effectiveness of the habitat.

When the case of lunar lava tubes is considered against the main engineering problems, they evidently score high on feasibility since little preparation is required to use them. However, feasibility is complicated by the need to provide all life support and infrastructure under the ground, possibly extending many meters for ensuring safety. The main consideration regarding robustness is the potential danger of a tube falling in on itself—either upon a meteoroid impact or vibrational excitation (e.g. from a nearby landing/launch). The main show-stopper for lava tubes utilization is surface access and human factors. Humanity seeks to explore the Moon; therefore long surface expeditions are desired. With lava tubes as habitats, astronauts will have to spend a significant amount of time and energy climbing out of their homes onto the surface. For longer expeditions, a surface solar storm shelter must be envisioned to provide immediate protection. In this case, double infrastructure is required, both underground and on the surface, which will largely increase mission's costs and complexity. Most importantly, the psycho-physical effects of living underground on the Moon with no visual reference system, access to natural light or a view of the Earth must be considered. A French "Deep Time" 2021 study [36] has investigated the effects of living in similar conditions on Earth for 40 days; however the lunar case is distinct and more complex due to high levels of stress and alienation which are a part of astronaut life in space.

Most of the engineering problems can be partially answered with regolith utilization. Nevertheless, some additional materials seem inevitable and even desirable—to compensate for certain peculiar behaviors of regolith, thus optimizing material choices for habitat construction.

2.2 Regolith problems: the peculiar behavior of a special material

The lunar soil has been unprotected and constantly bombarded by meteoroids and radiation for several billion years. Such space weathering effects led the material to be crushed and mixed. Particles range in size from a few μm up to a couple of 100 μm, and differ largely in shapes. A distinct property of regolith grains is their extreme adherence and sharpness. These characteristics make regolith uniquely difficult to operate in an effective and safe way. Grains interlock among each other and stick to materials that they come in contact with. They are extremely light, as the average density of a grain is about 3.0 g/cm^3 and most particles measure only a few μm.

A particularly peculiar behavior of regolith on the lunar surface is levitation. Previously considered as the result of meteoritic impacts, particle levitation has recently been tied to the charge buildup from exposure to protons [8]. The difference in charge from the side exposed directly to the solar wind and the side away from the Sun causes charged regolith particles to levitate in attempt to cross the line of difference. This line is the place of the switch between the lunar day and night.

2.3 Radiation problems: the duel of ionizing radiation and radiobiology

In the context of lunar settlement or long-duration missions, astronauts will experience continuous low dose exposure. This type of exposure is higher than that on Earth, which is protected by its magnetosphere and atmosphere, yet it is significantly lower than the single doses delivered as part of radiotherapy. However, some of the radiobiological effects and mechanisms are the same in both cases. Historically, the space sector has been borrowing the findings from radio therapeutic treatments and radiobiology to calculate mission health risks. But space radiation poses important scientific questions about the effects of low doses on cellular and organ levels which can be useful in radio diagnostics and the case of repeated doses.

The so-called absorbed dose, often simply called *dose*, is a measure of energy deposition of a particle in a target material, which is the human tissue in this case. There are several methods to go from energy deposition to the notion of dose which takes into account the biological effects and the harm to organs and the body. Calculating such doses helps to quantify the harmfulness of exposure and cross-compare protective solutions. Based on doses and the associated health risks, which largely depend on the medical history of a person and can be outlined as acute (e.g. nausea) and cumulative short- (e.g. cataracts) and long-term ones (e.g. nervous system function degradation, carcinogenesis), the total mission risks are estimated for astronauts. NASA proposed a model of risk of exposure-induced death (REID) which calculates the risk of death from cancer depending on the age, sex and previous exposure of the astronaut. REID has a hard limit of 3% which means that the total career lifetime exposure should not lead to an increase in the probability of mortality from cancer higher than 3%.

To determine whether a mission is acceptable in terms of radiation exposure, national space agencies set certain exposure limits. As such, there is a short-term limit on 30 day exposure and a career limit, which varies slightly from one agency to another and is also defined by gender in some cases. The former is set by NASA to 250 mSv [37] and the latter averages at 1 Sv across agencies [38]. There is also a specific limit on the exposure to blood-forming organs (BFO). The limit for short-term non-cancer effects is 250 mGy-Eq [37]. Radiation protection solutions must respect these limits and even go above and beyond in looking for dose reduction methods. That is the existing working principle in the context of lunar exploration and settlement, and the global space community is currently putting efforts together to establish specific exploration-type mission limits for joint space activities [38].

3. Existing solutions: the armor

3.1 ISRU technologies

ISRU technologies on the Moon will cover a vast number of activities ranging from collection, storage, manipulation, recycling, treatment, and post-processing. Regarding habitat construction, it should be noted that first, the construction area needs to be cleared, leveled and compacted to control the spread of lunar dust. Then, such an area can be used for building a habitat.

Currently, the global space community investigates sintering, molding, brick-making, and 3D-printing with regolith. The techniques require different types of expertise, machinery, level of automation/human presence, power, and supplementary materials. The readiness levels of the technologies varies drastically as some techniques have been investigated for a number of decades while other started to gain a significant level of industrial and engineering interest in more recent years. As such, the idea of piling up loose regolith dates back to the Apollo era, cement and concrete production has been investigated since the 1980s [32], and additive manufacturing has been attracting a lot of attention in the last tens of years.

3.2 Regolith simulants

Typically simulants are made by crushing down terrestrial rocks of basaltic origins that largely resemble the chemical composition of the rock component of the lunar soil. The mixture can be improved by adding any particular minerals or glasses, as was done for the very first lunar regolith simulant JSC [13] when knowledge about lunar soils advanced thanks to sample return.

Including both mare and highlands types, there are a few tens of simulants that are being produced and used across academia and industry. These simulants respond to different engineering and scientific needs, and are used in technological demonstrations and experiments. In a user guide [11], NASA suggests that particle composition, size distribution, shape distribution and bulk density are the most important properties in a regolith simulant. Indeed, these factors will largely define the thermo-mechanical and chemical properties of the raw material and also outline how it will interact with its environment (e.g. static charge) and other materials (e.g. abrasive nature of the material). For radiation protection purposes, chemical composition and areal density are key factors that will define the effectiveness of regolith shielding. Radiation cross-sections are calculated from molecular formulas and are used to predict the interactions between the incoming radiation and matter. Areal density in g/cm^2, measures how much passive shielding is present in the way of the incident particles. Simply put, in dense materials where molecules sit closely together, there is a higher chance for an incoming primary particle to interact either with the nucleus or the electrons of the molecules. Bulk density in g/cm^3, defines whether and how much the simulant needs to be compressed in order to reach the areal density required for radiation protection.

3.3 Radiation protection

Deviation, distance, time, counter measures, and materials are the only units to put forward at the front line against radiation. In a lunar habitat however, large-scale particle deviation is not a feasible option. Increasing the distance to radiation source in space is impossible as the primary particles are omnipresent in interstellar space, and reducing time exposure may be in conflict with the scientific and exploratory missions' objectives. Although biological counter measures are currently being explored, this research is in its early stages and it is further challenged by individual responses to repeated exposures and hyper sensitivity to low doses. This leaves it to the strategic choice of passing shielding to protect astronauts from radiation. The best choice consists in the material that will absorb the maximum amount of primary radiation while producing the least amount of secondary emissions. The complexity and diversity of the space radiation environment makes this choice all the more difficult. However due to the large shipment costs to the Moon and the abundance of loose regolith on the surface, it becomes the main shielding material in a habitat.

As most units do, the radiation protection community has a guiding motto—a principle proposed by NASA—As Low As Reasonably Achievable (ALARA). It pushes the community to engineer ways to bring down the organ and whole-body doses, ultimately aiming at lower health risks associated with exposure.

As outlined in previous sections, one possible way to maximize radiation protection on the Moon is to build a habitat underground. Studies [3, 39] suggest that several meters under the surface, GCR exposure levels become comparable to those on Earth—a few mSv/year. However due to the major drawbacks of using and living in lava tubes expressed in Section 2.1, this option is not considered for an early settlement here. However, lava tubes should be investigated further for the potential use as shelters from SPEs.

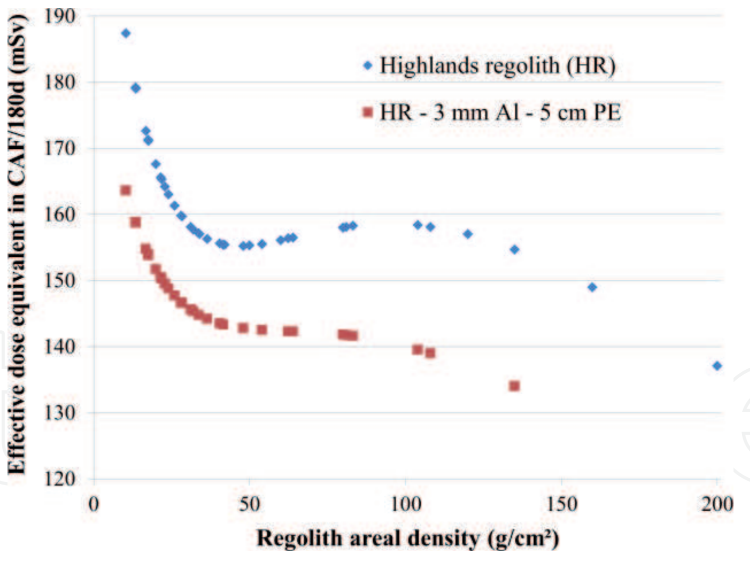

Figure 2.
Effective dose equivalent from GCR in CAF/180 days behind highlands regolith (HR) and multilayer shielding (HR—3 mm aluminum, Al—5 cm polyethylene, PE) as a function of regolith areal density. Based on results in [39].

The best way to optimize passive shielding is to utilize the most effective molecules in terms of radiation protection. Extensive studies [23, 40, 41] show that low atomic mass materials act best as shielding against heavy ions and high-energy protons as they present more nuclei in the path of the incoming particles, thus maximizing the stopping power for the same shield thickness in mass per unit area, if compared to heavier atomic mass counterparts. The top sergeant in this respect is protium or hydrogen ^{1}H because on top of its low atomic mass, it contains no neutrons and thus its utilization enables to bring down the secondary neutron production.

When the choice of chemistry of the main shielding is done or limited, the two cards left to play are areal density (of regolith in the lunar case) and the combination of supplementary materials which can be brought from Earth in moderate amounts, or possibly fabricated in-situ in the future. The term *combination* here includes both the types of added materials (their chemistry, density, H-richness, etc.) and the order or composition of the different layers together. Dense materials present a higher probability for primary radiation to interact with the target molecules since they sit tightly together. Therefore compression and sintering techniques are investigated with regolith and regolith simulants. If compressed regolith is complemented by low-atomic mass or hydrogen-rich materials in a multilayer structure then ALARA principle may be approached. This effect is illustrated in **Figure 2** which summaries the results of a deterministic study [39] with highlands regolith and a multilayer of regolith, aluminum and polyethylene, the latter being rich in hydrogen. The results demonstrate how the addition of aluminum and especially polyethylene leads to a significant reduction in the effective (whole-body) dose equivalent in a Computerized Anatomical Female (CAF) model in lunar GCR environment, simulated in OLTARIS [42] using the BON2014 model.

4. On the lookout for new solutions

To follow the ALARA principle implies to be on the lookout for material enhancements, new materials, and the evolution of ISRU technology. Starting with an evaluation of commonly used materials, it is wise to look into possible combinations of those with regolith. As such, a study of 59 space materials [40] concluded that polymers should be used instead of metals in space where possible. In parallel, polymer 3D printing and sintering techniques with regolith are being developed (e.g. [43, 44]).

Besides the development of new materials, the utilization of multilayered structures is being investigated. The use of multiple layers of different complementary materials is not a new concept is space, as it has been used since the very first days of exploration, in particular in Extravehicular Mobility Units (EMUs). However, the radioprotective properties of such commonplace materials as Kevlar in EMUs has only been investigated recently [45]. The ROSSINI study [45] performed accelerator-based tests of several multilayers with He, F, and C beams of 1000, 962–972, and 430 MeV/u respectively. Among other, it concluded that the addition of LiH to a Moon regolith simulant enhanced protection from radiation by up to 20%. However, any such study is limited to the particular energy and type of primary particles. Overall recommendations require further tests and consideration of secondary emissions—especially neutrons [45].

5. Conclusion

The unpredictability of solar behavior is being anticipated and compensated for with large margins for error, where no error is accepted. Models of GCR are being improved to provide more precise calculations of doses and associated risk estimations. New technologies, experiments, measurements, materials, and simulation models are being developed and tested. Observational missions, such as those to Lagrange points (e.g. ESA missions [46] and NASA's DSCOVR mission [47]) are aimed at providing fast capabilities of forecasting and alerting. All these elements make an intellectual playground for radiation protection engineers and scientists—to make a safe ground for living on the Moon.

Guided by the best practices and prioritizing human comfort and well-being, the specialists on Earth will be making crucial choices for those who will go to the Moon. Under the assumption that habitats are to remain highly effective and functional for several astronaut generations to come, global and diversified efforts are required to design, qualify and supervise their construction. Habitat construction working groups are expected to incorporate wide research expertise, originating from fields such as radiobiology, medicine, aerospace engineering, mining, construction, architecture, material sciences, etc. In cooperation, such groups are better equipped to challenge the stressors of the lunar environment.

Acknowledgements

The authors would like to express gratitude for offered financial support and expertise that enabled the publishing of this chapter. Gratitude is extended to the European Space Agency, TRAD Tests & Radiations, Inserm the National Institute of Health and Medical Research, and the Department of Mechanics, Structures and Materials of ISAE-SUPAERO, l'Institut Supérieur de l'Aéronautique et de l'Espace. Specifically, the authors would like to thank Dr. Advenit Makaya from ESA and the experts from TRAD Tests & Radiations for their expertise and implication in the project called Protective Use of Regolith for Planetary and Lunar Exploration (PURPLE), which is the framework under which this chapter was developed. At ISAE-SUPAERO, the authors would like to thank V. Godivier and X. Foulquier.

Nomenclature

C	carbon
eV	electron volt
F	flourine
G	giga
Gy-Eq	gray-equivalent
H	hydrogen
He	helium
LiH	lithium hydride
m	milli
M	mega
Sv	Sievert
T	terra
u	atomic mass unit
X	X ray
γ	gamma ray

Author details

Yulia Akisheva[1]*, Yves Gourinat[2], Nicolas Foray[3] and Aidan Cowley[4]

1 Institut Supérieur de l'Aéronautique et de l'Espace (ISAE-SUPAERO), Toulouse, France

2 ISAE-SUPAERO, Toulouse, France

3 Inserm U1296 Unit "Radiation: Defence, Health, Environment"—Centre Léon-Bérard, Lyon, France

4 European Space Agency (ESA), European Astronaut Centre (EAC), Köln, Germany

*Address all correspondence to: yulia.akisheva@isae-supaero.fr

References

[1] Köpping Athanasopoulos H. The moon village and space 4.0: The 'Open Concept' as a new way of doing space? Space Policy. 2019;**49**:101323. DOI: 10.1016/j.spacepol.2019.05.001

[2] Laurini KC, Hufenbach B, Hill J, Ouellet A. The global exploration roadmap and expanding human/robotic exploration mission collaboration opportunities. Jerusalem, Israel: Presented at the 66th International Astronautical Congress, International Astronautical Federation; 2015. p. 9

[3] Angelis GD, Wilson JW, Clowdsley MS, Nealy JE, Humes DH, Clem JM. Lunar lava tube radiation safety analysis. Journal of Radiation Research. 2002;**43**(S):S41-S45. DOI: 10.1269/jrr.43.S41

[4] Benaroya H, Bernold L. Engineering of lunar bases. Acta Astronautica. 2008;**62**(4-5):277-299. DOI: 10.1016/j.actaastro.2007.05.001

[5] Haruyama J et al. Lunar holes and lava tubes as resources for lunar science and exploration. In: Badescu V, editor. Moon. Berlin, Heidelberg: Springer Berlin Heidelberg; 2012. pp. 139-163. DOI: 10.1007/978-3-642-27969-0_6

[6] Heiken GH, Vaniman DT, French BM. Lunar Sourcebook: A User's Guide to the Moon. Cambridge: Cambridge University Press; 1991

[7] Stoeser D, Wilson S, Rickman D. Design and Specifications for the Highland Regolith Prototype Simulants NU-LHT-1M and -2M. p. 24

[8] Colwell JE, Batiste S, Horányi M, Robertson S, Sture S. Lunar surface: Dust dynamics and regolith mechanics. Reviews of Geophysics. 2007;**45**(2): RG2006. DOI: 10.1029/2005RG000184

[9] International Space Exploration Coordination Group. In-Situ Resource Utilization Gap Assessment Report. 2021

[10] Lunar Rocks and Soils from Apollo Missions. Available from: https://curator.jsc.nasa.gov/lunar/ [Accessed: October 12, 2021]

[11] Schrader CM, Systems B, Rickman DL, McLemore CA, Fikes JC. Lunar Regolith Simulant User's Guide. NASA/TM—2010-216446. National Aeronautics and Space Administration; 2010

[12] He C. Geotechnical Characterization of Lunar Regolith Simulants. p. 241.

[13] Taylor LA, Pieters CM, Britt D. Evaluations of lunar regolith simulants. Planetary and Space Science. 2016;**126**: 1-7. DOI: 10.1016/j.pss.2016.04.005

[14] ICRP. Assessment of radiation exposure of astronauts in space. ICRP Publication 123. Ann. ICRP; 2013;**42**(4)

[15] Blasi P. Origin of Galactic Cosmic Rays. Nuclear Physics B. Proceedings Supplements. 2013;**239-240**:140-147. DOI: 10.1016/j.nuclphysbps.2013.05.023

[16] Cronin JW. Cosmic rays: The most energetic particles in the universe. Cosmic Rays. 1999;**71**(2):8

[17] Dachev TP et al. An overview of RADOM results for earth and moon radiation environment on Chandrayaan-1 satellite. Advances in Space Research. 2011;**48**(5):779-791. DOI: 10.1016/j.asr.2011.05.009

[18] Amato E. The origin of galactic cosmic rays. International Journal of Modern Physics D. 2014;**23**(07):1430013. DOI: 10.1142/S0218271814300134

[19] Potgieter MS. Solar modulation of cosmic rays. Living Reviews in Solar Physics. 2013;**10**(1):3. DOI: 10.12942/lrsp-2013-3

[20] Usoskin IG, Bazilevskaya GA, Kovaltsov GA. Solar modulation parameter for cosmic rays since 1936 reconstructed from ground-based neutron monitors and ionization chambers: Cosmic ray modulation. Journal of Geophysical Research: Space Physics. 2011;**116**(A2). DOI: 10.1029/2010JA016105

[21] O'Neill PM. Badhwar-O'Neill galactic cosmic ray model update based on advanced composition explorer (ACE) energy spectra from 1997 to present. Advances in Space Research. 2006;**37**(9):1727-1733. DOI: 10.1016/j.asr.2005.02.001

[22] Slaba TC, Whitman K. The Badhwar-O'Neill 2020 GCR Model. Space Weather. 2020;**18**(6):1. DOI: 10.1029/2020SW002456

[23] Norbury JW et al. Advances in space radiation physics and transport at NASA. Life Sciences and Space Research. 2019;**22**:98-124. DOI: 10.1016/j.lssr.2019.07.003

[24] Kim M-HY, De Angelis G, Cucinotta FA. Probabilistic assessment of radiation risk for astronauts in space missions. Acta Astronautica. 2011;**68**(7-8):747-759. DOI: 10.1016/j.actaastro.2010.08.035

[25] Kim M-HY, Hayat MJ, Feiveson AH, Cucinotta FA. Prediction of frequency and exposure level of solar particle events. Health Physics. 2009;**97**(1):68-81. DOI: 10.1097/01.HP.0000346799.65001.9c

[26] Townsend LW et al. Solar particle event storm shelter requirements for missions beyond low Earth orbit. Life Sciences and Space Research. 2018;**17**:32-39. DOI: 10.1016/j.lssr.2018.02.002

[27] Peracchi S et al. Modelling of the silicon-on-insulator microdosimeter response within the International Space Station for astronauts' radiation protection. Radiation Measurements. 2019;**128**:106182. DOI: 10.1016/j.radmeas.2019.106182

[28] Ferlazzo M, Devic C, Foray N. "Premiers éléments de radiobiologie spatiale." Unpublished manuscript, Inserm U1296 Unit "radiation: defence, health, environment," 2021

[29] Allende MI, Miller JE, Davis BA, Christiansen EL, Lepech MD, Loftus DJ. Prediction of micrometeoroid damage to lunar construction materials using numerical modeling of hypervelocity impact events. International Journal of Impact Engineering. 2020;**138**:103499. DOI: 10.1016/j.ijimpeng.2020.103499

[30] Grun E, Zook HA, Fechtig H, Giese RH. Collisional balance of the meteoritic complex. Icarus. 1985;**62**:244-272. DOI: 10.1016/0019-1035(85)90121-6

[31] Holsapple KA. The scaling of impact processes in planetary sciences. Annual Review of Earth and Planetary Sciences. 1993;**21**:333-373

[32] Isachenkov M, Chugunov S, Akhatov I, Shishkovsky I. Regolith-based additive manufacturing for sustainable development of lunar infrastructure—An overview. Acta Astronautica. 2021;**180**:650-678. DOI: 10.1016/j.actaastro.2021.01.005

[33] Chang C et al. Life satisfaction linked to the diversity of nature experiences and nature views from the window. Landscape and Urban Planning. 2020;**202**:103874. DOI: 10.1016/j.landurbplan.2020.103874

[34] Elsadek M, Liu B, Xie J. Window view and relaxation: Viewing green space from a high-rise estate improves urban dwellers' wellbeing. Urban Forestry & Urban Greening. 2020;**55**:126846. DOI: 10.1016/j.ufug.2020.126846

[35] White WF. The overview effect and creative performance in extreme human environments. Frontiers in Psychology. 2021;**12**:584573. DOI: 10.3389/fpsyg.2021.584573

[36] Associated Press. French Isolation Study for 15 People Ends After 40 Days in Cave. VOA. Available from: https://www.voanews.com/a/science-health_french-isolation-study-15-people-ends-after-40-days-cave/6205014.html [Accessed: October 28, 2021]

[37] National Aeronautics and Space Administration. NASA space flight human-system standard volume 1, revision A: Crew health. NASA-STD-3001. 2014

[38] Walsh L et al. Research plans in Europe for radiation health hazard assessment in exploratory space missions. Life Sciences and Space Research. 2019;**21**:73-82. DOI: 10.1016/j.lssr.2019.04.002

[39] Akisheva Y, Gourinat Y. Utilisation of Moon regolith for radiation protection and thermal insulation in permanent lunar habitats. Applied Science. 2021;**11**(9):3853. DOI: 10.3390/app11093853

[40] Bond DK, Goddard B, Singleterry RC, León SB y. Evaluating the effectiveness of common aerospace materials at lowering the whole body effective dose equivalent in deep space. Acta Astronautica. 2019;**165**:68-95. DOI: 10.1016/j.actaastro.2019.07.022

[41] DeWitt JM, Benton ER. Shielding effectiveness: A weighted figure of merit for space radiation shielding. Applied Radiation and Isotopes. 2020;**161**:109141. DOI: 10.1016/j.apradiso.2020.109141

[42] Singleterry RC et al. OLTARIS: On-line tool for the assessment of radiation in space. Acta Astronautica. 2011;**68**(7-8):1086-1097. DOI: 10.1016/j.actaastro.2010.09.022

[43] Montes C et al. Evaluation of lunar regolith geopolymer binder as a radioactive shielding material for space exploration applications. Advances in Space Research. 2015;**56**(6):1212-1221. DOI: 10.1016/j.asr.2015.05.044

[44] Sik Lee T, Lee J, Yong Ann K. Manufacture of polymeric concrete on the Moon. Acta Astronautica. 2015;**114**:60-64. DOI: 10.1016/j.actaastro.2015.04.004

[45] Giraudo M et al. Accelerator-based tests of shielding effectiveness of different materials and multilayers using high-energy light and heavy ions. Radiation Research. 2018;**190**(5):526. DOI: 10.1667/RR15111.1

[46] Monitoring space weather. Available from: https://www.esa.int/Safety_Security/Monitoring_space_weather2 [Accessed: October 15, 2021]

[47] DSCOVR: Deep Space Climate Observatory, NESDIS. Available from: https://www.nesdis.noaa.gov/current-satellite-missions/currently-flying/dscovr-deep-space-climate-observatory [Accessed: October 15, 2021]