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In situ resource utilization of structural material from planetary regolith

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Abstract

Maximizing *in situ* resource utilization (ISRU) will be a necessary precept for all space faring nations wishing to establish a sustainable habitat on the Moon and Mars. As off-world infrastructure development advances and longer sustainable habitats are produced, what determines ISRU will also need to evolve. In this paper we explore a period in lunar colonization following the NASA Artemis program, where the available energy for manufacturing is still limited, where lunar chemical processing plants have not yet been constructed, and where the mass/weight of material transport from Earth is still confined to super heavy rockets. We present a multilayer construct, called a Regishell, that utilizes surface regolith mixed with a binder material. The Regishell is a robotic-build system that lands intact and is utilized multiple times. The focus of this paper is not the robot system but the binder materials that could be taken from the Artemis landers or produced *in situ* that when mixed with the regolith form a hardened structure under lunar solar radiation. The hardened material when integrated into the Regishell forms a protective structural support for a human habitat. We present examples of fused material along with measured hardness values for a polymer and a geopolymer binder. Moreover, we have conducted Monte Carlo simulations using the Regishell construct with the regolith mixture that includes a water layer to prove viability as a radiation shield. We find that the lunar regolith layer alone is adequate to substantially reduce astronaut space radiation dose due to solar particle events and galactic cosmic rays for a 14-day lunar surface mission.

Keywords: ISRU; In Situ Resource Utilization; Lunar regolith; Space radiation; Radiation Shielding

1. Introduction

As the Artemis program embarks on a return to the Moon, NASA hopes to jump start a future lunar economy.

> ``Establishing a sustained lunar presence [...] will drive technology and innovation using the country's unparalleled scientific capabilities, dynamic economy, and robust industrial base. [...] Artemis Base Camp will be our first sustainable foothold on the lunar frontier. [...] We will [...] discover new resources that will help grow our economy." (NASA 2020a, 2020b)

Sustained living on the Moon brings a number of construction-related topics to the forefront. In decreasing order of importance, these are approaches for sustainability, the use of *in situ* materials, and the properties of lunar regolith of which we only have tacit knowledge from a few select locations. These key topics must be integrated with similar, less-studied problems for constructing lunar infrastructure. These include development of processes for maintaining/servicing equipment in the lunar environment, the issue of raised dust during construction, and because the Moon lacks an atmosphere, the propensity for higher electrostatic effects. It is clear that the concept of *in situ*

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resource utilization (ISRU) must be a part of any lunar construction design, coupled with recycling and repurposing. Finally, and this seems to be an imperative for sustainable construction to proceed at an accelerated pace enabling the wider exploration of the available resources on the Moon, the use of automation and telerobotic operations must be at the foundation of the processes to be used for construction and resource gathering.

What connects all these topics is the usefulness of lunar regolith as a construction material. There have been many investigations on the use of lunar regolith as construction material for the manufacture of living habitats (pressurized) or "garage" habitats (unpressurized) (Indyk and Benaroya 2017; Faierson et al. 2010; Montes et al. 2015). The former is for astronauts and critical equipment, while the latter is for mobile vehicles and automatons. The habitat requirements for astronauts or mobile automatons are likely to be different with emphasis on increased radiation and solar wind shielding and reduced temperature variability for astronauts' quarters. In both cases, the structural material must be manufactured on the lunar surface whether the result is in the form of a "roofing" tile, a shaped mold, or a paste that hardens. ISRU has been present in the many prior investigations and also plays a central role in this paper. The general idea being the maximum use of lunar material with minimal material transported from Earth.

This paper explores a manufacturing process that could be quickly produced using the surface regolith as the most immediately available local resource. The most straightforward application is human habitation infrastructure due to the passive radiation shielding, but potentially roads, launch pads, or berms that prevent accumulation of dust from launches and landings could also be created. Over time, in a vibrant lunar economy given enough energy resources present on the Moon and coupled with large mass transports from Earth, the development of structural habitat material based on variants of chemical processing as done on Earth could produce the necessary metallic ceramic composites that would enable the formation of other structural materials. This paper is focused on a period in lunar colonization following the NASA Artemis program, where the available energy for manufacturing is still limited, where lunar chemical processing plants have not yet been constructed, and where the mass/weight of material transport from Earth is still confined to rockets like the Falcon Heavy, SLS, Starship, Long March 9, Yenisei, etc. Perhaps NASA will have shifted focus to Mars and beyond, leaving behind an emerging lunar economy based at the Lunar South Pole. We anticipate military, commercial, or private entities may be interested in constructing a permanent lunar surface outpost with a continuing presence for space research and activities.

In this publication we present experiment and simulation results on the use of lunar regolith as a medium for structural material. Simulations have been done using GEANT4 to address the radiation properties of the test composite materials. The experimental results are derived from the use of lunar regolith simulations to fabricate coupons for structural testing.

The main facets of the concept presented are:

- Inflatable and/or rigidized structures that will support human and robotic operations,
- Material that maximizes ISRU of local resources for planetary construction,
- Space radiation protection.

2. The Regishell structure

Aerospace has developed an ISRU concept for creating a building material used for hardening an inflatable environment on planetary surfaces. Constructed using a combination of planetary regolith (surface dirt) and binder material, the resultant "Regishell" material is applied in layers incorporating an inflated airform to rigidization of the form. This concept does not require complex 3D printing or additive heating of the material. These environments, or habitats, could be fitted with life support systems for astronauts, used as equipment garages for radiation and dust protection on the planetary surface, or as berms protecting base camps from launch plume dust. The Regishell material itself could even be used for the creation of launch pads and/or roads. Regishell habitats could be constructed on the surface in proximity to a launch/landing site, or underground in areas such as ancient hollow lava tubes.

For the purposes of this paper, we describe the layers of a structure as part of a commercial lunar base camp extension. Optionally, the Regishell material could be created independent of a specific structure and harden to form bricks or tiles used in protecting other infrastructure. For the envisioned inflatable habitat extension, robotic construction will be assumed, using an airform delivered as a package to the Lunar surface. One can envision the primary layers as described below. Fig. 1 shows a schematic of the layers as viewed from two perspectives leaving out pattern details for doors and interconnections.

- **Inner Layer:** The airform is deployed, optionally within a utility scaffolding. The innermost layer is the "bladder" of the inflated shell. It has a series of portholes designed for injecting other construction layers, as well as venting during curing.
- **Middle Layer:** The middle layer can be used as storage for water and provides additional radiation protection.
- **Outer Layer:** The outermost layer permits the insertion of the Regishell (regolith and binder mixture) in the form of the paste. The reactive gases are released from the outer layer and the paste hardens to become structural material that can support weight.

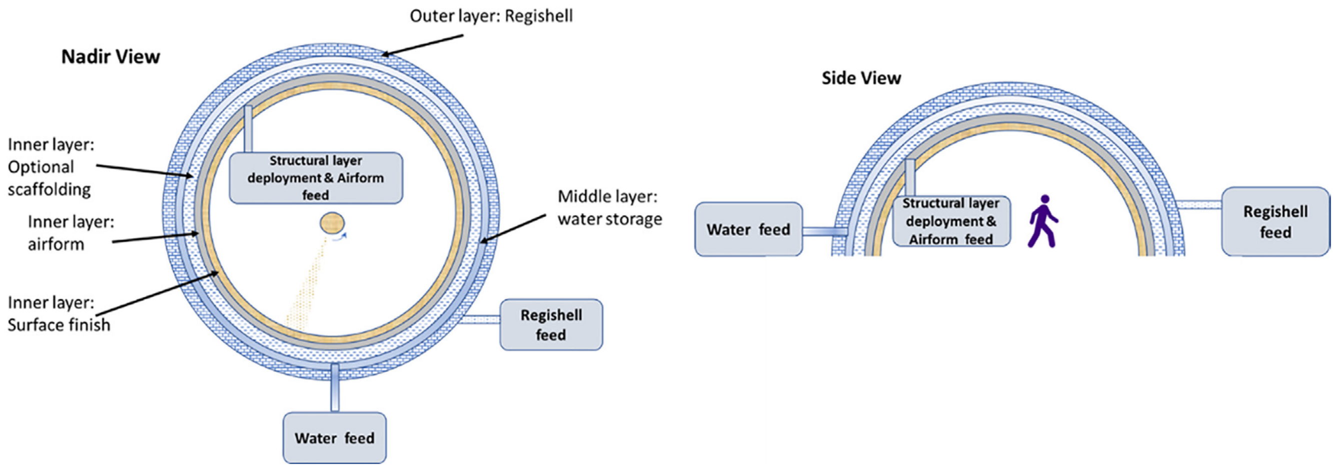

Fig. 1. Schematic of the Regishell concept as viewed from Nadir (left) and Side (right).

The binder used in the Regishell mixture is likely an "alkali activator" that could either be supplied from Earth or created from local lunar resources. Alternatively, a polymer foam in the form of beads, sheets, or waste from packaging (as from equipment transport from launch to delivery) could also be used with/without a solvent as a binder. Our experimental investigations show the types of binder and simulant mixtures that might be processed on the Moon, taking the ISRU mandate to include the available solar heat and vacuum. These investigations are described in Section 3, while the potential thicknesses of each of these layers is described in the Section 4.

3. Experiments

The lunar regolith, returned for the Apollo missions, has been extensively investigated (The Lunar Sample Preliminary Examination Team 1969, 1971; Magnus and Larsen 2004; Morris et al. 1983; Moynier et al. 2006; Wänke et al. 1972). The key minerals with approximate concentration values are ilmenite (~15%), pyroxene (~50%), olivine (15%) and anorthite (~20%) (Mueller 2017). A Lunar Mare simulant (LMS-1, CLASS Exolith Lab, Orlando, FL) is used for preparing coupon samples. Fig. 2a shows the result of the simulant placed in a crucible and heated to 1500 °C, while Fig. 2b shows the same simulant but only heated to 1100 °C.

In the case of higher temperature processing, the result is a glassy structure having a Rockwell Hardness (RH) value of 71, while the lower temperature processed sample failed the RH test. In both cases the temperatures are extraordinarily high, requiring an external energy source. On average the lunar surface temperatures vary from −173 °C to 152 °C and it is not possible to argue that the use of the solar heat (unless very strongly concentrated) alone could be used to prepare structural tiles (i.e. ISRU of the available sun flux). Consequently, a binder material must be included that has a low glass transition temperature to operate as a "network" material. Plastics were available by the time of Apollo 11 mission and were uses in packaging, thermal blankets (Rosato, 2019) A 1 m^3 volume of polystyrene beads (50 kg) weighs 490 N on Earth but only 80 N on the Moon. Moreover, extruded polystyrene foam is about as strong as an unalloyed aluminum but more flexible and less dense (0.05 g/cm^3 vs. 2.7 g/cm^2). The glass transition temperature of polystyrene is 100 °C and it

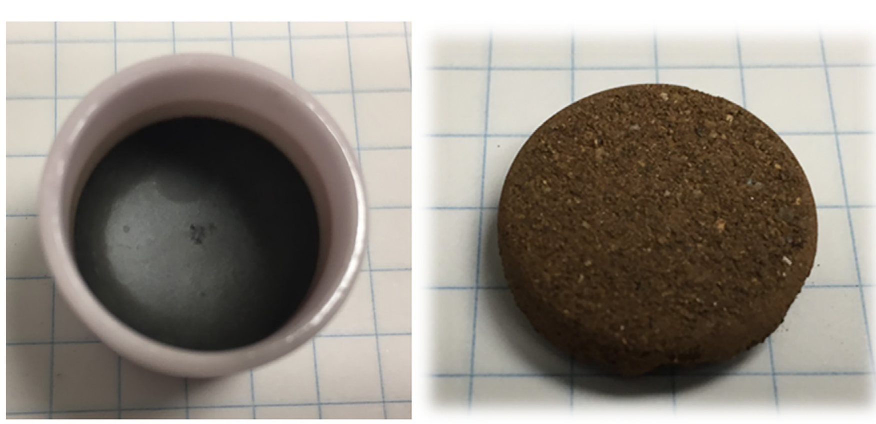

Fig. 2. a) Lunar Mare simulant heated to 1500 °C for 3 h with argon purge, b) heated to 1100 °C for 3 h with argon purge.

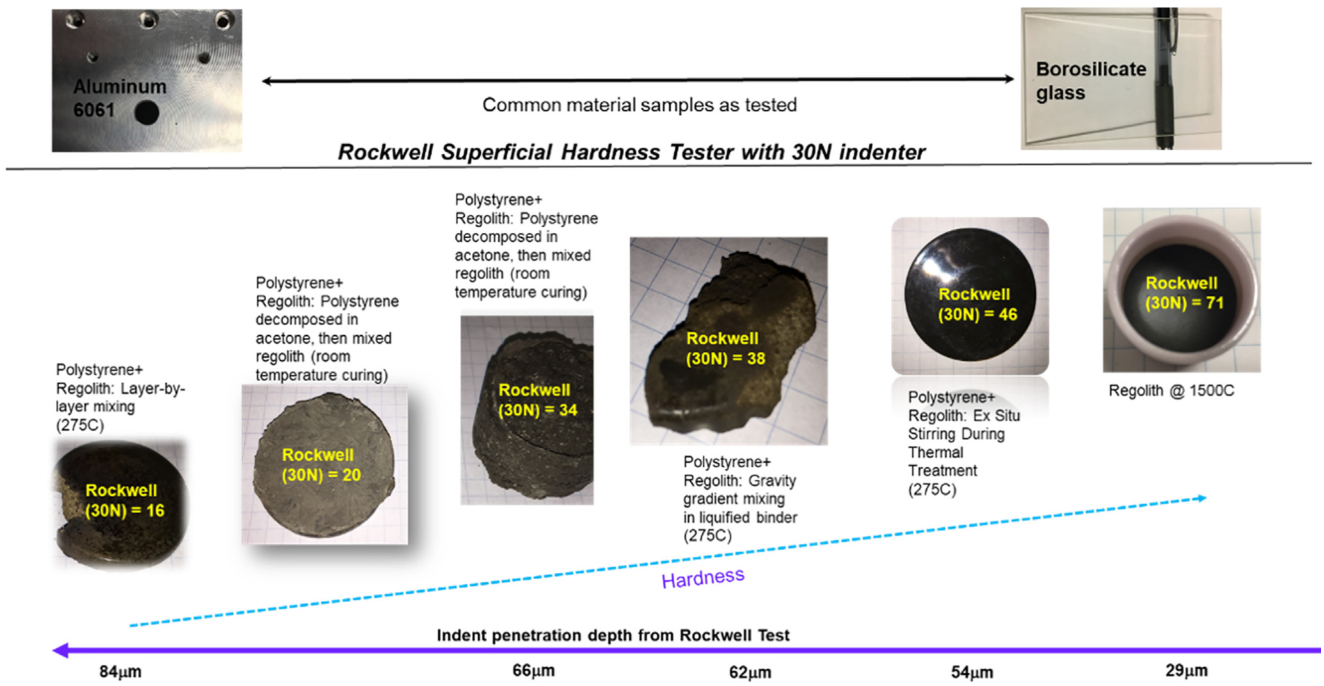

Fig. 3. Test of manufacturing processes that mix regolith simulant and polystyrene for producing structural material for possible use on the Moon. A Rockwell Superficial Hardness tester is used for sample comparisons. The processing temperatures for all the composite materials is fixed at 275 °C, except for the sample on the far left which is there for comparison and is simulant only and heat treated to 1500 °C.

melts near 240 °C. Fig. 3 shows an array of samples made that explore different mixing and processing conditions with the mixture of simulant to polystyrene ratio by weight varied from 0.6:1 to 2:1. The higher simulant to polystyrene ratios produced harder materials. The RH measurement (Superficial Hardness with 30 N indenter) is used to compare samples. Both Hardness values and penetration depths from the test are shown. On the same hardness scale and for comparative reference, we also placed two other commercial samples (Aluminum 6061 and a Borosilicate glass) and the high temperature (1500 °C) processed sample of Fig. 2a. The processing temperatures in all binder included tests were fixed at 275 °C. This was done to get closer to utilizing the peak lunar surface temperatures (152 °C) to advantage. The results of these experiments suggest that it might be possible to mix transported foam material, used for general equipment protection, and regolith for producing some structural material. The lunar surface is deficient in carbon (<150 ppm), therefore producing polymers via ISRU is problematic. However, transportation of polymers in the form of polystyrene, for example, is a low mass proposition.

What the lunar surface lacks in carbon, it makes in sodium, potassium, silicon, and aluminum, all in oxide forms, along with some water. These are components that can be found in a class of materials called "alkali activators" and used in the concrete industry (Luukkonen et al, 2018). A commercially available example is sodium silicate (Na_2SiO_3) and sold in liquid form called "liquid glass." This is a "binder" material that could be produced on the Moon. A pasty version of this mixture could also be produced by mixing solid aluminosilicate with solid alkali activator followed by calcining at high temperature and then adding simulant and some water to form a geopolymer paste. In these experiments, the sodium silicate was commercially procured (CQ Concept, Inc, Technical grade, 40–42 Bè) and mixed with simulant and heated in a crucible mold at 260 °C for one hour. Fig. 4 shows photographs of the initial samples produced under relevant processing steps: a) processed at 260 °C in air, b) processed at 127 °C in air which is close to the lunar surface temperature, and c) processed at 127 °C under vacuum conditions (100 mTorr). For the 80% by weight simulant and processed at 260 °C (in air) the measured RH is 78.5. The highest measured RH values measured. The RH values come down in vacuum because of percolation and release of gases. Controllably varying the temperature during the curing phase should increase the RH values. The goal in these experiments was less to find the optimum processing conditions and more on demonstrating initial feasibility.

4. Radiation simulations

Exploration of interplanetary space presents significant hazards to human health and survival. The radiation environment on a lunar mission is unlike any other on Earth or within Earth orbit. Radiation in the lunar environment is comprised of high-energy heavy ions (Z = 1 to Z = 26, 10 MeV to greater than 1 TeV) from galactic cosmic rays (GCRs) and moderate energy protons (10 MeV to

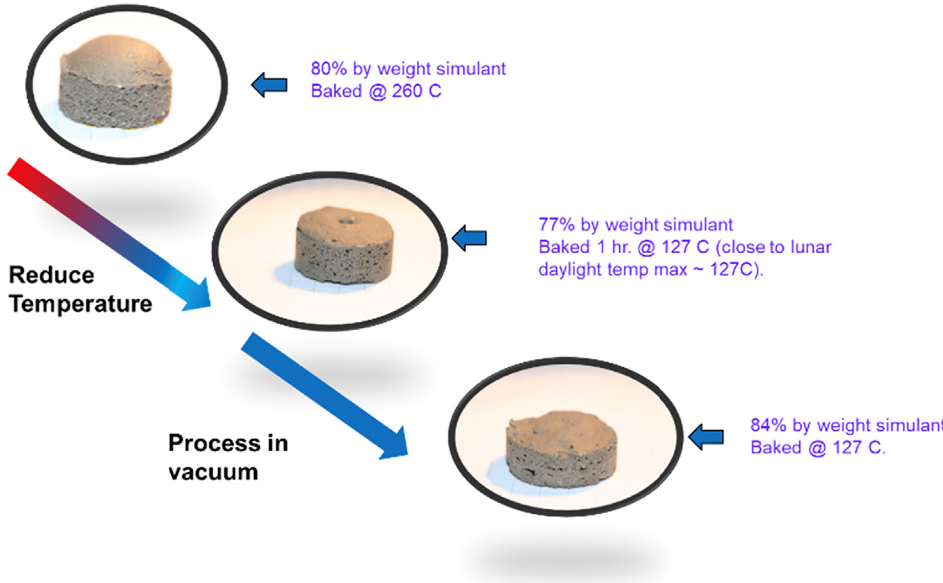

Fig. 4. a) processed at 260 °C in air b) processed at 127 °C in air which is close to the lunar surface temperature c) processed at 127 °C under vacuum conditions (100 mTorr).

1 GeV) from solar particle events (SPEs). These space radiation hazards being present outside the protection of the Earth's magnetosphere can cause both acute and chronic health effects including carcinogenesis (Huff et al. 2016) and degeneration of the cardiovascular (Patel et al. 2016) and central nervous systems (Nelson et al. 2016). At present, space radiation exposure is considered to be the least well-managed risk for long-duration human spaceflight (Francisco 2015). Therefore, mitigation of space radiation risks is critical to enabling human missions beyond Earth orbit. A simulation has been conducted to analyze the optimal thickness of lunar regolith simulant with binder for the purpose of space radiation shielding of a lunar surface habitat. with the intent to analyze the extent to which *in situ* resource utilization (ISRU) can be applied for space radiation shielding and the manufacturing processes needed to form tiles/bricks for that purpose.

4.1. Methods

Because the space radiation environment is extremely difficult to replicate experimentally, this investigation analyzed the effectiveness of lunar regolith simulant for space radiation shielding via Monte Carlo simulations. The Monte Carlo method is a recognized standard for simulating radiation transport for the purposes of shielding calculations. The Monte Carlo schema for approaching physics problems includes formulating the problem mathematically, developing a statistical interpretation of the problem, creating an algorithm for sampling the distribution, estimating the uncertainty in parameters, optimizing simulation using variance reduction methods, and estimating the solution with a generated sample and associated uncertainties (Vassiliev 2017).

4.1.1. Simulation setup

For this study, Monte Carlo simulations were conducted using the GEANT4 toolkit (version 10.03.p03, QBBC physics list) (Agostinelli et al. 2003) because it is well-validated for space radiation transport and dosimetry (Geng et al. 2015; Ivantchenko et al. 2012; Truscott et al. 2000). The space environment model was based on NASA's Badhwar-O'Neill 2014 model for GCRs (O'Neill et al. 2015), the August 1972 SPE spectra as a "worst-case" example, typical "average" SPE spectra, and historical SPE frequency based on solar cycle (Shea and Smart 1990; Cucinotta et al. 2013). Separate simulations were run to calculate dose equivalent from an average SPE, worst-case SPE, and daily GCRs. The effect of the 11-year solar cycle on the frequency and intensity of SPEs was also considered, and the worst-case dose estimates were selected for each case. Doses from these components were combined to determine the worst-case dose for a 14-day lunar surface mission. The 14-day lunar surface mission duration was selected as a likely early mission profile of NASA's Artemis program (NASA 2020a, 2020b).

4.1.2. Geometry

The lunar surface was approximated as a 40 m square plane of lunar regolith. The lunar habitat design was a geodesic dome (e.g. https://monolithicdome.com/monolithic-dome) with integral graphite composite support and lunar regolith tiles placed in the open areas of the structure. The dome shape was chosen because of the selected manufac-

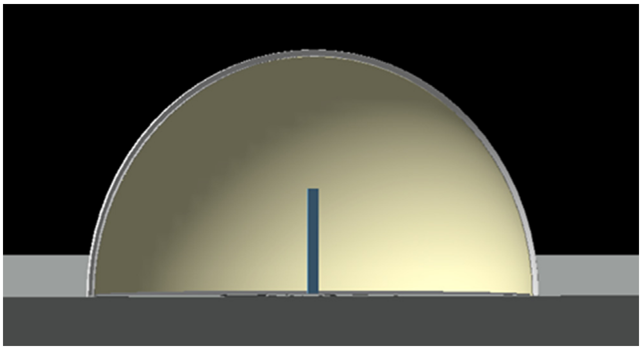

Fig. 5. Simulated lunar habitat and astronaut phantom in GEANT4.

turing approached and for structural strength. However, the dome structure is a complex geometry to simulate in GEANT4. The habitat structure, for this study, was approximated as a hemisphere with 4 m radius (see Fig. 5), modeled after a design proposed by Sierra Nevada Corporation (Pearlman 2019). The inflatable portion of the dome habitat layers were modeled as a 5 mm layer of inflatable polymer (butyl elastomer), a 10 cm air or water gap layer, a 5 mm layer of Mylar, a 5 mm layer of Dacron, and a 5 mm layer of Kevlar (see Fig. 6). The water layer served as both a reservoir for crew potable water supply as well as neutron shielding. The Mylar, Dacron, and Kevlar layers were modeled after the protective layers of the ISS (NASA 2001). The floor of the habitat was modeled as a 3 cm sheet of graphite. The astronaut was modeled with a standard 70 kg water phantom (Fig. 7) placed at the center of the habitat interior volume.

The lunar regolith shielding tiles were approximated as a dome shell of material on the outside of the inflatable habitat of varying thickness (see Fig. 7). A scaffold structure

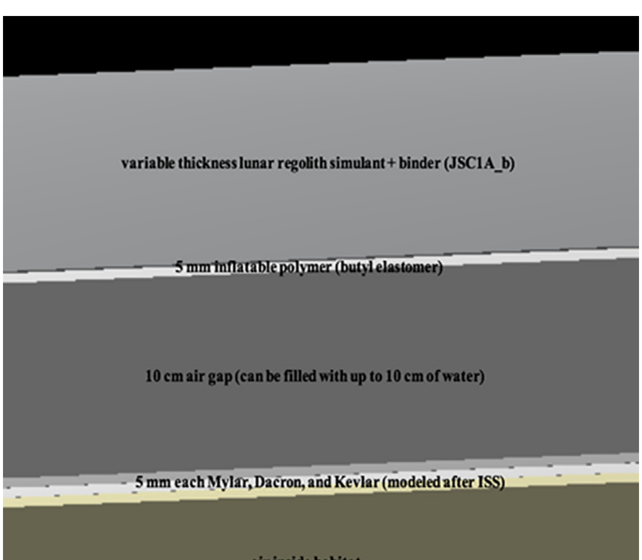

Fig. 6. Description of simulated habitat and lunar regolith shielding layers.

designed to hold the shielding tiles and likely made of carbon composite materials is assumed to be part of the dome but not included separately in the simulated geometry. The lunar regolith material used in the simulations was modeled after the JSC-1A simulant (McKay et al. 1994; Sibille et al. 2006) with a 10% sodium silicate binder. The chemical makeup and weighted density of the JSC-1A simulant and JSC-1A_b simulant with binder used for this study are provided in Table 1.

4.1.3. Dosimetry method

Absorbed dose (D) is the fundamental dose quantity that describes the energy deposited by ionizing radiation. It has the SI unit of joule per kilogram (J/kg) or gray (Gy) (ICRP 1991, 2007). Absorbed dose is the main concern for noncancer effects, such as acute radiation syndrome. Absorbed dose was calculated in our simulations by collecting the energy deposited in the scoring volume (water phantom) per unit mass. This calculation was done within the GEANT4 code and also included a calculation of the standard error of the mean (SEM) of the dose deposited in the volume of interest. SEM was less than 10% for all data points and typically less than 5%.

4.1.4. Dose comparisons

The background radiation dose received by an individual on Earth is ~ 2–4 mGy/year, mostly due to exposure to naturally occurring radioactive isotopes (e.g. radon) and cosmic ray residual particles at ground level (ICRP 2007; NCRP 2009). Radiation workers including nuclear power plant operators; medical doctors, nurses, and technicians; and military and commercial air crews have recommended radiation dose limits of 20 mGy/year (ICRP 2007). By contrast, astronauts on the International Space Station receive radiation doses of ~ 150–200 mGy/year (NCRP 2000, 2002; Sihver et al. 2015) due to the lack of protection from Earth's atmosphere. However, ISS astronauts still receive radiation protection from the Earth's magnetic field. Astronauts in interplanetary space or on the lunar surface will not enjoy the radiation protection provided by a planetary atmosphere or magnetic field and thus will experience higher in-flight radiation doses. NASA predicts that if Apollo astronauts had been in-flight during the infamous August 1972 SPE, that they could have received an acute radiation dose of up to 4 Gy if protected only by a space suit and 0.35 Gy if inside the Apollo spacecraft (Philips 2005).

4.2. Simulation results

Figs. 8 and 9 are screenshots from GEANT4 simulations showing example particle tracks and interactions. Protons are represented by blue tracks in these figures, heavy ions by red/green/yellow/magenta tracks grouped by atomic number, and secondary electrons and gammas by gray and white tracks. Interaction points are colored cyan. From these figures we observed that the higher energy par-

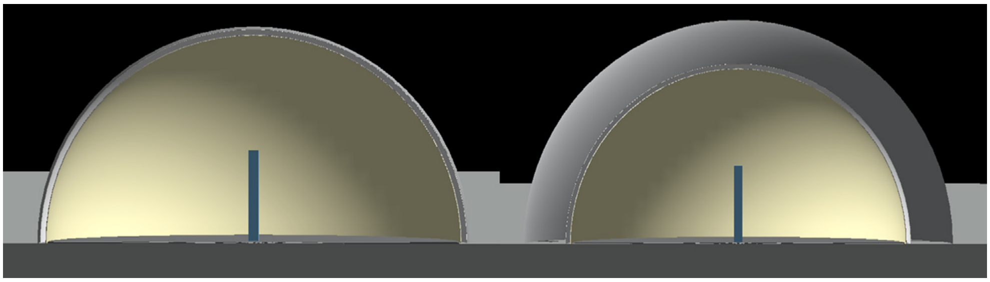

Fig. 7. Simulated habitat and water phantom with a) 5 cm, b) 100 cm lunar regolith shielding in GEANT4.

Table 1
Chemical Makeup of JSC-1A Lunar Simulant and JSC-1A_b Lunar Simulant with 10% Sodium Silicate Binder.

Component	Density (g/cm^3)	JSC-1A (%)	JSC-1A w/binder (%)
SiO_2	2.65	47.50%	42.75%
Al_2O_3	3.95	16.21%	14.59%
CaO	3.34	10.60%	9.54%
MgO	3.58	7.80%	7.02%
Fe_2O_3	5.24	11.50%	10.35%
Na_2O	2.27	3.02%	2.72%
TiO_2	4.23	1.71%	1.54%
K_2O	2.35	0.81%	0.73%
P_2O_5	2.39	0.61%	0.55%
MnO	5.37	0.21%	0.19%
Cr_2O_3	5.22	0.03%	0.03%
Na_2SiO_3	2.4	0.03%	10.00%
	TOTAL	**100.0%**	**100.0%**
	DENSITY (WEIGHTED)	**3.32**	**3.23**

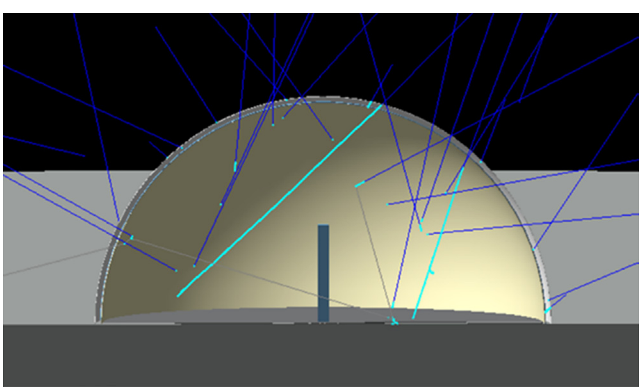

Fig. 8. Example of simulated SPE interactions in GEANT4.

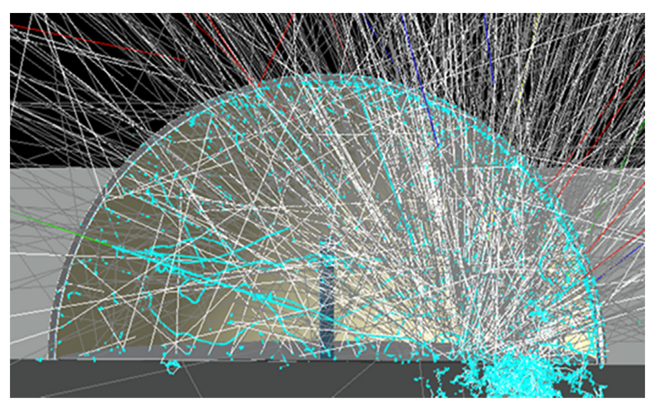

Fig. 9. Example of simulated GCR interactions in GEANT4.

ticles are more penetrating and produce many more secondary particles.

4.2.1. SPE and GCR dose reduction with regolith layer ≤10 cm

Absorbed dose vs. regolith shielding thickness for a time-integrated average SPE is displayed in Fig. 10a, the same plot for a worst-case SPE is displayed in Fig. 10b, and the same plot for 14-days in the GCR environment on the lunar surface is displayed in Fig. 10c. The dome habitat only case is represented as 0 cm regolith shielding. Exponential fit curves were added to the average and worst-case SPE data points with fit equations and R^2 values displayed on the charts. The exponential curves are excellent fits for both the average and worst-case SPE cases with exception of the habitat only, 0 cm regolith shielding data point. We believe this is due to the substantial shielding of lower energy SPE protons with even a thin layer of regolith, which causes the dose equivalent to drop off steeply between 0 and 1 cm regolith shielding thickness. The GCR data points oscillate between a range of approximately 20 and 27 mGy for the 14-day mission, indicating dose is mostly independent of the regolith shielding at thicknesses between 0 and 10 cm. Future simulations could work to reduce uncertainties and characterize the relationship in better detail.

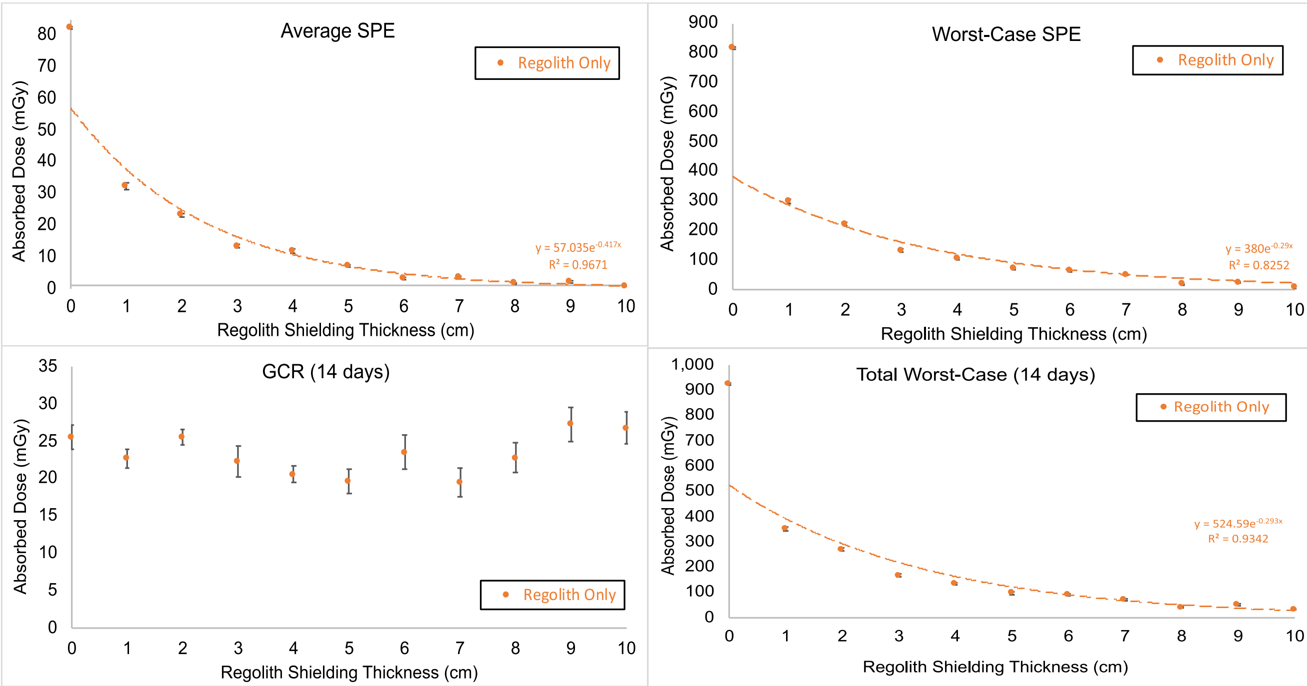

Fig. 10. Absorbed dose vs. regolith shielding thickness for a) average SPE b) worst-case SPE c) 14-day GCR d) total 14-day mission.

From this data we observed that the addition of a ≤10 cm layer of lunar regolith to the inflatable habitat is highly effective at reducing astronaut dose due to SPEs. The addition of 1 cm of regolith decreases the SPE dose by more than 50% and additional thickness of regolith shielding reduces the SPE dose via an exponential relationship. Further, we observed that the addition of 0 to 10 cm of lunar regolith to the inflatable habitat is not effective at reducing dose due to GCRs. These high-energy particles are extremely penetrating and also create showers of secondary particles. The secondary radiation can actually cause a negative shielding effective under certain passive shielding conditions. However, the GCR dose represents a small contribution (<5%) to the total unshielded worst-case dose for a 14-day lunar surface mission.

The total worst-case dose vs. regolith shielding thickness for a 14-day lunar surface mission is shown in Fig. 10d. The worst-case dose is calculated by assuming 14-days exposure to the GCR environment, one worst-case SPE, and one average SPE (at solar max, average SPEs occur approximately every 14 days). The dome habitat only case is represented as 0 cm regolith shielding. An exponential fit curve was added to these data points with the fit equation and R^2 value displayed on the chart. The exponential curve is an excellent fit for the total worst-case dose for a 14-day lunar surface mission with exception of the habitat only, 0 cm regolith shielding data point, we believe for the same reason described earlier in this section.

Overall, we observed from this data that the worst-case SPE is the largest contributor to the total dose for this type of mission and a 1 cm regolith shielding thickness decreased the total dose by 50%. Due to the exponential shape of the curve, however, adding additional regolith shielding thickness does not provide a linear decrease in dose.

4.2.2. GCR dose reduction with regolith Layer greater than 10 cm

Because we did not observe a reduction in GCR dose with regolith shielding ≤10 cm, we decided to run simulations up to 500 cm regolith thickness to determine the thickness at which the GCR dose would begin to decrease. Fig. 11 shows the total GCR dose for a 14-day lunar surface mission with regolith thicknesses of 10 cm to 500 cm. From this figure we observed that regolith thickness on the order of 1 m (100 cm) is required to reduce GCR dose by approximately half and regolith thickness on the order of 2 m (200 cm) is required to reduce GCR dose by approximately one order of magnitude. A recent study indicated that a 50 cm layer of lunar regolith would be required to ensure a safe lunar surface mission (Zhang

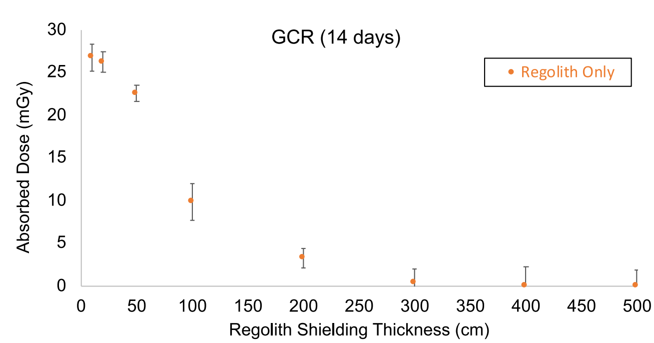

Fig. 11. GCR absorbed dose vs. regolith shielding thickness (10–500 cm).

et al. 2020), but the specifics of the duration of the stay and whether the environment was taken as worst-case or most likely remain unknown such that we are unable to compare these results to our own other than to show first-order agreement. These thicknesses would also require a complex architecture. Thicknesses on the order of meters are more typically associated with concepts with habitat buried underground. Future simulations may be completed with a modified geometry using an underground habitat.

4.2.3. SPE and GCR dose reduction with water layer ≤10 cm

Absorbed dose vs. water shielding thickness for a time-integrated average SPE is displayed in Fig. 12a, the same plot for a worst-case SPE is displayed in Fig. 12b, and the same plot for 14-days in the GCR environment on the lunar surface is displayed in Fig. 12c. The dome habitat only case is again represented as 0 cm water shielding. Exponential fit curves were added to these data points with fit equations and R^2 values displayed on the charts. The exponential curves are excellent fits for both the average and worst-case SPE cases with exception of the habitat only, 0 cm water shielding data point. As with the regolith shielding cases, we believe this is due to the substantial shielding of lower energy SPE protons with even a thin layer of water, which causes the dose to drop off steeply between 0 and 1 cm water shielding thickness. The GCR data points oscillate between a range of approximately 20 and 25 mGy for the 14-day mission, indicating the dose equivalent is mostly independent of the water shielding at thicknesses between 0 and 10 cm. If desired, future simulations could work to reduce uncertainties and characterize the relationship in better detail.

From this data we observed that the addition of a ≤10 cm layer of water to the interior of the inflatable habitat is also effective at reducing astronaut dose due to SPEs. The addition of 2 cm of water decreases the SPE dose by more than 50% and additional thickness of water shielding reduces the SPE dose via an exponential relationship. While the water shielding is not as effective per centimeter of thickness as the lunar regolith shielding, the total mass of the water shielding is lower due to its lower density. Further, we observed that the addition of a ≤10 cm layer of water to the inflatable habitat is not effective at reducing dose due to GCRs for the same reasons the regolith was also ineffective in shielding against these particles.

The total worst-case dose (calculated in the same way as for the regolith shielding) vs. water shielding thickness for a 14-day lunar surface mission is shown in Fig. 12d. The dome habitat only case is represented as 0 cm water shielding. An exponential fit curve was added to these data points with the fit equation and R^2 value displayed on the chart. The exponential curve is an excellent fit for the total worst-case dose for a 14-day lunar surface mission with exception of the habitat only, 0 cm water shielding data point, we believe for the same reason described earlier in this section.

Overall, we observed from this data that the worst-case SPE is the largest contributor to the total dose for this type of mission. and passive water shielding thickness of 2–3 cm may decrease the total dose by 50%. Due to the exponential shape of the curve, additional water shielding may not provide a linear decrease in dose.

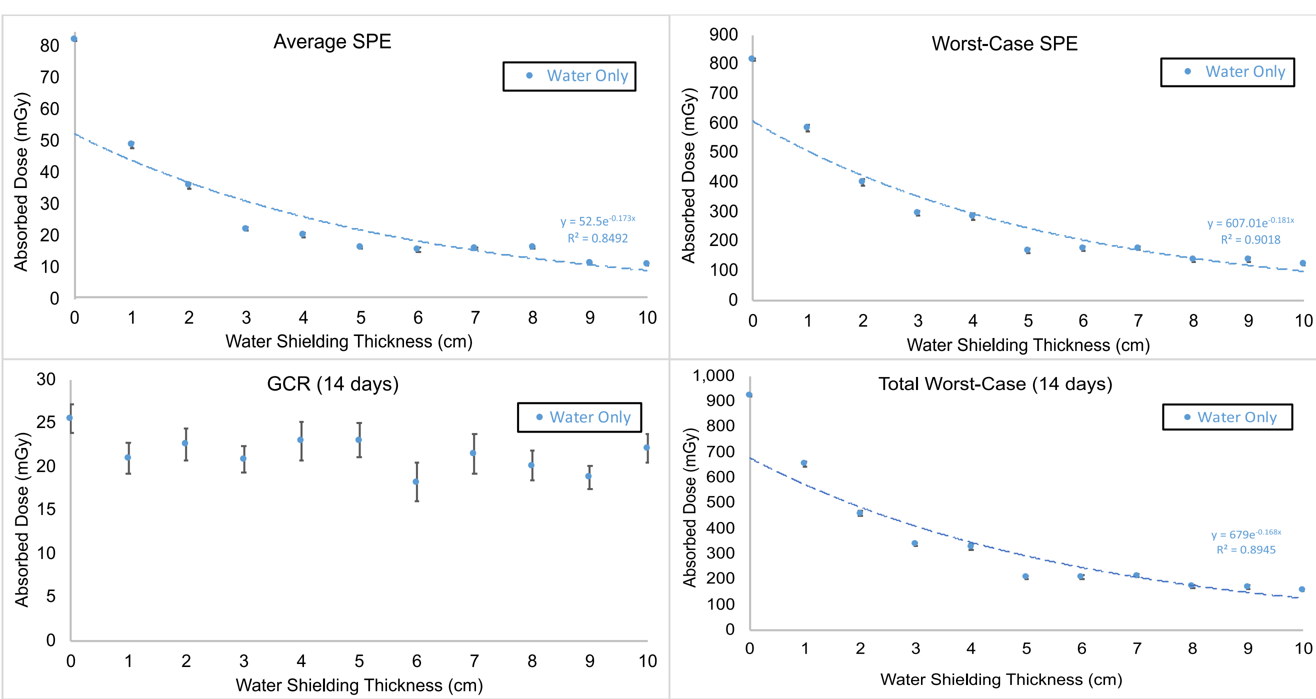

Fig. 12. absorbed dose vs. water shielding thickness for a) average SPE b) worst-case SPE c) 14-day GCR d) total 14-day mission.

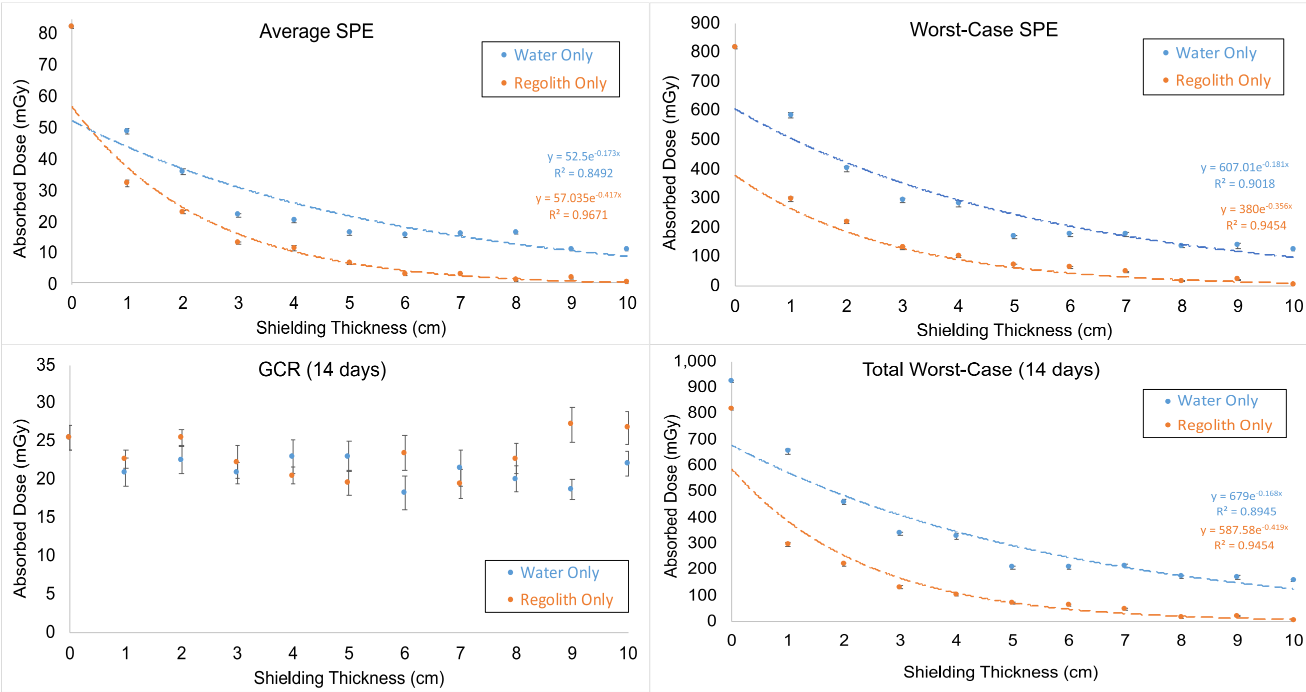

Fig. 13. Absorbed dose vs. water and regolith shielding thicknesses for: a) average SPE b) worst-case SPE c) 14-day GCR d) total 14-day mission.

4.2.4. *Optimization of regolith and water layers*

Fig. 13 summarizes the relative effectiveness of water and lunar regolith at shielding thicknesses of ≤10 cm. Fig. 13a and b indicate that lunar regolith is more effective than water in shielding against SPEs for a given shielding thickness. This makes sense from a physics perspective since the density of the lunar regolith (3.23 g/cm^3) is greater than the density of water (1 g/cm^3), and density is an important factor in passive shielding effectiveness. Fig. 13c indicates that neither passive shielding material is effective at shielding GCRs. These high-energy particles are extremely penetrating and also create showers of secondary particles. The secondary radiation can actually cause a negative shielding effective under certain passive shielding conditions. However, the GCR dose represents a small contribution (<5%) to the total unshielded worst-case dose for a 14-day lunar surface mission (Fig. 13d).

We further investigated this result with an optimization exercise, analyzing the relative effectiveness of combinations of water and lunar regolith shielding layers between 0 and 5 cm each. Fig. 14 summarizes the relative shielding effectiveness of a lunar regolith layer of thickness 0 to 5 cm when paired with a water shielding later of thickness 0 to 5 cm. Exponential fit curves are added to the SPE data as in the prior cases with fit equations and R^2 values displayed on the charts. Again, we observed that no combination of the passive shielding materials up to 10 cm was effective in shielding against GCRs. However, all combinations of passive shielding were successful in shielding against SPEs with a similar exponential relationship depending on shielding thickness. We observed from this data that the minimum lunar regolith thickness to ensure protection against a worst-case radiation environment for a 14-day lunar surface mission may be reduced with the addition of a 2–3 cm layer of water shielding.

The additional mass introduced by a 2–3 cm water layer is substantial. For our 4 m radius simulated habitat, the volume of a 2 or 3 cm water layer volume is 0.965 m^3 or 1.45 m^3, respectively. This corresponds to a mass of water of 965 – 1450 kg. Astronauts on the ISS use approximately 11 L (11 kg) of water per crewmember per day (NASA 2007). Assuming a crew size of 4 for our simulated mission and a mission duration of 14 days, the total water need for the mission is thus 616 kg. With a generous 50% margin, the astronauts would require 924 kg water for a 14-day surface mission. The 2 cm water layer provides 41 kg and the 3 cm water layer 526 kg excess than the water required for the mission including the generous 50% margin. This indicated excess launch mass would be required for water simply for shielding purposes. However, if *in situ* water sources are available, this may become a viable alternative.

5. Discussion/Conclusions

We have presented a concept for a multilayer structure for planetary surface use, which we call Regishell. The innermost layer can be inflated to temporarily determine the shape of the habitat construct. The outermost layer permits the insertion of a mixture of lunar simulant with an alkali binder in the form of a paste. Under lunar sun conditions, reactive gases are released from the outer layer and the paste hardens to become a structural material that can support weight. The inflatable portion can then either be deflated or remain as such to allow an ambient environ-

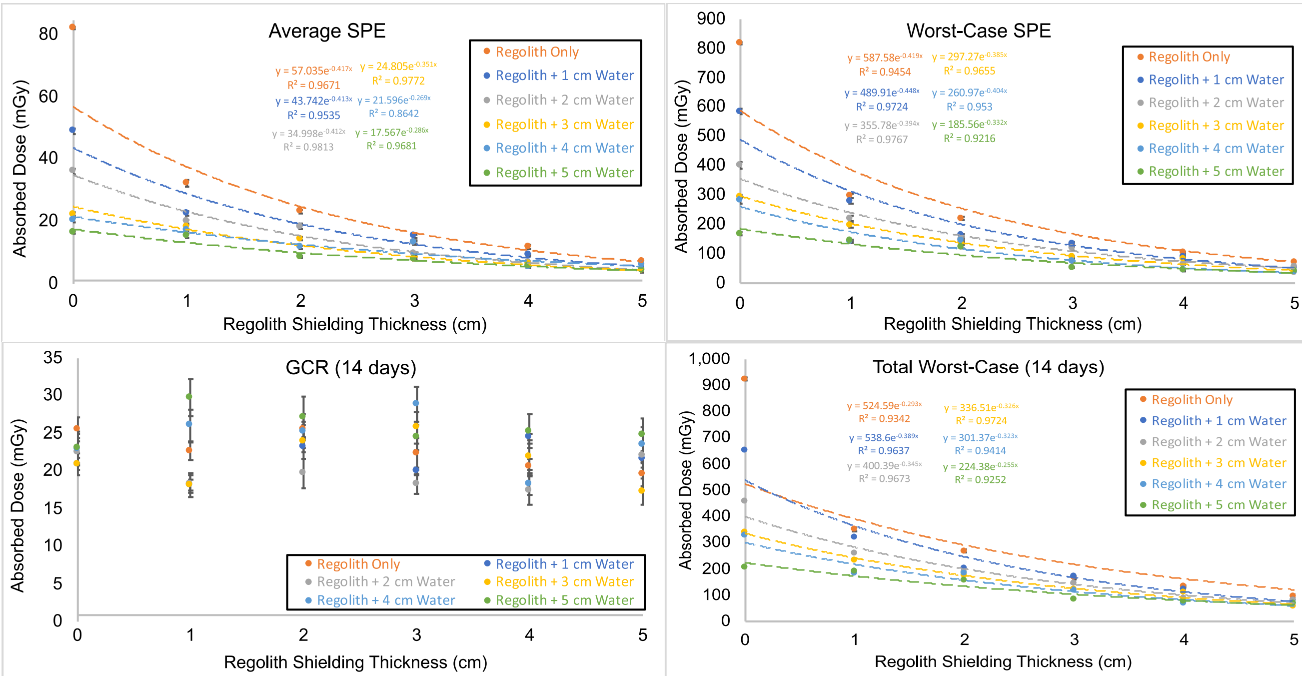

Fig. 14. Absorbed dose vs. regolith shielding thickness with additional water layer for: a) average SPE b) worst-case SPE c) 14-day GCR d) total 14-day mission.

ment for astronauts or other instrument operations. The middle layer can be used as storage for water and providing additional radiation protection. We have conducted a set of experimental investigations on the types of binder and regolith simulant mixtures that might be processed on the moon taking the ISRU mandate to include the available solar heat and vacuum. Our initial results indicate that the use of regolith to form a structural material without a binder requires exceedingly high temperatures and energy. Two types of binder material were investigated: 1) a polymer-based material that would be brought from Earth in the form of packaging and 2) a geopolymer based on an alkali activator and aluminosilicates, with the latter approach being producible on the moon. Results show that structural material having a Rockwell hardness of 46 could be produced with the polymer, but the use of the alkali activator enables materials with Rockwell Hardness that can approach 75 (annealed titanium has RH of 80).

Finally, using the GEANT4 radiation simulation toolkit, we evaluated the passive shielding effect of the Regishell under various combinations of water and simulant mixture. Results of the simulation study indicated that the total worst-case mission dose to astronauts can be substantially reduced using a shielding layer of lunar regolith simulant mixture. Both water and the lunar regolith mixture were effective in reducing the dose due to SPEs, but no combination of lunar regolith and/or water shielding up to 10 cm was effective at shielding against GCRs. Fortunately, the GCR dose contributes a small portion (<5%) of the total unshielded dose and therefore, total mission dose is substantially reduced by shielding a large portion of the SPE dose equivalent. Additional work in this study included analysis of higher density lunar simulant additives that could be readily harvested from the lunar surface including magnetite, ilmenite, and hematite. Results of this portion of the study can be found in Appendix A, and external validation of simulation results in Appendix B.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A:. Regolith additives

We further investigated the passive shielding effectiveness of lunar regolith with selected additives. The additives we selected were chosen due to their composition including iron and presence on the Moon. Further, these materials have magnetic properties under heating which allow for harvest and separation from the regolith by dragging a magnet on the lunar surface. The harvested material can then be added to the regolith and binder material to potentially improve the shielding effectiveness by increasing the density of the shielding material (Ouda, 2015 Davraz et al. 2017).

The additives we considered included magnetite (Fe_3O_4, ρ = 5.15 g/cm^3) (http://mindat.org/min-2538.html), ilmenite ($FeTiO_3$, ρ = 4.72 g/cm^3) (http://mindat.org/min-2013.html), and hematite (Fe_2O_3, ρ = 5.24 g/cm^3) (http://mindat.org/min-1856.html). For this preliminary analysis, we decided to focus on 20% or 40% magnetite additive mixed into the lunar regolith simulant material including 10% binder (JSC-1A_b) in our simulations (see Table 2).

Fig. 15 shows dose equivalent vs. regolith + magnetite additive material thickness for a time-integrated average SPE, worst-case SPE, 14-days in the GCR environment, and the total worst-case 14-day dose. The dome habitat only case is represented as 0 cm regolith + additive material. From this data we observed that the inclusion of magnetite additive materials to the lunar regolith caused the dose due to SPEs to decrease by 3% on average with 20% magnetite additive and by 5% on average with 40% magnetite additive as compared to the dose due to SPEs using regolith shielding alone. Further, we observed that the dose due to GCRs was largely unaffected by the inclusion of the magnetite additive material to the lunar regolith.

The total worst-case dose (calculated in the same way as in previous sections) vs. regolith + additive shielding thickness for a 14-day lunar surface mission is shown in Fig. 15. The dome habitat only case is represented as 0 cm regolith + additive shielding. An exponential fit curve was added to these data points with the fit equation and R^2 value displayed on the chart. The exponential curve is an excellent fit for the total worst-case dose for a 14-day lunar surface mission with exception of the habitat only, 0 cm water shielding data point, we believe for the same reason described earlier in this section. From this data we observed that the inclusion of the additive materials to the lunar regolith caused the total dose to decrease by 3% on average with 20% magnetite additive and by 5% on average with 40% magnetite additive as compared to the total dose using regolith shielding alone.

Appendix B:. External validation of results

Passive shielding is typically characterized by its areal density (ρ_A) such that materials of different densities can be compared. The Apollo spacecraft offered ~ 7–8 g/cm^2 of passive shielding, the Space Shuttle ~ 10–11 g/cm^2 and the ISS ~ 15 g/cm^2 (Phillips 2005). Space suits offer much less, typically ~ 0.25 g/cm^2, and therefore astronauts are advised against extra vehicular activity when high radiation dose rates are predicted.

The baseline habitat design for this project included a 5 mm layer of inflatable polymer (butyl elastomer; ρ = 1.25 g/cm^3), a 10 cm air gap (ρ = 0.001 g/cm^3), a 5 mm layer of Mylar (ρ = 1.39 g/cm^3), a 5 mm layer of Dacron (ρ = 1.39 g/cm^3), and a 5 mm layer of Kevlar (ρ = 1.44 g/cm^3). The Mylar, Dacron, and Kevlar layers were modeled after the protective layers of the ISS (NASA 2001). This baseline habitat configuration gives an areal density (ρ_A):

$$\rho_A = 0.5cm \times 1.25\frac{g}{cm^3} + 10cm \times 0.001\frac{g}{cm^3} + 0.5cm \times 1.39 \times \frac{g}{cm^3} + 0.5cm \times 1.39\frac{g}{cm^3} + 0.5cm \times 1.44\frac{g}{cm^3} = 2.75\frac{g}{cm^2}$$

For the baseline case (habitat only) we calculated the worst-case SPE dose to be 0.82 ± 0.004 Gy. NASA's predicted dose inside the Apollo spacecraft if astronauts had been exposed to the August 1972 SPE was ~ 0.35 Gy.

Table 2
Chemical Makeup of Lunar Regolith Simulant with Additives.

Component	Density (g/cm3)	JSC-1A	JSC-1A_b	JSC-1A_b w/20% magnetite	JSC-1A_b w/40% magnetite
SiO_2	2.65	47.50%	42.75%	33.25%	23.75%
Al_2O_3	3.95	16.21%	14.59%	11.35%	8.11%
CaO	3.34	10.60%	9.54%	7.42%	5.30%
MgO	3.58	7.80%	7.02%	5.46%	3.90%
Fe_2O_3	5.24	11.50%	10.35%	8.05%	5.75%
Na_2O	2.27	3.02%	2.72%	2.11%	1.51%
TiO_2	4.23	1.71%	1.54%	1.20%	0.86%
K_2O	2.35	0.81%	0.73%	0.57%	0.41%
P_2O_5	2.39	0.61%	0.55%	0.43%	0.31%
MnO	5.37	0.21%	0.19%	0.15%	0.11%
Cr_2O_3	5.22	0.03%	0.03%	0.02%	0.02%
Binder					
Na_2SiO_3	2.4	0.03%	10.00%	10.00%	10.00%
Additive					
Fe_3O_4	5.15	–	–	20.00%	40.00%
$FeTiO_3$	4.72	–	–	–	–
Fe_2O_3	5.24	–	–	–	–
	TOTAL	100.0%	100.0%	100.0%	100.0%
	DENSITY (WEIGHTED)	3.32	3.23	3.60	3.96

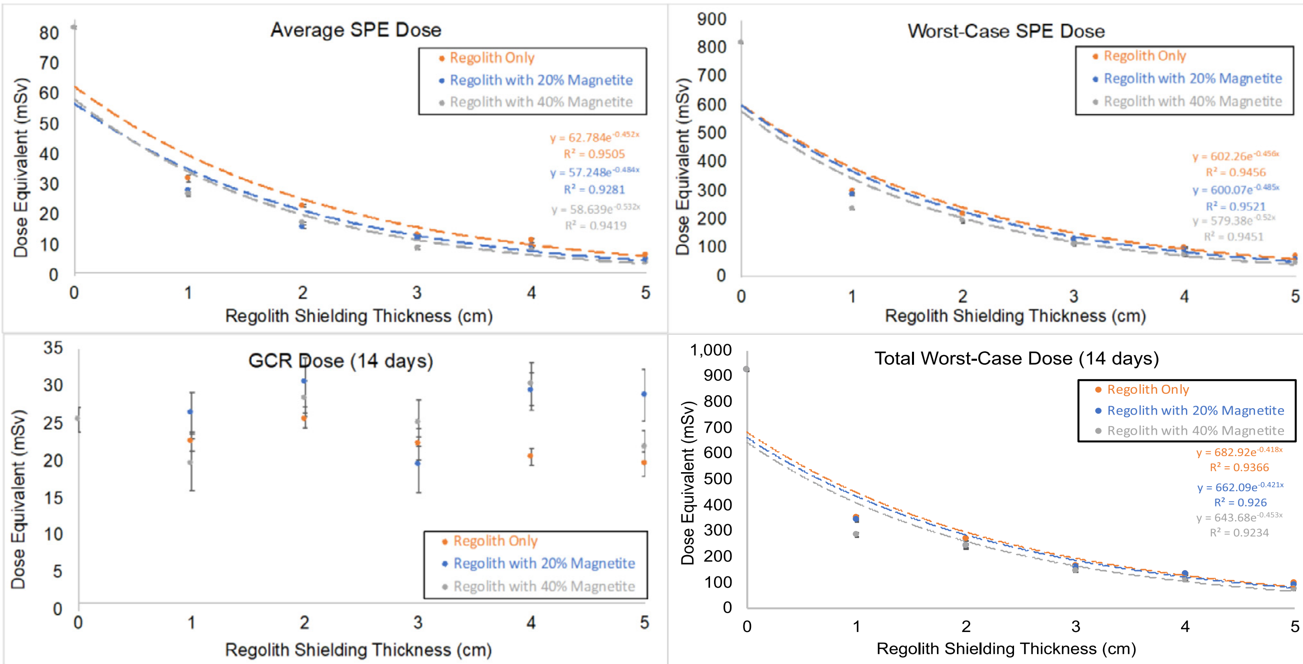

Fig. 15. dose equivalent vs. regolith + additive shielding thickness for a) average SPE b) worst-case SPE c) 14-day GCR d) total 14-day mission.

These results are consistent because passive shielding areal density (ρ_A) of the habitat simulated in this project ($2.75\frac{g}{cm^2}$) is ~ 40% the passive shielding areal density (ρ_A) provided by the Apollo spacecraft (~7–8 $\frac{g}{cm^2}$) and our calculated dose (0.82 ± 0.004 Gy) is approximately 2.5 × higher than the predicted dose (~0.35 Gy) for the August 1972 SPE within the Apollo spacecraft. We know that the passive shielding effect vs. thickness is an exponential rather than linear relationship, but these results agree to first order despite many differences in design and approximations.

With lunar regolith + 10% binder ($\rho = 3.23$ g/cm^3) layers added to the baseline habitat, the areal density (ρ_A) increases as follows for 1–10 cm layer thickness.

Baseline habitat ($2.75\frac{g}{cm^2}$) with 1 cm layer of lunar regolith + 10% binder:

$$\rho_A = 1cm \times 3.23\frac{g}{cm^3} + 2.75\frac{g}{cm^2} = 5.98\frac{g}{cm^2}$$

Baseline habitat ($2.75\frac{g}{cm^2}$) with 2 cm layer of lunar regolith + 10% binder:

$$\rho_A = 2cm \times 3.23\frac{g}{cm^3} + 2.75\frac{g}{cm^2} = 9.23\frac{g}{cm^2}$$

Baseline habitat ($2.75\frac{g}{cm^2}$) with 3 cm layer of lunar regolith + 10% binder:

$$\rho_A = 3cm \times 3.23\frac{g}{cm^3} + 2.75\frac{g}{cm^2} = 12.44\frac{g}{cm^2}$$

Baseline habitat ($2.75\frac{g}{cm^2}$) with 4 cm layer of lunar regolith + 10% binder:

$$\rho_A = 4cm \times 3.23\frac{g}{cm^3} + 2.75\frac{g}{cm^2} = 15.67\frac{g}{cm^2}$$

Baseline habitat ($2.75\frac{g}{cm^2}$) with 5 cm layer of lunar regolith + 10% binder:

$$\rho_A = 5cm \times 3.23\frac{g}{cm^3} + 2.75\frac{g}{cm^2} = 18.90\frac{g}{cm^2}$$

Baseline habitat ($2.75\frac{g}{cm^2}$) with 6 cm layer of lunar regolith + 10% binder:

$$\rho_A = 6cm \times 3.23\frac{g}{cm^3} + 2.75\frac{g}{cm^2} = 22.13\frac{g}{cm^2}$$

Baseline habitat ($2.75\frac{g}{cm^2}$) with 7 cm layer of lunar regolith + 10% binder:

$$\rho_A = 7cm \times 3.23\frac{g}{cm^3} + 2.75\frac{g}{cm^2} = 25.36\frac{g}{cm^2}$$

Baseline habitat ($2.75\frac{g}{cm^2}$) with 8 cm layer of lunar regolith + 10% binder:

$$\rho_A = 8cm \times 3.23\frac{g}{cm^3} + 2.75\frac{g}{cm^2} = 28.59\frac{g}{cm^2}$$

Baseline habitat ($2.75\frac{g}{cm^2}$) with 9 cm layer of lunar regolith + 10% binder:

$$\rho_A = 9cm \times 3.23\frac{g}{cm^3} + 2.75\frac{g}{cm^2} = 31.82\frac{g}{cm^2}$$

Baseline habitat ($2.75\frac{g}{cm^2}$) with 10 cm layer of lunar regolith + 10% binder:

$$\rho_A = 10cm \times 3.23\frac{g}{cm^3} + 2.75\frac{g}{cm^2} = 35.05\frac{g}{cm^2}$$

From these results, the best areal density comparison of our setup to the Apollo spacecraft (~7–8 $\frac{g}{cm^2}$) is the scenario with a lunar regolith thickness of ~ 1.5 cm. Our results show that at this lunar regolith layer thickness, the approximate dose to the astronaut for a worst-case SPE was 0.2 6 ± 0.01 Gy. This result is consistent with the approximate Apollo estimate of ∼ 0.35 Gy.

With this first-order external validation of worst-case SPE dose and areal density, we are confident that our simulations are set up and working properly.

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