Lunar Station Protection: Lunar Regolith Shielding

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ABSTRACT

The Moon's environment consists of a combination of atmospheric, thermal, meteoroids, radiation, magnetic field, and gravitational field mechanisms. However, shielding can only be used to protect a lunar station and its inhabitants from the effects of the thermal, radiation, and meteoroid mechanisms.

This paper provides an evaluation the effectiveness of the in-situ resource, lunar regolith, to mitigate the effects of the lunar environment on lunar station and its inhabitants when used as a shield. It includes a lunar environmental human life threat assessment, calculates regolith required for crew protection, and provides a regolith usage viability summary showing how lunar regolith should be viewed as a viable and effective in-situ life support system resource today, due to its shielding properties, and in the future, due to its O_2 generating and heat storage potential as well as its shielding properties.

BACKGROUND

Lunar Environmental Details

The Moon's environment consists of a combination of atmospheric, thermal, meteoroids, radiation, magnetic field, and gravitational field mechanisms. However, lunar regolith can only be used to shield a lunar station and its inhabitants from the effects of the thermal, radiation, and meteoroid mechanisms. Therefore only the magnitude of each of these environmental mechanisms on the Moon is detailed in the following sections, thereby establishing a reference environment for human risk and regolith protection effectiveness determination.

Thermal Mechanism:

Lunar surface temperatures vary dramatically from extremely hot (107^{o}C) to extremely cold (-153^{o}C) in conjunction with lunar day-night transitions [Spudis, 1996]. This thermal variation is due to the lack of a significant enough lunar atmosphere, which would regulate heat acquired from solar illumination and control heat loss to space. Specifically, these very high lunar day temperatures expose an unprotected crewmember to the risk of heat exhaustion with symptoms including hypotension, fatigue, breathing difficulties, confusion, and fainting. In addition, the very low lunar night temperatures expose an unprotected crewmember to the risk of frostbite and hypothermia with symptoms including initial pain, weakness, loss of coordination, slurred speech, little or no breathing, and gradual loss of consciousness.

Radiation Mechanism:

In space, radiation energy comes from three major sources that are geomagnetically trapped particles, solar, and galactic cosmic rays. The Moon is at such a distance (384,400 km) from the Earth that the radiation effect of geomagnetically trapped particles can be considered negligible. While the radiation of the sun and galaxy come to the Moon in the form of solar wind, solar events (high concentrations of energetic electrons) and cosmic rays (including heavy, unenergetic ions of elements such as iron from outside the solar system) and create its radiation environment since the Moon's atmosphere and magnetic field are not significant enough to provide shielding. Therefore the Moon receives an annual radiation dosage of 25.0 rem (versus 0.360 rem/yr on Earth) on its surface [Churchill 1997]. This lunar radiation will "silently attack" the unprotected crewmember. The nominal lunar radiation dose of 25 rem/yr, as described above, exposes the unprotected crewmember to 69 times his Earthly annual exposure and therefore increases his risk of cancer in the future. In addition, a single solar event can expose an unprotected crewmember to up to 1000 rem over a short period of time and therefore can produce radiation sickness or death (~600 rem) in the unprotected crewmember.

Meteoroid Mechanism:

In space, meteoroids, small bits of cometary ice or rock, travel at 20-70 km/s causing yet another hazard, penetration/damage, for space operations and their occupants. For this reason several models have been developed to characterize the quantity of meteoroids in an operational area (i.e., orbit, trajectory, etc.). The currently accepted model for meteoroid predictions is the NASA Technical Memorandum - 4527 model [Anderson 1994]. This model utilizes operational altitude, diameter of the meteoroid, and particle density/mass to predict fluence. Utilizing this model meteoroid fluence for the Moon ranges from 1088.42 meteoroid impacts/m^2/yr for meteoroids of 1 X 10^{-4} cm or greater in diameter to 1.61142 X 10^{-18} meteoroid impacts/m^2/yr for meteoroids of 700 cm or greater in diameter, as shown in the Figure 2. Specifically, these fluxes expose an unprotected station to penetration or damage. Penetration or damage of a station would put its inhabitants at risk for hypoxic hypoxia due to the lack of O_2 in the atmosphere that does exist and Ebullism/Decompression Sickness (DCS) from exposure to the vacuum of space since very little lunar atmosphere does exist.

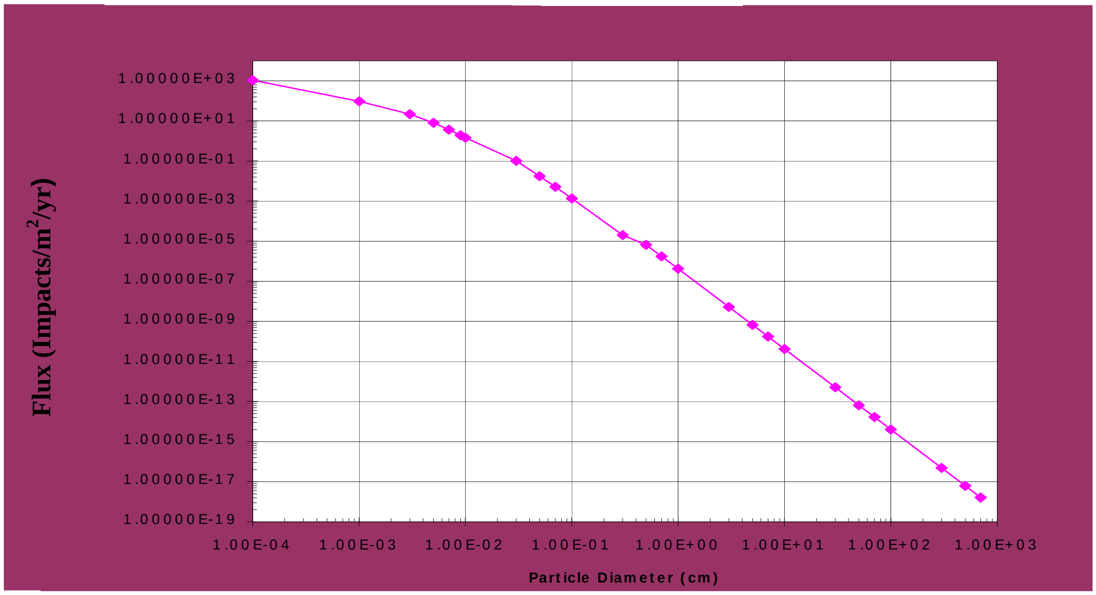
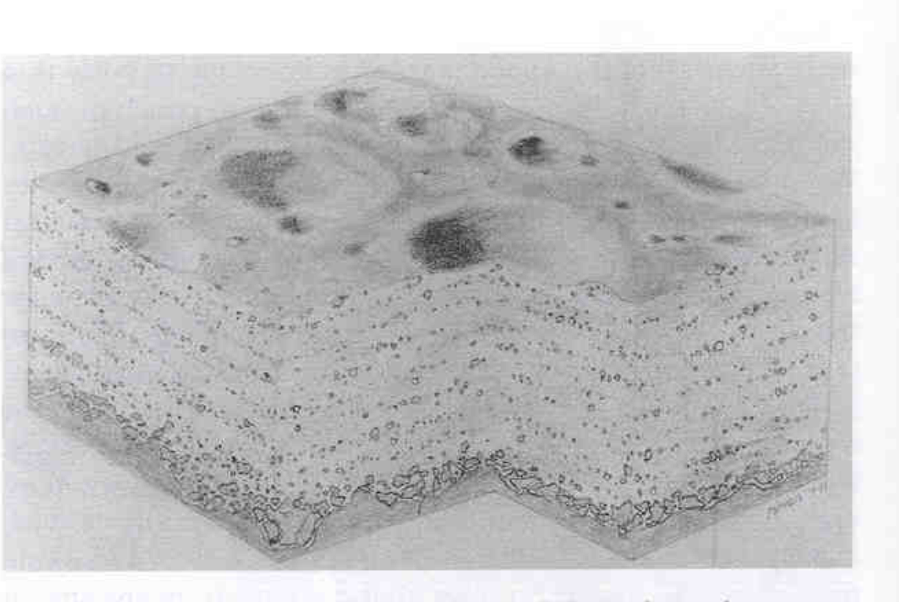


Figure 2: Meteoroid Predictions

LUNAR CREW PROTECTION

There are many options for protecting a crew on the Moon from the lunar environment each with its own mission/schedule/cost/health advantages and disadvantages. This paper will focus on how lunar regolith (See Figure 3) can be used to provide protection for a lunar station and its inhabitants from the Moon's shieldable environment mechanisms.

Figure 3: Lunar Regolith



Lunar regolith is the impact debris blanket that covers the surface of the Moon which is a combination of very fine soil, broken rocks, mineral fragments, glasses, blocks of pure metal (Fe), breccias and meteoroid fragments [Spudis 1996].

Lunar Regolith Usage

Regolith protection would be in the form of a shield or blanket of regolith covering the habitat with each threat requiring a different blanket thickness for adequate/ acceptable protection.

Radiation:

A shield to protect against radiation exposure in a lunar habitat must reduce crew exposure levels from lunar radiation sources (GCR & Solar) to acceptable levels. A layer/shield of regolith accomplishes this reduction by increasing the mass/material a radiation source must traverse to reach the crew. The more material a radiation source passes through the more its radiation energies are reduced or stopped by its particles interacting with the material. Specifically, solar wind particles have such low energies (keV) that they are stopped in less than a micrometer of regolith while solar event particles will pass through ~50-100 centimeters of regolith before being significantly mitigated (See Figure 4). In addition, heavy nuclei GCR particles are stopped by ~10 centimeters of regolith while all other GCR (GeV) particles are stopped by 1000g/cm^3 of material which equates to 5 meters of lunar regolith (2g/cm^3) or the Earth's atmosphere [Heiken 1991]. However since NASA's current acceptable limit for radiation exposure is 25 rem/month not zero, less than 5 meters of regolith shielding (i.e., 10cm$_{AL-}$ - Standard Space Vehicle Shielding = 13cm$_{regolith}$) would be acceptable GCR protection. Therefore based on the maximum protection required, as described above, 1–2 meters of regolith appears to be adequate for effective shielding of a lunar habitat to avoid radiation sickness in the crew [Silberberg 1988].

Figure 4: 5-cm Body Depth Dosage Comparison
for Three Large Flares [Nealy 1988]

Flare Date	Shield Thickness (cm)	Predicted Dose (rem)
1956	50	13.30
	100	5.55
1960	50	3.59
	100	0.43
1972	50	0.56
	100	0.07

Thermal:

A shield to protect against the extreme thermal variations on the lunar surface must maintain the lunar habitat structure at a relatively constant and reasonable temperature so that an internal habitat Thermal Control System (TCS) can be optimally designed. A regolith layer/shield accomplishes this because regolith has low thermal conductivity (2-4 x 10^{-6} W/cm^2 [Heiken 1991]), which makes it relatively unaffected by lunar day-night transitions at depth. Lunar test data has shown that the temperature under a few centimeters of regolith or in a lava tube (~10m depth) is a nearly constant -35^{o}C and -20^{o}C respectively [Artemis 1996]. Therefore a regolith shield of <10 centimeters to 10 meters (although minimum would be sought due to logistic reasons) would serve to protect the crew from thermal extremes exposure even with a total habitat TCS failure.

Meteoroids:

A shield to protect against meteoroid impact, which would compromise the protection of the lunar habitat and thereby the crew, must reduce the probability of such an occurrence. A regolith shield accomplishes this by increasing the mass/material that a meteor must penetrate to reach the habitat's surface. To determine the mass required the Fish-Summer Penetration Equation [Hayashida 1991] is used as shown to predict depth of penetration (t) based on meteoroid size/mass.

$$\text{Fish-Summer Equation: } t_s = k_s * M_m^{0.352} * V_m^{0.875} * \rho_m^{1/6}$$

(where m = meteoroid & s = surface)

$k_s = .57$ for AL

$\rho_{AL} = 2.7$ g/cm^3

$V_m = 20$ km/s

$\rho_{Regolith} = 2$ g/cm^3

Based on selecting the size of 7 cm (conservative selection based on its fluence of 1.76×10^{-10} impacts/m^2/yr) to be the maximum size a shield will prevent from penetrating means Mass (M_m) = 89.75g with $\rho_m = 0.5$ g/cm^3 (from TM4527 Output) therefore,

$t_{AL} = 34$ cm and when translated to Regolith $(((t_{AL} * \rho_{AL})/\rho_{Regolith}) = t_{Regolith})$

$t_{Regolith} = 45.9$ cm

Therefore conservative meteoroid protection of a structure and its occupants is attained with at least 45.9 centimeters of regolith.

CONCLUSIONS

Based on the individual threat assessments above a lunar regolith barrier/shield of 1-2 meters would serve to provide adequate overall protection for a lunar crew within a lunar habitat. Since using such a lunar regolith barrier/shield instead of other types of shields provides several advantages along with a few consequences each must be addressed/considered prior to its use.

Lunar Regolith Usage Advantages

Initially, usage of lunar regolith for shielding saves launch mass for systems/ supplies other than shielding or simply reduces launch mass thereby providing cost savings since it does not need to be transported to the Moon. It also does not add time to fabrication, testing and integration schedules for shielding integration. And once in place on a deployed lunar habitat it is easily repairable and refurbishable without ground re-supply. In addition, the barrier/shield thickness can be increased, within habitat structural limits, without re-design and/or replacement of the habitat if needs/environments change. All these factors make usage of lunar regolith as a shielding material overall very advantageous.

Lunar Regolith Usage Consequences

The most significant consequence from a life support/protection point-of-view of using lunar regolith as a shielding material is that the regolith material is not ready to be installed immediately. This means that the habitat/crew is not fully protected immediately, but scheduling initial deployment to avoid solar events and/or using naturally occurring lava tubes as safe havens, would significantly reduce this penalty. Again since the regolith is not pre-processed for immediate installation it must be dug, lifted, and dumped which requires time and additional tools and machinery (automate to minimize crew time required) be designed, tested, and deployed. However, the deployed tools and machinery for moving regolith are not limited to just deploying the shield but also provide the means to easily move regolith in the future for shield repair/refurbishment or other future uses of regolith. The other consequence of regolith usage is that additional structural analyses/ issues and habitat accessibility for exterior maintenance issues will need to be addressed if the regolith shield/barrier is dumped directly on a habitat. However some current design concepts avoid this consequence by utilizing standoffs to support the regolith thereby providing additional access to habitat exterior and extra-habitat areas that are protected from radiation, meteoroids, and thermal variations. In summary, even with its few rather easily mitigated consequences lunar regolith is a very practical shielding source for a lunar habitat/crew.

RECOMMENDATION

Therefore it is recommended that lunar regolith be viewed as a viable and effective in-situ life support system resource, today due to its shielding properties, and in the future due to its O_2 generating and heat storage potential as well as its shielding properties.

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