"Interim Report for the Human Exploration of the Moon and Mars: Space radiation protection and mitigation strategies for a long term duration lunar base (a NASA funded study)"

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Nomenclature

BFO = blood forming organs
cSv = centi Sieverts.
cGy = centi Gray
GCR = Galactic Cosmic rays
SPEs = Solar Particle Events
HDPE = High Density Polyethelyne.
HZETRN = High Charge and Energy Transport code

I. Abstract

Space radiation is known to pose a real and complex challenge to future human space missions to the Moon and beyond. Radiation protection encompasses all mission aspects starting with mission architecture and planning, mitigation strategies through the integration of appropriate shielding within all the mission elements, and overall detailed operational procedures are as well critical to ensure the highest probability for a manned mission to become an operational reality as well a success. Once surface outpost structures such as habitats and rovers have been designed to integrate radiation protection materials, then detailed operational procedures must be developed to ensure the ALARA philosophy in order as well to minimize the risk of impact from exposure to SPEs and to keep overall mission doses at an operational minimum. All these concepts are intrinsically dependant upon the surface outpost design and construction elements and must be developed and must be thoroughly tested beforehand in order to accomplish minimal exposure to space weather of the crew members. This will in turn aim to avoid the occurrence of worse case scenarios such as Loss of Crew (LOC) and loss of mission (LOM) if severe radiation events such as solar storms of the August 1972 type are not avoided in time. On the surface, in particular, radiation protection of the lunar base is achieved mostly through the proper management of the shielding within the habitats. The surface infrastructure, therefore, plays a significant role in controlling the total overall mission dose, especially when considering a long term human mission as the one in this project.

This paper will present an interim progress report of the project during its first year.

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II. Introduction

In early 2009, a team led by the Department of Space Studies at the University of North Dakota, was awarded a 3-year NASA grant to study advanced inflatable architectural concepts for possible use on the surfaces of the Moon and Mars integrating the radiation mitigation strategies and protection measures within all mission elements for the long term lunar base. The main element of the lunar outpost, the lunar habitat, is based on a hybrid inflatable design concept in which it may be possible to maximize the commonality of technologies used in several different pressurized subsystems, namely the habitat, airlocks and connecting structures, spacesuits, and pressurized rover interfaces. The technology concept for the habitat involves an inflatable structure that is stiffened and constrained by an internal rigid frame. A unique feature of the internal frame is that it is composed of a kit of parts that are palleted within the inflatable bladder package for transport to the planetary surface. Once in place, the bladder is inflated to partial pressure whereupon astronauts enter the interior pressurized volume and from where they are able to work from the inside without the encumbrance of spacesuits. The internal space frame, composed of interlocking hub and strut elements, is constructed within the bladder by the astronauts. Once erected the frame provides support for mounting interior architectural elements, such as floor and wall panels, life support equipment, and storage racks. A unique node connector is used to marry the pneumatic bladder to the frame, thereby allowing substantial structural loads to pass through the bladder without penetration. This configuration permits an inflatable structure to hold form during periods of deflation, and is capable of supporting an overburden of heavy regolith for deep space radiation shielding. With this integrated systems approach, radiation protection from cosmic rays and space weather is being studied and implemented from the beginning to ensure a realistic and comprehensive solution to a manned base on the Moon or Mars.

III. Research Goals and Objectives of the Radiation Project

1. Study and develop a radiation shielding system for the inflatable-rigid frame habitat concept further based on parallel space suit research efforts and evolving NASA requirements and establish the technical feasibility of this approach as well as the radiation reduction provided by such system. Feasible, optimal radiation shielding materials will be selected and tested simulating the weight of the object under lunar gravity. The habitat will serve as storm shelter at the same time.

2. Study the possible integration of radiation storm shelter concepts either deployable/portable ones or ones which are implicit within the design of the pressurized rover as to increase EVA excursion field range.

3. Field deploy and test these concepts and operational protocols in the North Dakota Badlands, with the presence and input of NASA personnel

4. Develop the first radiation emergency operational procedures for future human crews during EVAs, for the Moon to prevent the LOC and LOM scenarios, (“site tagging”)

In this paper we discuss the study for the development of research goals 1 & 2.

IV. Background for the Development of Research Goals 1 & 2.

The radiation protection aspect of a long term human mission is one of the most complex issues as well as mission critical and therefore it cannot be undermined nor avoided at any cost. Detail planning and studies are required to make the best projections in order to reduce the risk of critical mission scenarios such as those arising from powerful SPEs which can deliver lethal doses to crew members and thus incur in mission critical scenarios such as LOC and LOM. This is as well a heavy issue when looked solely from the economical perspective as the loss of an entire multimillion dollar manned space mission is not an acceptable outcome. The cost of underestimating even the relatively small risk of 1-10% occurrence of a major SPE during mission duration is far greater than the joint multimillion dollar investment, time employed, human resources consumed and public impact due to a loss of mission.

In our simulation, we are assuming a 180 day mission to the Moon. Given the fact that for a manned space base settlement, from the radiation perspective the Moon is a significantly harsher radiation environment as that of Mars, our simulation will as well serve as a conservative and limiting baseline for human exploration for the case of Mars. Due to the fact that the effects of space radiation increase with mission duration, for our 180 day mission span we must take into account the doses originating from GCRs as they are no longer negligible within such time frame.
After careful consideration and taking into account latest NASA HZETRN simulation results, we chose to run our mission simulation under the hypothesis that it takes place during a **solar maximum** scenario during which the Galactic Cosmic Ray background contribution (GCR) is approximately half of that during solar minimum. Despite the fact that during solar maximum the likelihood of solar flare events are much higher, the probability of a major solar flare type such as the benchmarking August 1972 or the February 1956 flare taking place during a lunar mission 6 months of duration is between 1-10% depending upon SPE energy for solar maximum scenario. However, we are willing to run with this risk due to the fact that SPEs are much easier to shield from that GCRs. NASA HZETRN simulations and actual measurements with real lunar regolith show that SPE delivered doses can be substantially reduced with properly designed shielding, careful material selection and overall mission operations. Figs.1 & 2.

HZETRN [Ref. 5] simulations show that on the surface of the Moon and without any shielding, the equivalent dose contribution from the GCR background is approximately of 28 cSv for half a year during solar maximum (Table.1). Taking into account that lunar regolith has shown to exhibit slightly superior shielding capabilities than Aluminum (Fig.2), we show data of Aluminum as a reference in Table1. If we add carefully designed shielding, we can reduce this dose to under 12.5 cSv considering some of our shielding configurations, which we will be studying as we progress. We start first with a layer of regolith that could go from 1 m to 5 m, depending on the final habitat design and then we will be adding and testing subsequent layers of approximately 15 gr/cm^2 of polyethylene type composites, 10 gr/cm^2 of water or hydrogen, a minimum of 75cm of surrounding regolith material (beyond this depth the shielding properties of regolith do not improve significantly) and later we will consider the strategic positioning of the consumables the water storage tanks within the habitat/sleeping quarters.

Shield Area Density [gr/cm2]	*Aluminum Thickness[cm]	Dose Eq.[cSv/yr]	DoseEq. ♥[cSv/6months]
0	0.0	57.8	28.9
10	3.7	46.3	23.15
50	18.5	28.3	14.15
150	55.6	24.4	12.2
♣300	111.1	16.7	8.3
500	185.2	8.0	4.0
750	277.8	2.7	1.3
1000	370.4	0.8	0.4
1500	555.6	0.1	0.05

♥ Doses include planetary shielding.

♣ Highlighted in blue are the thicknesses of interest. [Ref.1]

Table 1. Radiation depth profile data for different area densities on the Moon at Solar Maximum. Highlighted in blue are the thicknesses of interest. [Ref.1]

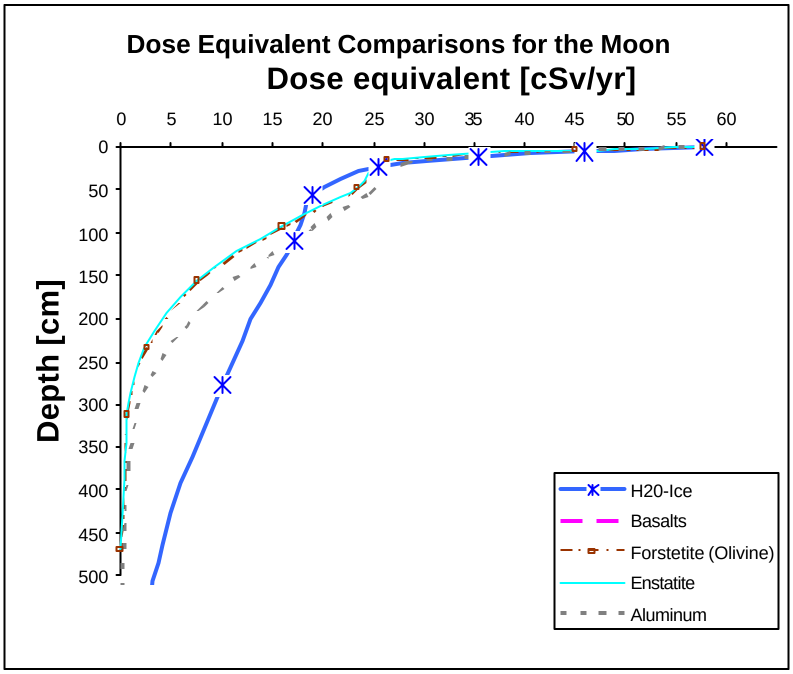


Fig 1. Comparison of radiation depth profiles for different in situ materials of potential interest on the Moon including Aluminum for a radiation scenario at Solar Maximum.

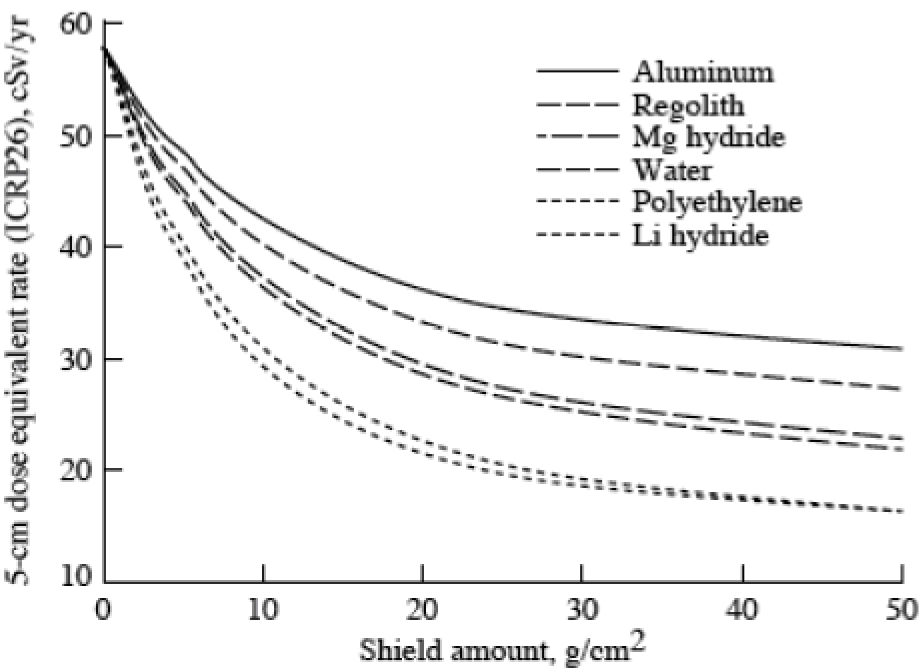


Fig 2 Point estimates of 5-cm depth dose equivalent for the GCR scenario of Solar Minimum as a function of areal density for various materials of interest. [Ref.3]

Note that although water shows a significantly better shielding behavior, the amount of water that would be required to reduce the annual GCR dose by a factor of 2 would be of more than 50 t, for a solar minimum scenario. And water is not an in situ resource [Ref.7]. [Fig.2]

If we consider the regolith to have a density of 1,5 g/cm3, the maximum regolith depth shown in Fig. 2 this simulation would correspond to a depth of 33 cm. Here the simulation has been performed for the solar minimum scenario which is the most conservative since GCR background is at its maximum intensity, however we are considering solar maximum scenario for our 180 day mission as explained before.

This results in an overall dose decrease of approximately 2 times less, thus an estimate of 20 cSv/yr would yield closer to 10 cSv/yr and 5cSv per 6 months lunar surface stay. (since this is a point dose estimate appropriate corrections must be made to account for the more accurate estimates provided by the 95% CI which can be approximated by multiplying the point doses by 3.5, thus yielding a dose of 17.5 cSv for the GCR background for the 6 month stay. These simulation results are further enhanced by the fact that empirical tests performed on lunar soil and lunar regolith simulants, have shown that even a small amount of lunar regolith, with an area density ranging from 1 to 1.5 g/cm^2, or a layer of an approximately 46 cm of thickness can provide substantial protection against primary GCR nuclei and SPE protons These results do not take into account neutron doses nor residual heavier nuclei energy deposition. Fig. 2. shows the actual empirical data. [Ref.1]

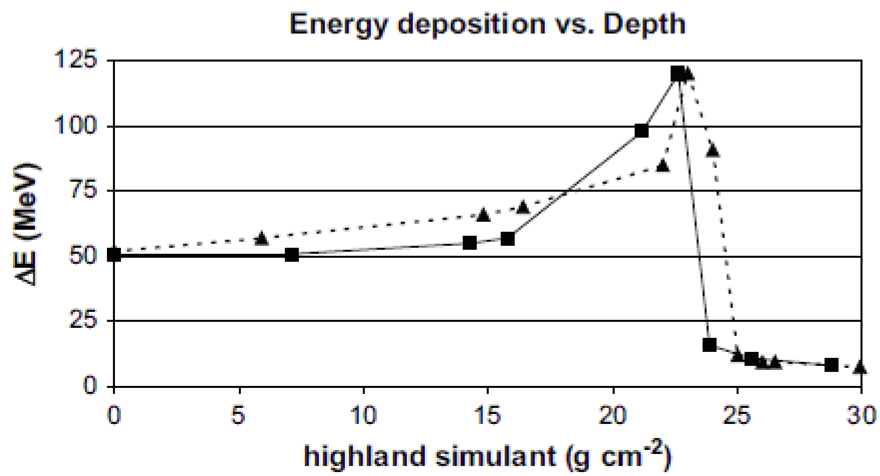


Fig 3. Energy deposition in a 3mm Silicon detector for a 290 MeV/nucleon ^{10}B beam after passing through a lunar regolith stimulant. This simulates an average energy for SPEs as well as primary GCRs. [Ref.4]

In Fig. 3, one can see how the most of the high energy particles deposit the bulk of their energy within the first 17 cm of lunar regolith.

For the lunar soil, approximately 90 percent of the dose is estimated to result from nucleons (mostly secondaries) for shield layers greater than approximately 20 g/cm2. which at 1.5 g/cm3, is 13 cm.

For the much higher energetic GCR spectrum, the greatest reduction in the dose takes place in the first 20–30 g/cm2, (30 g/cm2 is at 1, 5 g/cm3 = 20 cm) with the magnitude of the dose gradient decreasing at larger thicknesses. [Ref.3]

We choose lunar regolith for other reasons as well. Although, lunar regolith behaves similarly to Aluminum as a radiation shielding material it shows improved behavior, and has the added benefits of being an in situ resource, as well as being as well a great material to provide protection against meteorite impact, and diurnal cycle temperature buffering.

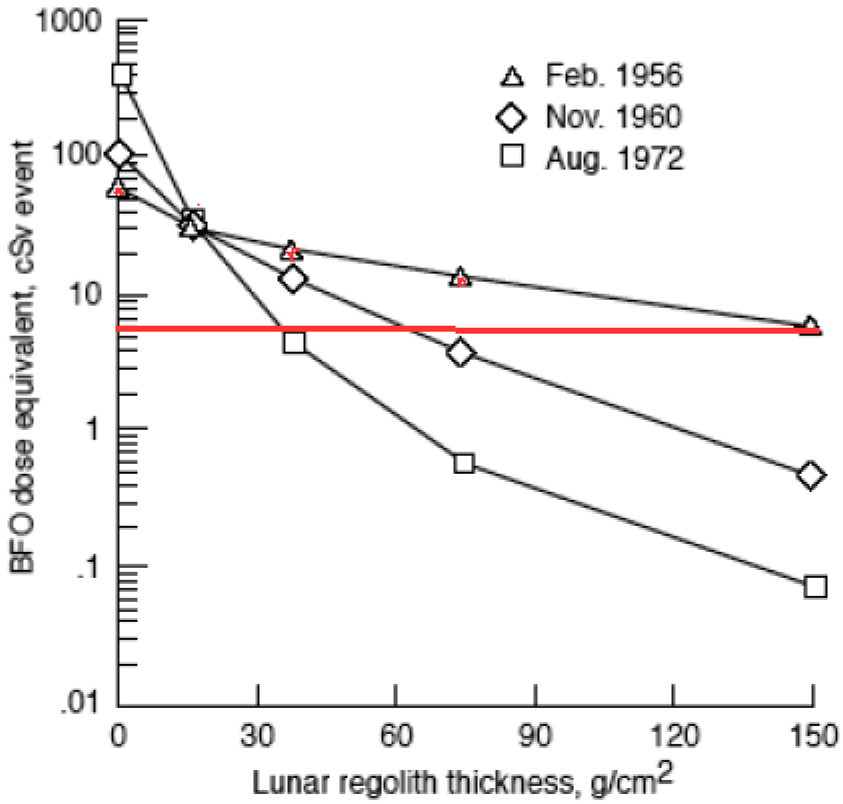


Fig 4. Point estimates of BFO dose equivalent as a function of lunar regolith thickness for three large SPEs. [Ref.3]

For our study, we choose 1 worse case SPE scenario in this case, February 1956. The doses in Fig.5 are per event only. We can see that for the maximum areal density of regolith in this simulation, the corresponding depth is of 100cm, or 1m. For our design bases large SPE we get a dose as delivered to the Blood forming Organs of approximately 5 cSv. Considering the radiation scenario so far described above, we get a total estimated dose of approximately 5cSv + 5cSv =10cSv point dose which is well below the NCPR-98 limits recommended limits, however when considering the 95% CI we get 17,5 cSv + 17.5cSv = 35 cSv total dose. This dose would be within the recommended annual dose limit of 50cSv, however given a stay of only half a year, it would exceed it.
In this still preliminary estimate we have considered a minimum of a 1m depth of regolith shielding, however, we intent to consider added depths of regolith according to engineering structural capabilities and design specifications. Although further increase in regolith shield depth does not drastically increase shielding effectiveness against the CGR component, it will greatly aid in the attenuation of SPE dose impact.
Since we will be as well considering additional shielding options with strategically added materials such as HDPE and some mixtures of epoxy, as well the careful allocation of the consumables within the habitat structure such as the water storage tanks, the doses here described will be further reduced.
In addition to this, our landing site selection options will as well further reduce the overall mission doses by minimizing the chances of SPE occurrence at the base location.

Integrating SPEs doses with overall mission exposure estimates

Considering a risk of large solar flares occurrence during solar maximum of 1 event per year (of the type of February 1956), we can handle the dose delivered by the flare by means of careful design of our habitats shielding thus minimizing the doses significantly. If we run some calculations and according to NASA HZETRN simulation data, we find that we can reduce the dose delivered by a solar flare type event for example of August 1972 from more than 300 cSv to under 2 cSv by introducing the above mentioned shielding options. In these scenarios, we can see that the total integrated dose for half a year and despite being solar maximum can be reduced to stay below current yearly LEO NCPR-132 (2001) dose requirements. In addition to this, we have to take into account the time during transit to and from the Moon, in an improved Apollo type capsule which we can assume is of 3 days each way. Since the dose per day in free space excluding an SPE event is of 0.14 cSv/day or 0.84 cSv for the six days of Earth Moon transit, we can expect a lower dose due to shielding configuration within the spacecraft. This would thus add less than 1 cSv to the overall mission dose resulting in approximately 13.5 cSv for the 180 days mission duration. The rest of the dose received by the crew will come from EVA operations which we believe that through careful EVA operational procedures, the utilization of early warning SPE detection systems (which can currently issue a 20-30 min warning against the onset of an SPE) and the placement of storm shelters within the early warning time frame, we can minimize dose exposure to the crew while keeping accumulated dose levels within ICPR recommendations as well as complying with the ALARA principle.
Mention must be made that the above numbers represent only preliminary dose estimates as we intend to see to the integration of other shielding materials within the habitat structure/fabric such as graphite and high density hydrogen polymers such as space qualified polyetherimide which can be used in the matrix resin as part of the habitats structural requirements thus serving dual purposes and reducing overall payload weight specifications.
With our methodology we not only intend to simulate but as well help issue prototype designs and operational guidelines to avoid mission critical scenarios for the Moon as well as for Mars manned missions such as Loss of Crew (LOC), and Loss of Mission (LOM).

Advantages of our proposed radiation mitigation solutions:

Due to the fact that our habitats will serve as storm radiation shelters at the same time, we will be reducing overall mission and operational complexity (if an SPE event takes place over night there is no need to transfer the crew to a storm shelter, the same goes for an injured crew member), increased reduction in the overall mission dose to the crew by being able to work inside a radiation sheltered environment.
In addition, we will be reducing launch payload mass, transfer of materials from Earth to the Moon and ease of construction since one of the main radiation shielding components would be regolith found in situ.

Long range EVAs, Emergency operational protocols and Site Tagging

Long range EVA operation planning will involve the development of detailed operational protocols to include standard emergency procedures and radiation emergency procedures. Before long range EVA excursions, careful planning of specific exploration path ways within reach of a predefined storm shelter, either man made or natural or both, unless it is an in situ deployable one, must be developed in order for crews to stay within communications range (with habitat control center), or in their defect, predefined markers or “tags” (physical or visual/electronic beacons), in order to minimize exposure risk to SPEs which might take place during any of the numerous EVA excursions. I will call this “site tagging”. This will be crucial specially in order to avoid SPE induced worse scenarios LOC, LOM.

In site tagging procedures, EVA teams could well deploy specific tags or markers/beacons along the excursion lines that will systematically identify the locations, even in case of communications failure. These tags will become the basis for mapping and to develop an entire grid network on the Moon which will serve for storm shelter identification and for streamlining of long range EVA operation planning.
in order to make sure that each crew member is within the optimal distance to a predefined storm shelter with the minimum time to reach it. Site tagging, will be intrinsically dictated by the specifics of the early warning systems, habitat communications systems and inter EVA crews communications systems, and individual active radiation monitoring devices. These procedures will be developed in subsequent phases of this 3 year project.

PRELIMINARY DOSIMETRY PROJECTIONS

LUNAR SURFACE	6 month Dose Without Shielding [cSv]	6 month Dose With Regolith Shielding [cSv]♦	
		50 cm	100cm
GCR background (Solar Minimum)	≈ 14.45	<6	<16
SPEs (1 February 1956)	100	15	2.7
Total dose preliminary estimate	128.5	< 21	<18.7

Proposed Innovative Design Approach for the habitat structure element

1. An inflatable fabric bladder and restraint layer is used to retain an atmosphere and define the life support envelope as well as to support the added layer of regolith acting as radiation shield. This element is to be deployed by pneumatic pressure once emplaced on the lunar surface. .

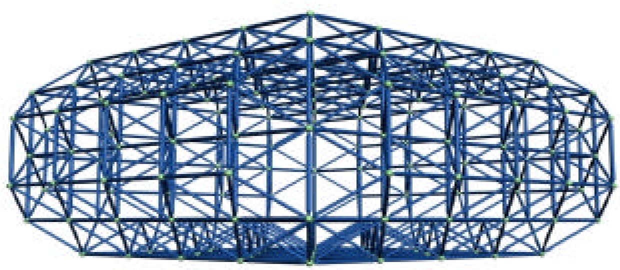


Figure 5. Internal hybrid structure for the lunar habitat.

It is to be preconfigured with an airlock or suitlock that will allow EVA astronauts to enter the pressurized volume. An important aspect of this design study will be to determine how this airlock or suitlock can be integrated effectively.

♦ Dose calculated after of lunar regolith attenuation, with an assumed density of 1,5 g/cm^3 taken as average of lunar regolith range of densities from 0.8–2.15 g/cm^3

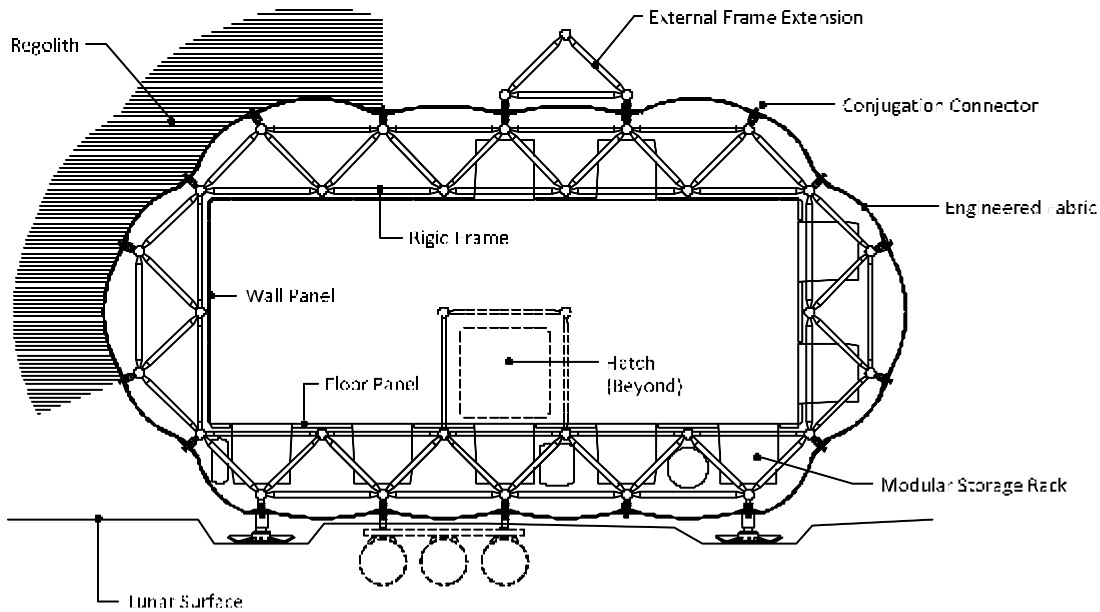
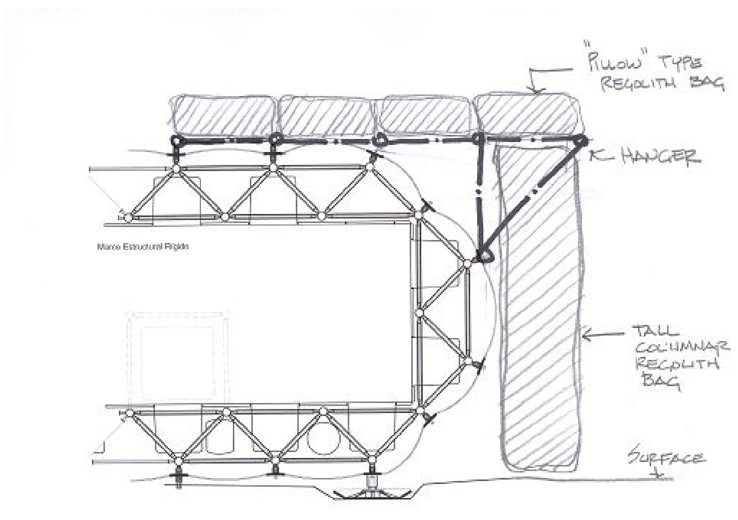


Figure 6. Conceptual view of Inflatable Habitat



below.

Figure 7. Sketch of possible mechanism of allocating the.

A possible mechanism of allocating the regolith onto the habitat could be by means of the attachment of "sacks" or bags which would hold the regolith to the habitat structure as shown and which could be staked on top each other. Fig. 7

One of the major functions of the rigid frame is to support the load imposed by possibly several meters of regolith. However, and according to the simulations, only approximately 1 meter of regolith would be optimal depth in terms of radiation protection due to the fact that additional depth provides minimal added shielding.

Thus, its added depth will solely depend on the habitats engineering structural requirements as well as the feasibility of the available methods for regolith aggregation and deployment onto the habitat structure itself. As it is logical, the greater the depth of the regolith surrounding layer the greater the protection against not only radiation but meteorite impacts and temperature buffering thus its depth will be a compromise in between the above mentioned tradeoffs. The regolith's weight will be borne by the fabric structure and transferred to the rigid frame via the conjugation joints. Since this in situ resource provides protection from micrometeorites, a separate MM fabric protection layer can be eliminated – this outer protective layer of fabric typically represents the most massive element in the composition of spacesuit and habitat fabric design. Our study will examine the interaction of the regolith particles with the fabric shell, look into means of protecting the shell fibers from micro-abrasion, and study how to place the regolith onto the habitat.

Landing site selection considerations regarding overall mission dossimetric estimates:

Currently NASA has as optimal landing site the South Pole, driven by the limitation imposed by solar power as source of energy in a long term lunar outpost. Solar energy is in fact a rather inadequate energy source while on the Moon and a much better option would be to use nuclear batteries instead, (such as RTGs).
These would liberate the landing site selection adding an extra degree of freedom when it comes to mission design specially benefiting radiation mitigation issues.
First, these are not nuclear reactors but small light weight batteries which instead of being powered by chemical reactions inside are powered by the conversion of radioactive decay into heat which in turn it is converted into electricity. For these the radiation exposure to humans is not an issue, as it would be when considering nuclear reactors. In addition, these are by less bulky, and cumbersome plus much more robust than solar power systems, they do not depend from the suns orientation for energy output nor on location. By using these instead of solar powered systems, more important mission critical issues such as SPEs exposure can be addressed.

Nuclear batteries are politically correct as they are used in every single deep space mission and pose no problems in terms of exposure nor launching risks (these are minimal and well understood). Choosing these as our source of energy we can then chose to land somewhere else than the poles, for instance, I would chose to land somewhere close to water ice reservoirs, and on one of the faces of the moon, so that 14 days in the lunar day (which is 28 days) are spent in complete darkness and 14 days in sun light. This way, we can minimize radiation SPE exposure risk by a half. The reason is that while in the dark side which receives no sun light during the 14 days, you crews do not wont get hit by an SPE, thus on surface mission operations such as long range EVAs and rover sorties will be operationally maximized since no risk of SOPE exposure is present and thus operational procedures are greatly simplified during the selected half of the month spent in darkness. Overall mission projected radiation exposure is reduced by half, and mission safety greatly increased as well as mission success.

Rovers

Two rovers, one pressurized and one unpressurized will be manufactured by a team of UND and NDSU students as part of this proposal. The pressurized rover will utilize the suitport concept to connect to the NDX-2 spacesuit, allowing the subject to enter the suit and "disconnect" from the rover while minimizing gas losses and reducing contamination inside the vehicle. Both rovers will be used for EVA simulations in the North Dakota Badlands and "Return to the Habitat" emergency simulations will be performed using the NDX-1 and NDX-2.

For the pressurized rover, a composite fiberglass shell will be manufactured to fit over the vehicle's welded aluminum space-frame, however we will as well be considering state of the art proposed new materials such as space qualified polyetherimide. Such type material would serve as well as radiation shielding against SPEs. In addition to this, we plan to integrate the operational protocols in such a manner that they will further reduce the overall mission exposure to the crew. For instance, operational procedures could be such that crews would only be engaging in long range EVAs during the 14 days in which there is no sunlight (see "Landing site selection" section). In principle, this shell would include an aluminum structural frame with attachment points to be bolted to the vehicle's frame, however will be studying the possibility of utilizing more radiation efficient materials to make up the frame. The rover will have two hatches, one on each side. One hatch will serve to access an emergency two-crewmember inflatable habitat, and the other will serve as an emergency exit for safety during testing. The back of the rover will have two built-in suit-ports.

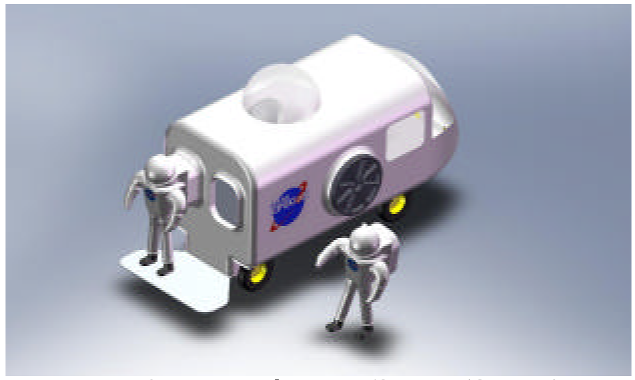


Figure 8. Pressurized Rover w/Suitport (Concept)

For the radiation emergency event protection we are considering as well the possibility of a deployable and/or portable radiation shelter.

The unpressurized rover will use the same GEM eL XD electric motorcar, but will not include a shell. In this rover, a portable storm shelter should be included unless we proceed to adopt the solution in which no unprotected EVAs are performed during the "sunny days". Instead, it will have modified forward seating to allow two suited test subjects easy on/off access to the rover. An open 70 inch by 48 inch flat bed with a 1,100 pound cargo capacity will be used to carry equipment and collected samples.

These vehicles meet federal safety standards for low-speed vehicles. They have top speeds of 25 mph in high mode and 15 mph in low mode. Both vehicles have an independent front suspension system and rack-and-pinion steering to improve vehicle control and stability. Regenerative braking using front-wheel disk brakes and rear-wheel hydraulic drum brakes improves the vehicles driving range by recharging the batteries.

Controls for the rovers will be upgraded to include GPS navigation and radio communication. Within this, we will consider the existence of the communication capability with early warning detection systems in order to receive updates on space weather events and specially to receive critical updates to handle radiation emergency scenarios

Both rovers are integral parts of this proposal. They are needed to demonstrate the suitport concept, spacesuit/habitat compatibility, and increased field range for human planetary missions.

V. Conclusion

Our overall preliminary dossimetry estimates are well within the recommended limits for the surface outpost duration however they need to be refined much more and lowered further in order to take into account amongst several other mission factors, the more acceptable 95%CI estimates. We plan to achieve this by refining our habitats radiation shielding design, testing additional materials such as HDPE, water, epoxy mixtures, by carefully developing our operational procedures specially the procedures for long range EVAs, and analyzing the advantages of selective landing sites.

References

[1] Schneider, S.I., "An Astrobiological Evolution of Mars with a focus on its Radiation Environments and the Implications for Planetary Habitability," MS. Dissertation, College of Earth and Mineral Sciences. The Pennsylvania State Univ., University Park PA, 2007

[2] Rapp, D., " Radiation Effects and Shielding Requirements in Human Missions for the Moon and Mars," MARS. The International *Journal of Mars Science and Exploration* [online journal], Vol. 2, p46-71, (2006). URL: http://www.marsjournal.org/contents/2006/0004/index.shtml doi:10.1555/mars.2006.0004.

[3] Simonsen, L. C., W. Schimmerling, J. W. Wilson, and S. A. Thibeault (1997) "Construction Technologies For Lunar Base: Prefabr icated Versus In Situ," in "Shielding Strategies for Human Space Exploration," Edited by J. W. Wilson, J. Miller, A. Konradi, and F. A. Cucinotta. NASA Conference Publication 3360

[4] Miller, J., et al., "Lunar soil as shielding against space radiation, Radiation Measurements" p1-5. (2009), doi:10.1016/ j.radmeas.2009.01.010 URL: www.elsevier.com/locate/radmeas

[5] Managing Space Radiation Risk in the New Era of Space Exploration Committee on the Evaluation of Radiation Shielding for Space Exploration, National Research Council, 2008

[6]J.W.Wilson,F.A.Cucinotta,G.D.Badhwar,R.Silberberg,C.H.Tsao,L.W.Townsend,R.K.Tripathi,'HZETRN: Description of a Free-Space Ion and Nucleon Transport and Schielding Computer Program'. NASA TP 3495. 1995

[7] Cesare Lobascio et al. "Radiation Exposure and Mission Strategies for Interplanetary Manned Missions (REMSIM)" DOC : ALS-RMS-VRP-0002, 2004