Radiation Shielding for a Lunar Base

Conceptual Design Report

Jared Bell
Dustin Lail
Chris Martin
Paul Nguyen

December 3, 2010

Table of Contents

Design Objective

To design the outer structure and material components of a lunar base to reduce radiation exposure to an annual dosage of 50 rems or less for astronauts occupying the moon for up to six months.

Project Description

The National Aeronautics and Space Administration's (NASA) Vision for Space Exploration is to send humans back to the moon by 2020 to potentially start up outposts for human habitat and research on the moon. Long term exploration of the lunar surface will have many challenges. Current and near future technological advancements in life support and propulsion systems have made the possibility of creating an extended duration lunar habitat a greater reality. A critical concern to the advancement of extended duration space exploration is long term radiation exposure.

Radiation is dangerous to spaceflight because it can cause adverse effects to the human body as well as equipment on board the craft. Radiation exposure to the human body can damage DNA and cause lethal diseases like cancer. At varying levels of radiation exposure, humans can feel extremes from mild fatigue, weakness, and nausea at low exposure, all the way to instant death at high levels. The reliability of crucial electronic equipment on board space vehicles and future lunar habitats will be adversely affected in the presence of radiation in space.

Radiation on the Earth is not as severe due to the protection that we are offered by the atmosphere and magnetic poles. Because the moon lacks both an atmosphere and magnetic poles, the surface of the moon is constantly subjected to unimpeded radiation. A lunar habitat would be exposed to two types of radiation, solar energetic particles (SEPs) and galactic cosmic rays (GCRs). Solar events are a major concern of radiation because they are large releases of energy on the surface of the sun that send high energy particles throughout the galaxy. Had a solar flare occurred during the Apollo Missions, many believe the lack of protection could have been catastrophic on the astronauts.

Conventional spacecraft materials such as aluminum have been proven to reduce radiation exposure below acceptable limits for missions in low-earth orbit. If these radiation limits were to remain the same for an extended mission on the moon, large amounts of conventional materials would be required resulting in excessive launch costs from added mass. Conventional materials may also produce secondary particles during collisions which may be just harmful, if not more, than the original cosmic particles themselves.

In 2005, a technical memorandum from NASA entitled "Revolutionary Concepts in Radiation Shielding for Human Exploration of Space" outlined the findings of a workshop to analyze the current and future radiation shielding technologies. The goal of the workshop was to direct future research towards those concepts which were believed to be most plausible excluding those involving propulsion (getting there faster) or from medical science. The prevalent concepts highlighted by the conference and workshop fell into one of three categories including electromagnetic shielding, extraterrestrial materials such as lunar regolith, and advanced material shielding [1].

While theoretically feasible, the reliability of active electromagnetic shielding would undoubtedly require a lunar base design to include use of radiation shielding materials in case of power failure or unforeseen failures. Further research and development must be done before active electromagnetic shielding can be considered a viable option. [1] Extraterrestrial material especially lunar regolith is believed to be a viable option to be used as shielding. Robotic technology will most likely be required if excavation is involved in the design of a lunar base.

Recent research has primarily been centered on the development of advanced material shielding composed of low atomic mass constituents. Low-atomic-mass constituents such as hydrogen, boron, lithium, carbon, and others are more desirable than high-mass nuclei because, when struck by high-energy primary cosmic particles, they do not fragment into smaller secondary particles like conventional spacecraft material.

Hydrogen's low atomic mass and lack of neutrons make it a prime candidate to be used in the radiation shielding. Present technologies using hydrogen recommended for further study include polyethylene laminates, carbon nanotubes, metal hydrides, palladium alloys for hydrogen storage, quasi-crystals, and pure liquid/solid hydrogen [1].

Mission Architecture:

In order to build a lunar base multiple scheduled missions will be necessary. NASAs Constellation program and its vehicles will be used to transport the crew, base modules, and necessary life support functions to create the first lunar outpost. The Orion crew transport vehicle will have a four man crew capacity for delivery of astronauts into lunar orbit. Once in lunar orbit, the Orion crew module will dock with the Altair lunar lander module and make the descent to the surface of the moon.

The initial crew of four will live in the Altair lunar lander module for the initial two month testing mission stay on the moon. The first crew will do temperature checks, radiation checks, terrain observation, etc. to make sure that all is what was assumed from calculations and observations by satellites. Unmanned cargo vehicles will deliver required excavation equipment so that the astronauts can prepare the foundation for the lunar base.

A subsequent launch approximately 2-3 months later will bring four more astronauts to the moon. Two crew members from the previous mission will accompany the second Orion module back to Earth. Soon after, Ares V will deliver the first modules in the base design along with any additional building equipment required in the design of the habitat. The first module delivered to the base will incorporate all necessary life support and habitation requirements for a maximum of eight astronauts for limited duration periods and six astronauts for more extended durations up to six months.

Mission Activities

While initially living at the lunar base, astronauts will be primarily responsible for doing research. Initial research topics of interest include:

- Processing of lunar regolith into usable constituents
- Exploration of lunar terrain including the search for water
- Feasibility analysis of creating a lunar Mars mission launch site

Base Location:

Factors taken into consideration when choosing the ideal location of a lunar base include:

- Lunar topography and surface aspects
    - Navigable terrain

    - Solid foundation to support base
- Lunar base accessibility from orbit
- Lighting requirements
    - Full vs. Partial exposure to sunlight
    - Necessity for battery backup
- Radiation impact and surface temperatures
- Communication and tracking requirements
- Resource utilization aspects
    - Extractable elements including iron, titanium, magnesium, aluminum, silicon and oxygen[2]
    - Level of compaction and accessibility of usable regolith quantities

Peary Crater is located closer to the lunar North Pole than any other impact crater at 88.6˚ N by 33.0˚ E. The crater is nearly circular and has a diameter of 73 km across. A lunar habitat located atop the northern rim of the crater would receive full sunlight. Temperature ranges near the poles do not fluctuate as much as they do in areas near the equator. Areas inside the crater are constantly shaded by the outer walls. More hydrogen is located at the poles of the moon which seems to indicate the unconfirmed presence of water or ice at one time. The potential of finding ice within the crater presents the opportunity for research into a sustainable supply of water, oxygen, and hydrogen [4].

Quantitative Design Constraints

According to NASA Man Systems Integration Standards, a minimum necessary space requirement to maintain performance for missions of 4 months or longer is estimated to be 20 m^3. A design volume of 120 m^3 per astronaut is recommended for incorporating both living and working quarters. Minimum total floor area required for a crew of six is estimated to be 250 m^2. The height of the base structure is recommended to be approximately 4 meters high [6].

The location specific environmental factors of Peary crater will include:

- A temperature range from -50 ± 10 degrees Celsius[10]
- Gravity that is 1.62 m/s^2 (1/6 the gravity of Earth)
- Radiation exposure of 30 to 100 rems per year
- Peary Crater is permanently lit by the Sun, light availability will not be a factor

According to the Space Biomedical Research Institute article *Humans in Space* (1995), during a solar minimum, radiation exposure levels on the moon are at 30 rems per year and during a solar maximum radiation exposure can reach levels of 100 rems per year. According to National Council on Radiation Protection, the annual limit of radiation exposure for astronauts is approximately 50 rems [11]. A lunar base must sufficiently shield astronauts from exposure above this limit.

User Requirements

Functional and Performance Requirements

Radiation Exposure Reduction:

- Adequate radiation shielding material will be required on the outer layer of the lunar base when radiation levels are in the normal range (not SEP events).

- During solar events, additional radiation protection will be required. An emergency SEP shelter located within the lunar habitat will provide additional protection to astronauts during times of increased solar activity. Because astronauts spend a significant portion of their time in space within the confines of their sleeping compartments, an ideal location for additional shielding is on walls of these compartments.

Structural Integrity:

- Materials chosen for radiation shielding must be strong enough to withstand the environmental conditions that it will be exposed to in space.
    - Temperature fluctuations
    - Impact resistance
    - Load-bearing properties

Weight:

- One of the fundamental requirements of all materials used in the lunar base is that they be lightweight. Every component of a space habitat must be designed as lightweight as possible due to launch-payload weight restrictions

Costs:

- Costs will come from:
    - Development of materials,
    - Production of base components using the materials
    - Transportation of components to the moon.
        - Transportation costs are significantly affected by the mass of the material.

Interfaces

A radiation protection system will require detection devices that will regularly monitor radiation levels within the lunar base. The system will require a user interface that will alert occupants if the shielding has been breached by excessive radiation, meteorite impact, or structural damage. Auditory and visual signals will alert astronauts if the shielding is not functioning properly. When solar events are detected either from ground control or from equipment located on the moon, the alarm is sounded and astronauts will seek shelter in the SEP emergency shelter.

A ground support interface will be used by mission support in order to ensure that astronauts' career exposure to radiation does not exceed allowable limits. The interface will track past exposure, current exposure, and predict if a future mission will result in an astronaut being exposed to too much radiation.

Environmental

In the development of a radiation shield for the lunar base, several environmental factors contribute to life span and development of the system. Environmental aspects to consider in the design include temperature, atmosphere, meteorite impacts, seismic activity, gravity, and radiation.

Light

Peary's Crater is at the North Pole where there is continuous sunlight. Also at Peary's Crater are several mountain peaks that create areas of long term darkness, but also areas of continuous illumination at the peaks [10].

It is theorized that continuous illumination, at the least, for the lunar summers and can be harnessed for solar energy resources as well as manage temperature changes by reducing the range.

Temperature

Unlike the equator of the moon, the temperature at the North Pole is steady. This feature is initiated by the constant illumination at the peaks of the mountains in the area. In particular, the temperature at the Peary Crater ranges from roughly -40°C to -60°C throughout the year [10].

The major concern with temperature fluctuations is that low temperatures will cause material brittleness, while constant changes can cause damage to the shielding material and structure by altering material proprieties [11].

Atmosphere

For practical purposes, the moon is considered to be surrounded by a vacuum because of the negligible comparison to Earth's atmosphere and other planets in the solar system. Some of the elements that compose this negligible atmosphere are [12]:

- Sodium
- Potassium
- Radon
- Argon
- Helium
- Oxygen
- Nitrogen
- Polonium

Concerns are derived again from material properties and how they interact with the atmosphere during the constructing phase of the shielding and outer structure.

- Air is required to buffer around drilling tools, this lack of air will cause high amounts heat to be generated and bits to fuse to rocks [13].
- Any demolition would cause damaging high velocity flying particles due to the lack of atmosphere to slow them down.

Meteorite Impacts

The moon is constantly bombarded by micrometeorites that could have an effect to the design of the shielding system.

- A meteoroid with a mass of about 10^{-6} grams can produce craters with a diameter of 500 micrometers in metal [14].
- The rate of micrometeorite impacts is 0.16 perforations per m^2 per day [15].

Research shows that two to three millimeters of a tough composite material is relatively successful at shielding against micrometeorites [14]. Thus, a base that has adequate radiation protection from tough composite materials will be able to withstand the impacts, but it should be clear that these impacts could still cause damages to the system. Possible solutions to prevent major damage to the radiation barriers include daily inspections to identify affected areas, a regolith layer to absorb the kinetic energy of the meteorites, and to bring extra materials to repair any damaged areas of the shield.

Seismic Activity

Although seismic activity plays a large role on Earth, the moon is relatively stable and inert because it lacks the same tectonic activity. Compared to Earth:

- the seismic energy release from a "moonquake" is only on the scale of 10^{-12} times as much
- the moon experiences roughly 500 quakes per year [9].

These lunar quakes, although infrequent, could provide potential damage to the shielding if experienced and unaccounted for due to vibrations.

Gravity

Gravity will play a significant role in the construction of the radiation shielding. Compared to the Earth, the moon only has one sixth of the gravity.

This affects material handling in the construction phase of the design because:

- the weight of materials is lower compared to their constant mass
- It changes the load capacities and stresses on the material which is another factor in a lunar base design.
- The low-G environment poses some difficulty to construction workers to maneuver and construct the shielding. [13]

Radiation

The most relevant environmental factor for the radiation shielding for a lunar base is the radiation exposure on the lunar surface. The lunar surface experiences multiple avenues of radiation that include:

- solar radiation
- cosmic radiation
- radioactive decay from the surface of the moon

Each of these sources can be broken down further into types of radiation that range from the low energy neutrons to high energy heavy ions.

This essentially provides a large spectrum of radiation protection required for all stages of the mission to protect the astronauts. Some concerns that will affect the design of a lunar base include solar flares and radiation reactions to materials used for shielding. Solar flares represent the larger end of the radiation spectrum that would have to be considered since the cycle occurs every 11 years. The frequency of flares varies from three to four per day, when the sun is particularly "active", to one a week, when the sun is particularly "quiet" [5]. Whether the sun is "active" or "quiet" depends on the current state of the solar cycle. The sun is "active" during a solar maximum and "quiet" during a solar minimum.

Most importantly, radiation also can create secondary and tertiary radiation when it impacts the material that could still penetrate the shield and cause destructive radiation exposure to the astronauts. The secondary and tertiary radiation are often more harmful than the initial radiation.

Factors contributing to the dose of radiation received:

- Time spent in the presence of radiation
- Distance from the source of radiation
- Shielding Effectiveness

Factors affecting the effectiveness of radiation shielding materials:

- Atomic and molecular cross sections
  - Density of electrons per unit volume
    - Most important factor
    - Hydrogen does well because it has the highest electron density
  - Electronic excitation energy
  - Tight binding corrections of the inner shell electrons
- Level of fragmentation of particles
  - Radiation can cause shielding nuclei to fragment
    - Secondary particles can be just as harmful as the primary
    - Hydrogen cannot fragment into other nuclei
  - Want to fragment high ion charge and energy (HZE) into smaller particles
    - The secondary particles may be easier to stop by the remainder of the material

Reliability and Safety

Reliability and safety are both important factors in the design and inception of the radiation shielding. The reliability factor will focus on the probability the shielding will last the duration of the mission. Factors included in the reliability of a lunar base structural shielding mechanism include:

- Radiation shielding effectiveness
- Structural and supportive strength
- Meteorite impact resistance

Radiation exposure calculations must be based on the shielding capabilities which are assumed to always fall within a certain range. If the exposure is greater than this range, astronauts will be exposed to levels of radiation that increase the risk of adverse effects. Testing of space radiation in a laboratory setting is very limited. Brookhaven National Laboratories in New York is home to NASA's Space Radiation Laboratories and is home to one of the only places in the world where high energy ions can be tested. In the GCR spectrum, a large component of the damage is from ions of high charge and energy (HZE) and Brookhaven Laboratories is one of the one facilities in the world that can perform experiments with high charge and energy particles.[]

Because of the difficulties involved of testing the effects of radiation passing through a material, transport coding has been developed in order to help produce more accurate models without the need for testing. Geant4 is an open source C++ based coding platform developed through the European Space Agency in order to help accurately model the effects of radiation. Determination of an approximate dose equivalent can be done using transport codes.

In order to minimize risk there needs to be redundancies in structural components and in case of complete system failure, an easy escape for the astronauts. If the structural components of a lunar base are not reliable, then the reliability of all critical systems within the base may potentially fail in the event of complete structural failure. It is therefore imperative to the sustainability of life on a lunar base that the structural and shielding components be as completely reliable as possible.

Design Evaluation Plan

The system used to evaluate and compare the project alternatives will use the following criteria and their corresponding weights:

1. Radiation Exposure Level - 50%
2. Impact Resistance - 25%
3. Technological Feasibility – 15%
4. Weight of the material - 10%

We will rank each of our alternatives based on these priorities the multiply each rank by the percentage of importance we assigned to each of them. The ranking system is as follows:

Rankings are based on a scale of one to six where:

6 - Best

5 - second best

4 - third best...etc.

Each alternative will receive a score based on the equation:

$$Score = \sum_{n=1}^{4} Ranking \times Weight\ \%$$

The design with the highest score will be chosen.

Conceptual Design

- Alternative 1: Aluminum
- Alternative 2: Hydrogen
- Alternative 3: Regolith
- Alternative 4: Lithium Hydroxide
- Alternative 5: RXF1

Alternative: Aluminum

Aluminum is a member of the boron group of elements. Aluminum is the most abundant metal on the Earth's crust and the third most abundant element. Pure aluminum is rare and applications of aluminum are typically aluminum alloys.

Aluminum is present in refinable quantities in anothosite rock deposits. Current technology presents a theoretical approach to refining the aluminum into usable alloys. Further testing of the processes involved in refining in an extreme environment must be done before astronauts' occupying a lunar base could make their own shields out of lunar aluminum.

Assessment

Radiation Reduction Rank: 2

- Aluminum is marginally effective at radiation shielding, since it has a low electron density [17].
- Aluminum shielding may be partially effective against galactic cosmic rays for lower energy ranges, but may actually make the problem worse for some of the higher energy rays (HZE) by producing secondary particles from the destruction of the nuclei of the colliding particle as well as stripping neutrons from the aluminum itself [17].
- Current estimated limits for the exposure of the blood forming organs to radiation in space would require that the aluminum to reach 50 g/cm^2 of areal density, which is the average density times the thickness [11].
- The neutrons produced throughout the material during collisions in such a heavily shielded vehicle also contribute significantly to the exposure.

Impact Resistance Rank: 4

- In comparison to the other alternatives, aluminum alloys have a high impact resistance.
- Lab results have shown aluminum alloy test shields can sustain meteorite impacts at speeds of 5.5 – 7.5 km/s.[16]

Feasibility Rank: 6

- Aluminum is considered to be the conventional spacecraft material. The main shielding and structural components of the outer walls of the International Space Station and the Space Shuttle consist of an aluminum shell. Aluminum shielding was also the primary shielding mechanism in the Mercury, Gemini and Apollo missions.

Weight Rank: 1

- The density of aluminum is 2.7 g/cm^3.
- Although aluminum is considered to be the most conventional of the alternatives, it is also considered to be the heaviest. Aluminum shielding would require excessive launch costs.

Alternative: Hydrogen

Hydrogen shields have been proposed both in gas and in liquid form. Because hydrogen can be harvested from water and the fact that technological advances of the present and future will allow the use of hydrogen as fuel for propulsion, hydrogen presents itself as a desirable option to be considered as shielding alternatives. Current technologies would require that the hydrogen be sent with the rest of the station until refined methods for its extraction on the moon are conceivable [11].

Hydrogen shields would undoubtedly require the use of some other materials to contain the gas and material. Therefore the effectiveness of hydrogen gas is innately linked to the methods and materials used to contain it.

Assessment

Radiation Reduction Rank: 6

- Hydrogen is the ideal radiation shield.
- A larger number of hydrogen atoms can fit in a small area, which results in more nuclei being placed in the way of the radiation.
- Hydrogen atoms do not have neutrons and will not produce secondary radiation particles

Impact Resistance Rank: 2

- The impact resistance of liquid or hydrogen gas is dependent on how it is contained.
- It is likely that aluminum or a similar metal would be required for the tank that contains the hydrogen. The resulting impact resistance of the system will be more susceptible to greater failure due to the fact that the tanks must be pressurized and leak proof.

Feasibility Rank: 2

- Although hydrogen undoubtedly effective at reducing radiation exposure, it "would require considerable departures from current vehicle design configurations" [11]. Transporting large quantities of liquid into space has not been tested at the scale that would be required.

Weight Rank: 2

- Designing a lunar base shielded by hydrogen would involve the transport of tens of tons of liquid hydrogen [1].
- The density is 1.08-1.3 g/cm^3, which is less than aluminum

This alternative does not require further research for this project. The amount of liquid hydrogen required to provide sufficient shielding would exceed current launch capacities.

Alternative: Regolith Shielding

Regolith is readily available on the lunar surface and can be useful in the protection of a lunar habitat.

The advantages of regolith as a shielding material are:

- Saves Launch Mass
- Saves Cost of Transportation
- Easily repairable and restore
- Flexible in design thickness [21]

On the other hand, regolith does provide some challenges in the usage of it:

- Immediate protection is not ready to install because shielding has to be built by astronauts
- Requires additional processing (digging, lifting, etc.)
- Requires usage of machinery for processing [21]

Overall, a design using regolith would be a very strong candidate for a lunar base because it is readily available on the moon. Some of the consequences can be mitigated by sending equipment to the lunar surface before the arrival of the astronauts and planning the manned missions during low solar activity.

The shielding design for regolith would be similar to an igloo design. Square cubic containers would be designed and filled with approximately 1 to 2 meters of regolith.

Based on this design, the regolith shielding is evaluated on radiation exposure reduction, structural impact resistance, feasibility, and weight to determine if it will meet the minimal requirements for the system.

Assessment

Radiation Reduction Rank: 3

From a radiation exposure reduction standpoint:

- 1 to 2 meters of thickness is sufficient to prevent radiation sickness

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

Table 1: Provides historical data of solar flares with a comparison of regolith thickness compared to predicted radiation exposure. [21]

Based on the data above, regolith passes the maximum dose exposure limit because at 1 to 2 meters thick, the radiation exposure is reduced below 50 rems.

Impact Resistance Rank: 6

From an impact perspective, for every 50 cm of regolith thickness, it is able to withstand a 20 km/s impact from a micrometeorite. Therefore, at 1 meter, the shielding can withstand impacts of up to 400 km/s for meteorites at 7 cm. This makes regolith very strong at withstanding impacts.

Feasibility Rank: 5

From a feasibility standpoint, regolith has a good potential for success. Although regolith is unable to actually stand on its own as a shielding material, it can be manipulated and formed into usable blocks of material that are 1 to 2 meters thick. Regolith alone does not bond to itself. It also lacks load bearing properties in its natural state, but can be reinforced if formed into blocks.

Once formed into compartments or blocks, regolith has several positive properties:

- It can withstand lunar temperature fluctuations
- 1 to 2 meters of thickness protects against impacts of micrometeorites
- If bonded properly, it can be a very rigid and strong in providing a base outer structure

Relatively speaking, the cost of the material is again low due to the availability on the lunar surface. Major costs will be incurred due to the transportation of machinery to process the regolith, but no additional costs would be incurred and alone, regolith has not cost on the lunar surface.

Weight Rank: 6

Based on weight factors, regolith is by far the best option since the material itself is readily available on the lunar surface. It would essentially require no payload to transport to the lunar surface, but the material does require other materials and equipment to be sent to support the building of the shielding.

For example, although there is no requirement to ship regolith to the moon, machinery would be required for processing the material. This is a payload requirement, but could again be mitigated by sending the machinery on unmanned lunar missions to deliver them.

The technology readiness of this alternative is very high. The majority of the machinery needed to process the regolith is already in existence and the regolith is very readily available on the lunar surface. Feasibility is very high for this alternative because the material is already there on the lunar surface driving down cost. In addition, the schedule of the setup can be during low solar flare activity to reduce exposure of radiation during the startup of the base.

Overall, this alternative does provide more consideration for testing because it meets all the user requirements set forth.

Alternative: Lithium Hydride

Lithium Hydride is formed by combining and treating lithium metal and hydrogen gas at high temperatures. Some characteristics and properties of the compound are:

- inorganic, colorless compound
- under normal conditions, found in a powder-like state
- useful, lightweight neutron shielding material
- used as both a coolant and as shielding in nuclear reactors
- Density: .82 g/cm^3
- Melting point: 692°C
- Solubility: reacts

Assessment

Radiation Reduction Rank [23]: 4

Lithium hydride has the highest hydrogen content of all hydrides, which means it has the highest electron density and greatest radiation shielding capabilities. In the following graph, radiation dose equivalent rates for GCR are illustrated for shield amounts from 0 to 50 grams per square centimeter:

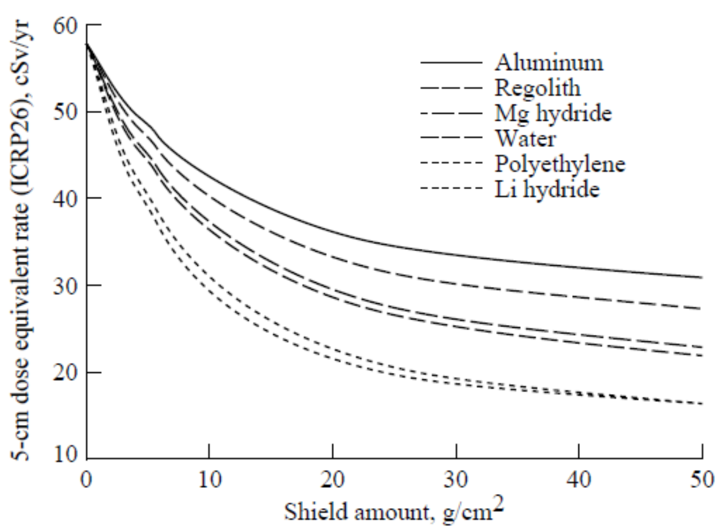

Figure 1: 5-cm depth dose for GCR at solar minimum

- As seen from the graph, lithium hydride and polyethylene have the better shielding effectiveness, with polyethylene being slightly better, due to their higher hydrogen content.
- Lithium hydride would also perform well as a radiation shield under the harsh conditions of solar flares. Lithium hydride withstands large proton fluxes due to its low electronic excitation energies and high electron density.
- These characteristics allow it to have substantially lower levels of heavy particle fluxes.

- Lithium hydride is currently in use as a radiation shielding material in nuclear reactors for neutron absorption and moderation.
- Its low secondary energetic particle production is another favorable radiation shielding characteristic.

Impact Resistance Rank [24]: 3

- From an impact resistance standpoint, lithium hydride, even when compressed, is not a good choice from an impact resistance perspective.
- Lithium Hydride's ultimate tensile strength ranges from 16.8 MPa (2437 psi) to 54.9 MPa (7962 psi) with an estimated average of 35.6 MPa.

Feasibility Rank [22]: 3

- Lithium Hydride has previously been compressed into a shielding using uniaxial compression and tension, bending, and radial compression in nuclear reactors. However, the material has not been tested in any lunar or space situations, so technological feasibility is somewhat uncertain.
- A safety hazard exists when the compound is combined with water.
    - The reaction is explosive that gives off hydrogen gas and lithium hydroxide, which is corrosive. The National Fire Protection Association rates the compound as a 2 in its Health Safety category, with 2 meaning that it is mildly dangerous.

Weight Rank [22]: 4

- Under normal conditions, lithium hydride is in a solid, powder-like form that is lightweight with a molecular weight of 7.95 g/mol.
- The compound has a density of .82 g/cm^3 which also shows that it is lightweight and would be a good choice from a weight perspective.

Overall, this alternative does not need further consideration due to the low ranking score, the possible safety hazards, and uncertain adaptability to a lunar situation.

Alternative: RXF1 Shielding

RXF1 is a recent development in materials science. So new, in fact, that the patent is still pending on this material. RXF1 is a *structural* polyethylene material. This is a major development because though polyethylene offers some of the best radiation shielding to date, it is not a structural material. RXF1 is made of 300 compressed sheets of polyethylene and a few other things that have yet to be disclosed to the public.

Some key attributes to RXF1:

- RXF1 is 2.6 times lighter than aluminum and has three times the tensile strength [20]

- On a chemical level, ethylene is the major building block of RXF1 and is comprised mostly of carbon and hydrogen atoms.
    - Hydrogen works best for Galactic Cosmic Rays (GCR) because it actually interacts with the charged particles.

- Polyethylene, when compared directly with 5 g/cm^2 of aluminum:
    - 50% better at shielding solar flares
    - 15% better at shielding cosmic rays

- Starts out as a fabric so it can be draped around molds to be shaped into any form necessary.

- The density is equal to 1.11 g/cm^3

Assessment

<u>Radiation Reduction Rank:</u> 5

Figure 2 plots the areal density (g/cm^2) versus the dose equivalent (cSv/yr) of three materials:

- Polyethylene (PE, blue line)
- RXF1 (green line)
- Aluminum (Al, red line)

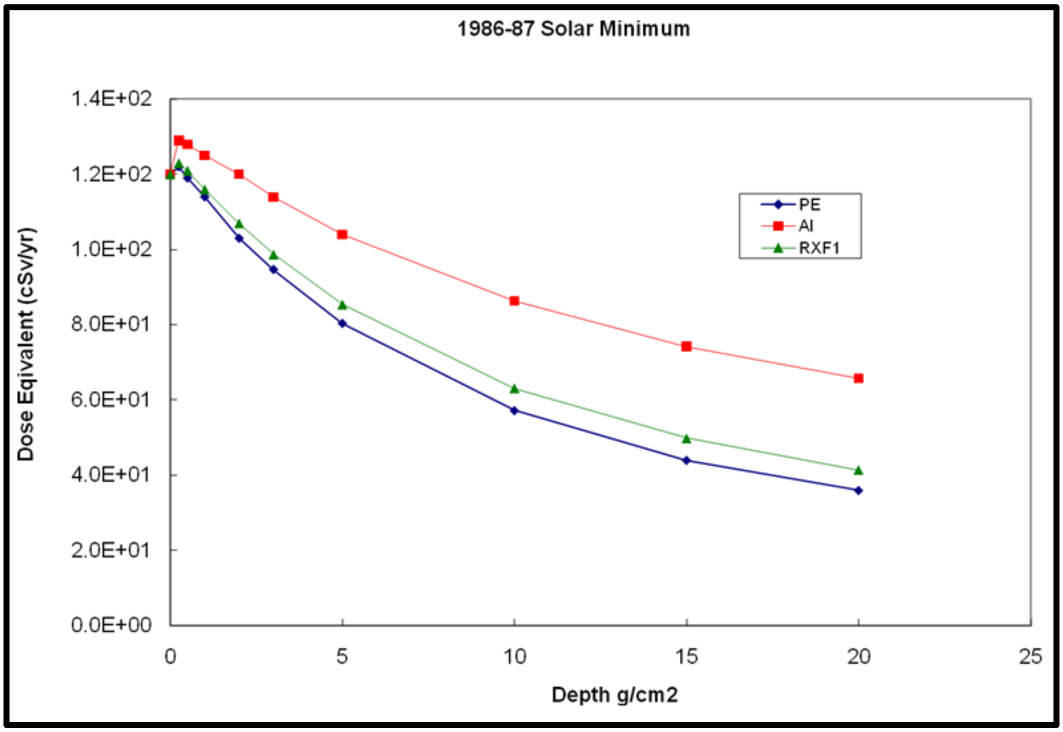

Figure 2: Dose Equivalent vs. Areal Density [19]

The figure is a great representation of how much better polyethylene and RXF1 is at reducing the dose equivalence than aluminum. According to this graph, an areal density of 15 g/cm^2 could keep the dose equivalence at the annual limit of 50 cSv/yr (or 50 rems/yr).

Impact Resistance Rank: 5

- RXF1 is a very strong material that has three times the tensile strength of aluminum.
- This material is also a ballistics material, which makes it efficient at deflecting meteorites.
  - About 0.5 cm of RXF1 can stop a 1-mm cylinder traveling 7.2 km/sec [19].

Feasibility Rank: 3

- RXF1 is currently still being patented and has yet to be mass produced.
- The goal of inventing this material was to have it ready for the Constellation program and the return of man to the moon in 2020.
- Since RXF1 is still in its infant stage, cost analysis has yet to be done on it, leaving us in the dark on its cost to develop and manufacture.

Weight: 4

- RXF1 is an extremely light-weight material, being 2.6 times lighter than aluminum.
- It has a density of 1.11 g/cm^3 [19]
    - A low density allows for more volume with less mass.
- A lighter mass means a lighter payload, which ripples down to a lower cost because less fuel would be required to launch the transport rocket.

RXF1 is definitely a material that requires further consideration for radiation shielding in our project. The benefits are tremendous and the potential is enormous. Since NASA was planning on having this material ready to go for lunar bases in 2020, this alternative requires more research and testing to come up with a solid solution in the end.

Alternative Selection

	Radiation Reduction (0.50)		Impact Resistance (0.25)		Feasibility (0.15)		Weight (0.1)	
Alternative	**Rank**	**Points**	**Rank**	**Points**	**Rank**	**Points**	**Rank**	**Points**
Aluminum	2	1	4	1	6	0.9	2	0.2
RXF 1	5	2.5	5	1.25	3	0.45	3	0.3
Regolith	3	1.5	6	1.5	5	0.75	6	0.6
LiH	4	2	3	0.75	3	0.45	4	0.4
Hydrogen	6	3	2	0.5	2	0.3	1	0.1

Figure 3: Alternative Criteria Ranking Data

Alternative	Final Score	Final Rank
Aluminum	3.1	5
RXF 1	4.5	1
Regolith	4.35	2
LiH	3.6	4
Hydrogen	3.9	3

Figure 4: Final Alternative Rankings

Figure 3 shows the individual rankings of each alternative, for each criterion. The points were determined by multiplying the rank of each alternative by the weight percentage of each criterion. Figure 4 shows the final score of each alternative calculated by the sum of the points allotted to each alternative per criterion. The Final Rank is determined from highest point value to lowest point value. According to our ranking system, the alternative using RXF1 ranked the highest, followed closely behind by the alternative using regolith.

Selected Concept Design

The highest ranking alternative is RXF1. This is a sensible option considering the structural strength of RXF1 and the amount of radiation protection it offers. Using the payload capacities of the Ares V rocket, the shape of the modules may resemble Figure 5.

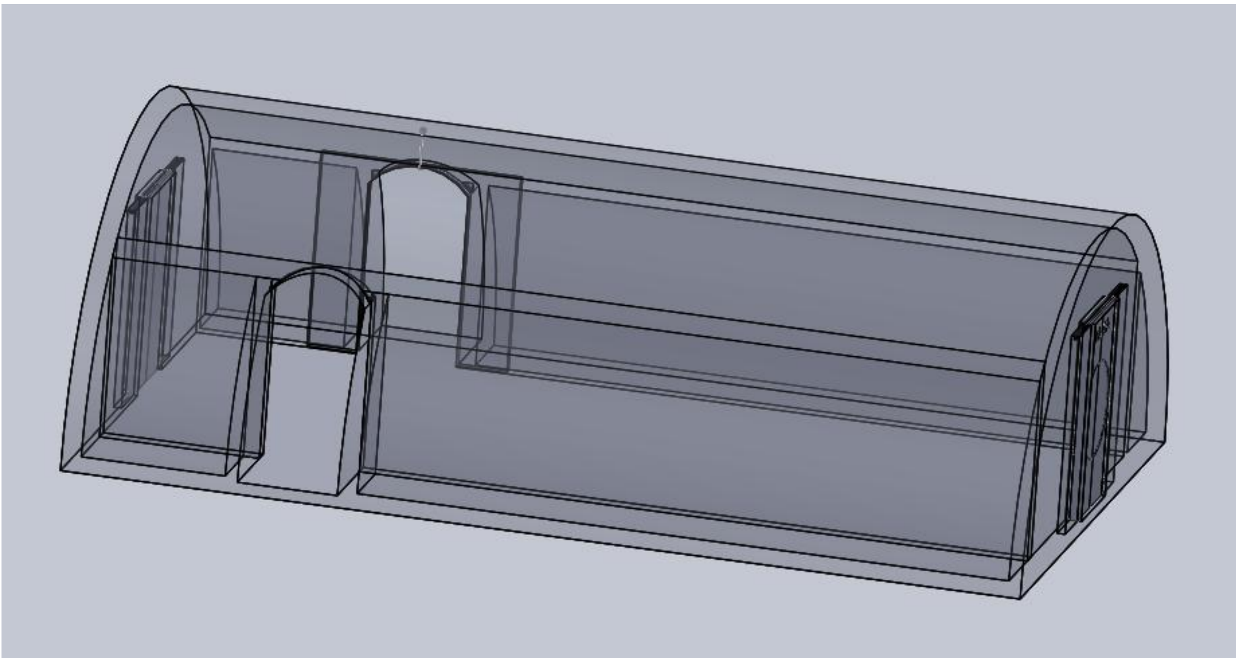

Figure 5: Lunar Module Shell

The material volume that makes up this shell is about 55 m^3. With a density of 1.11 g/cm^3, that would make the mass of this module equal to 61,050 kg which is nearly 10,000kg less the payload capacity of the Ares V rocket to Trans Lunar Injection (TLI). In fact, this module is comprised of 8 inch thick walls. The minimum thickness of RXF1 to keep the dose equivalence at 50 rems is:

$$\text{Areal Density} = \rho * \ell$$

ρ = average density
ℓ = average thickness

Using Figure 2

$$15\ g/cm^2 = (1.11 g/cm^3) * \ell$$

$$\ell = (15\ g/cm^2) / (1.11 g/cm^3)$$

$$\ell = 13.51\ cm \approx 5.32\ in$$

As calculated in the above equation, the minimum thickness is 5.32 inches. With 8 inch walls, there is room to reduce the thickness to lower the volume, to lower the mass of the module if necessary.

Ideally, once the module is on the lunar surface, the astronauts would do EVAs to begin to cover the module with regolith. While they are constructing the regolith shields, the astronauts would rely on the RXF1 to shield them from radiation. Covering the module with regolith would offer:

- Another layer of radiation shielding
- Another layer of meteorite shielding
    - This would be beneficial because it is much easier to cover a hole in the regolith caused by a meteorite, than to send an RXF1 "patch kit" with the module and have an astronaut repair the actual structure of the module.
- Insulation to reduce thermal variances

Adding the layer of regolith to the outside of the structure would reduce the amount of radiation exposure level to an insignificant amount.

Prototype and Evaluation Plan

Design of Prototype

- The outer structural and material components of a single inhabitable module will be designed
    - Structural support of radiation shielding
        - RXF1 can be used
    - Shielding Mechanism
        - RXF1
            - Compression into bricks
        - Lunar Regolith
            - Compression into bricks
            - Filling bags
            - Filling voids between structural components
- An emergency SPE shelter will be designed to protect astronauts during periods of increased radiation activity
    - RXF1 will be the primary material
    - Placement within the habitat
        - Sleeping quarters
        - Number of people to design for

Evaluation Plan

- Visit Marshall Space Flight Center and use their radiation software to run the necessary simulations based on our alternatives
    - Determine the dose equivalents and evaluate our proposed solution

If this is not authorized we will use web-based Geant 4 simulation software

- Web-based Geant 4 Simulation Software (Jared and Paul)
    - Geant4 based C++ code space radiation shielding transport platforms will be used to test the transport of radiation through RXF1 and Lunar Regolith

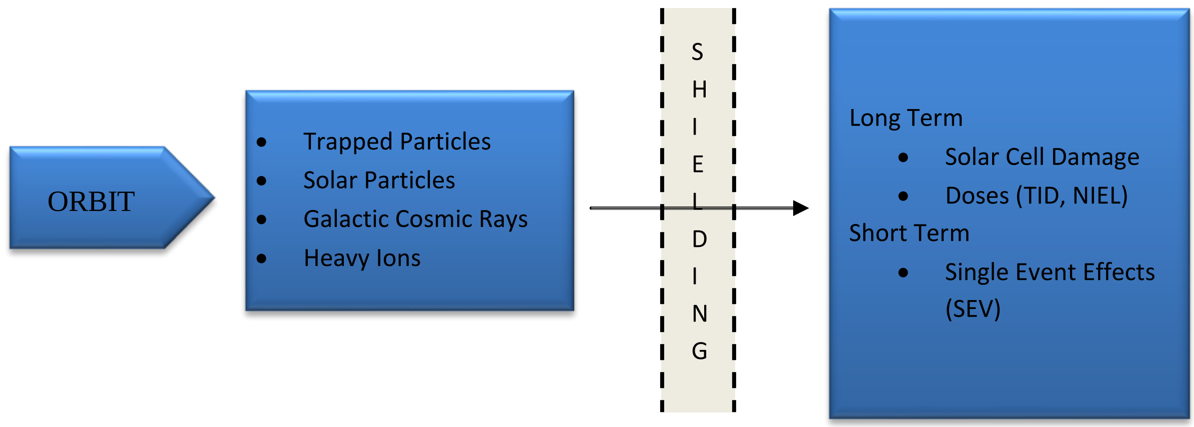

Figure 6: Radiation Simulation Input/Output Model

- Transport codes will be used to calculate the interaction and transport of radiation through materials
    - Primary Metric: Radiation Dose Equivalent (Sieverts/year)
        - Material and Design Inputs
            - Shield material
            - Shield area
            - Portion of habitable element mass effective as shielding
            - Habitable element pressurized volume
            - Habitable element mass
        - Mission architecture inputs:
            - Crew Size
            - Stay Time
            - Allowable Radiation dose equivalent
            - Storm shelter free volume per person
        - Environmental Inputs
            - Radiation Type
            - Location on moon

- Physical Mockup (Dustin and Chris)
    - Build a physical mockup of our emergency SPE shelter using the human factors lab
        - Enclose the lab using cardboard or curtains to simulate a lunar module
        - Test the subjects for a 12 to 24 hour period
        - Measure subject's :
            - comfort level
            - mental stability
            - ability to move
            - ability to maintain sufficient production levels

<u>Budget</u>

- Trip to Marshall Space Flight Center
    - LSU to MSFC – 994 miles round-trip
    - Average current gas price - $2.68/gal
    - 28 mpg
    - Total gas cost: <u>$95.14</u>
    - Hotel room for one night: <u>$150.00</u>
    - Total Cost: **<u>$245.14</u>**

- Regolith Processing Experiments
    - To do sufficient experiments, it is likely that we would need 12 cubic yards or so of dirt or sand.
    - Sand is a cheaper option
    - Load of sand runs less than <u>$50.00</u>

- <u>Miniature Model</u>
    - Building a physical model to show different regolith processes is an option for display.
    - Materials could cost <u>$100 - $300</u>

Total Estimated Cost: $595.14

****Disclaimer:** Subject to change with continued development of this project

Works Cited

1. Adams, J.H., T.A. Parnell, D.H. Hathaway, J.C. Gregory, and R.N. Grugel. United States. *Revolutionary Concepts of Radiation Shielding for Human*. Huntsville: The University of Alabama in Huntsville, 2005. (Adams, Parnell, Hathaway, Gregory, and Grugel)

2. Anderson, K. M. N. Toksöz, F. Press, A. Dainty, G. Latham, M. Ewing, J. Dorman, D. Lammlein, G. Sutton, F. Duennebier, Y. Nakamura "Lunar Crust: Structure and Composition." *Science*. 176.4038 (1972): 1012-1016. Print.

3. Benaroya, Haym, Leonhard Bernold, and Koon Meng Chua. United States. *Engineering, Design and Construction of Lunar Bases*. Chicago: Journal of Aero Space Engineering, 2002. Print.

4. Britt, Robert R. "Perfect Spot Found for Moon Base." *SPACE.com*. 13 Apr. 2005. Web. <http://www.space.com/scienceastronomy/050413_moon_perfect.html>.

5. Nealy, John E., John W. Wilson, and Larence W. Townsend. United States. *Solar-Flare Shielding With Regolith at a Lunar-Base Site*. Hampton, VA: 1988. Print.

6. Nealy, John E., and Lisa C. Simonson. United States. *Radiation Protection for Human Missions to the Moon and Mars*. Washington D.C.: 1991. Print.

7. Ruess, F., J. Schaenzlin, and H. Benaroya. "Structural Design of a Lunar Habitat." *Journal of Aerospace Engineering* July (2006): 133-57. *CE*. Web.

8. Stahl, Philip. *Ares V Launch Capability Enables Future Space Telescopes*. SPIE Proceedings 6687-17. Huntsville, AL, 2007. Print.

9. Seybold, Calina C. "Characteristics of the Lunar Environment." Aug. 1995. Web. 13 Oct. 2010. <http://www.tsgc.utexas.edu/tadp/1995/spects/environment.html>.

10. Bussey Ph. D., Ben J., Kirsten E. Fristad, Paul M. Schenk, Mark S. Robinson, and Paul D. Spudis. "Planetary Science: Constant Illumination at the Lunar North Pole." *Nature* 434 (2005). Web. 10 Oct. 2010. <http://www.nature.com/nature/journal/v434/n7035/full/434842a.html#a2>.

11. Wilson, J. W., J. Miller, A. Konradi, and F. A. Cucinotta. *Shielding Strategies for Human Space Exploration*. Publication no. 3360. Dec ed. Houston: LBJ Space Center, 1995. Print. Ser. 1997.

12. "Atmosphere of the Moon." *Atmosphere of the Moon*. Wikipedia, 24 Oct. 2010. Web. 5 Dec. 2010. <http://en.wikipedia.org/wiki/Lunar_atmosphere>.

13. O'Neill, Neil. *Building a Moon Base: Part 1 – Challenges and Hazards*. Universe Today, 1999. Web. 10 Nov. 2010. <http://www.universetoday.com/12726/building-a-base-on-the-moon-challenges-and-hazards/>.

14. Eckart, Peter. *The Lunar Base Handbook*. Second ed. Boston: McGraw-Hill Companies, 2006. Print.

15. Heiken, Grant H., David T. Vaniman, and Bevan M. French, eds. *Lunar Sourcebook: A User's Guide to the Moon*. New York: Cambridge UP, 1991. Print.

16. Campbell, P. D. *Crew Habitable Element Space Radiation Shielding for Exploration Mission*. Tech. no. NAS9-17900. Ed. J. D. Harris. Houston: Lockheed Engineering and Sciences. Print. Job Order K4-H13.

17. Noever, David A., David D. Smith, Laurent Sibille, Scott C. Brown, Raymond J. Cronise, and Sandor L. Lehoczky. *High Performance Materials Applications to Moon/Mars Missions and Bases*. Tech. 2nd ed. Vol. 34. Houston, 2005. Print.

18. Haas, Kathleen L., Francesco P. Bivona, Christopher J. Bryant, Matthew J. Fabian, Matthew J. SilvaSa, and Michael F. Scaduto. *Lunar and Near Earth-Development*. Tech. Worcester: Worcester Polytechnic Instittue, 2007. Print.

19. "RXF1 Specs." Message to Raj Kaul. 1 Nov. 2010. E-mail.

20. Barry, Patrick L., and Dr. Tony Phillips. "NASA - Plastic Spaceships." NASA, 25 Apr. 2005. Web.

21. Lindsey, Nancy J. "Lunar Station Protection: Lunar Regolith Shielding." Web. <http://www.rcktmom.com/njlworks/LunarRegolithPprenvi2.html>.

22. "Lithium Hydride, 98%." Analytyka. Oct. 2003. Web. <www.analytyka.com>.

23. United States. NASA. Shielding Strategies for Human Space Exploration. Ed. J.W. Wilson, J. Miller, F.A. Cucinotta, and A. Konradi. NASA Conference Publication, 1997. Print.

24. "Lithium Hydride." Lithium Hydride. Wikipedia, 22 Feb. 2010. Web. 5 Dec. 2010. <http://en.wikipedia.org/wiki/Lithium_Hydride>.

25. Healy, Thomas E. "Fatigue Crack Grow in Lithium Hydride" by Thomas E. Healy. Lawrence Livermore National Lab, 1993. Print.