

Radiation Shielding Materials for Extraterrestrial Construction: Integrating Regolith Derived Geopolymers and Multilayered Envelopes for Safe Human Habitation Beyond Earth

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Abstract

Human missions to the Moon and Mars expose astronauts to continuous ionizing radiation from Galactic Cosmic Rays (GCR) and Solar Particle Events (SPE). These radiation sources produce biological doses significantly higher than terrestrial safety limits and therefore represent one of the primary challenges for long-duration space habitation. Conventional shielding materials used on Earth, such as high-density metals, perform poorly in space environments because they generate secondary radiation during particle interactions. Consequently, the selection of effective radiation shielding materials for extraterrestrial construction requires a different material strategy.

This research evaluates multiple candidate materials for extraterrestrial habitat construction, including hydrogen-rich polymers, metal hydrides, and regolith-derived geopolymer systems. A comparative framework is developed using performance criteria such as radiation attenuation capability, mass efficiency, structural strength, and feasibility for in-situ resource utilization (ISRU).



Fig 1. Spacecraft being exposed to GCR and SPE

1. INTRODUCTION

Human settlement beyond Earth requires architectural systems that can sustain life in environments fundamentally different from terrestrial conditions. The absence of atmospheric protection and planetary magnetic fields exposes astronauts to continuous radiation. The extraterrestrial radiation environment consists primarily of Galactic Cosmic Rays (GCR) and Solar Particle Events (SPE), both of which produce radiation doses far above accepted safety limits for human habitation. Unshielded annual exposure in deep space environments may exceed 500 mSv, which is significantly higher than terrestrial safety thresholds for occupational exposure.

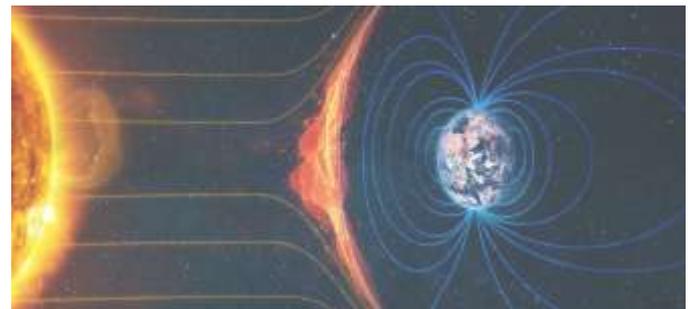


Fig 2. Earth being protected from GCR and SPE due to presence of atmosphere

These conditions create a central architectural and engineering challenge: habitats must incorporate radiation shielding directly into their material systems and structural design. Unlike Earth-based architecture, where radiation protection is rarely a design driver, extraterrestrial architecture must treat shielding as a primary constraint influencing material selection, geometry, and construction strategy.

Radiation physics demonstrates that shielding effectiveness depends strongly on the atomic composition of materials. Conventional terrestrial shielding systems rely on high atomic number (high-Z) materials such as lead due to their density and attenuation capacity. However, research on space radiation indicates that high-Z materials perform poorly against high-energy cosmic radiation. These materials generate secondary particle cascades through nuclear

spallation reactions, which can increase radiation dose behind the shield. Studies show that 20 g/cm² of lead shielding produces almost no reduction in Galactic Cosmic Ray dose, while hydrogen-rich materials significantly reduce radiation exposure.

Hydrogen-rich materials such as polyethylene, lithium hydride, and water therefore provide better shielding performance per unit mass. These materials moderate secondary neutrons and fragment heavy ions more efficiently than dense metals. However, such materials also present practical challenges. Many hydrogen-rich

materials have limited structural strength, dimensional instability, or chemical reactivity. Lithium hydride, for example, shows strong radiation attenuation performance but reacts with water vapor and requires careful encapsulation. Polyethylene demonstrates useful shielding capacity but cannot serve as a primary structural material for pressurized habitats.

At the same time, extraterrestrial missions face strict launch mass constraints. Transporting large quantities of shielding material from Earth is expensive and impractical. Launching 1 kg of payload to the lunar surface can exceed \$10,000, and transporting shielding mass for large habitats would require tens metric tons.

To address this limitation, space agencies increasingly emphasize In-Situ Resource Utilization (ISRU). ISRU refers to the use of local planetary materials for construction and resource production. Both the Moon and Mars possess extensive regolith layers composed primarily of silicate minerals. Lunar regolith contains approximately 40–50% SiO₂, 10–20% Al₂O₃, and up to 18% FeO, while Martian regolith also contains basaltic silicate minerals and localized water ice deposits.

These materials may serve as feedstock for construction processes such as geopolymerization, sintering, or additive manufacturing. Geopolymers formed from

aluminosilicate regolith can achieve compressive strengths exceeding 30 MPa, making them structurally viable building materials. Such materials also provide mass shielding against radiation.

Despite these developments, the architectural application of extraterrestrial shielding materials remains fragmented. Many studies in radiation physics evaluate materials in isolation using simplified slab geometries. Engineering research focuses primarily on spacecraft shielding rather than architectural systems. Architectural design proposals often assume generic shielding without systematic material comparison.

This research proposal addresses that gap. It aims to develop an integrated framework for selecting radiation shielding materials suitable for lunar and Martian construction. The study evaluates candidate materials across multiple criteria, including radiation attenuation performance, structural properties, ISRU feasibility, and architectural constructability. The research also investigates hybrid configurations that combine regolith-derived materials with hydrogen-rich polymers to achieve balanced performance.

By connecting radiation physics, materials science, and architectural design, this research seeks to support the development of safe and sustainable extraterrestrial habitats.

2. RESEARCH PROBLEM

Radiation exposure represents one of the most severe hazards for long-duration human presence beyond Earth. Current shielding strategies fall into two broad categories:

1. Earth-imported high-performance materials, which provide strong shielding but impose large launch mass penalties.
2. Indigenous regolith materials, which are readily available but often provide weaker shielding performance.

These approaches create a trade-off between radiation protection and construction feasibility.

The research problem can therefore be stated as follows:

Current strategies for radiation shielding in extraterrestrial habitats rely either on mass-intensive imported materials or performance-limited in-situ resources, without systematic evaluation of hybrid

configurations that optimize shielding effectiveness, structural performance, and construction feasibility.

This problem appears in three main dimensions:

2.1 Material Optimization

Hydrogen-rich materials provide superior shielding performance but lack structural strength. Structural materials such as metals and ceramics often generate secondary radiation. No single material provides optimal performance across all requirements.

2.2 Construction Feasibility

Materials that perform well in laboratory experiments may be impractical for extraterrestrial construction. For example:

- Liquid hydrogen requires cryogenic storage systems.
- Lithium hydride reacts strongly with moisture.
- Nanotube composites remain at low technology readiness levels.

These factors limit their use in architectural applications.

2.3 Architectural Integration

Radiation transport models typically evaluate flat slabs with normal particle incidence. Actual habitats require curved pressure vessels with penetrations, joints, and variable thickness. Translating material data into three-dimensional architectural configurations remains a methodological challenge.



Fig 3. Concept of Colonizing Space while dealing with radiation

3. AIM OF THE STUDY

To evaluate radiation shielding materials for lunar and Martian construction and to develop an architectural decision framework that supports effective material selection and envelope design for extraterrestrial habitats.

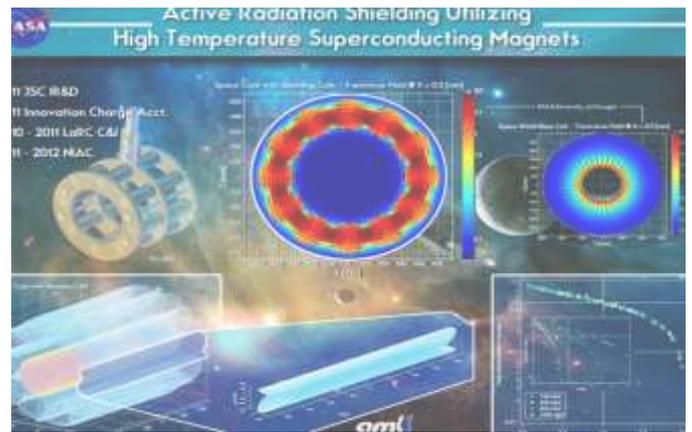


Fig 4. Radiation Protection utilizing superconducting magnets

4. RESEARCH OBJECTIVES

1. Review existing research on radiation shielding materials, including hydrogen-rich polymers, metal hydrides, and regolith-derived construction materials.
2. Develop a comparative evaluation method that analyzes candidate materials across multiple criteria.
3. Construct a ranked material database including eighteen candidate materials evaluated for shielding effectiveness, structural performance, and ISRU feasibility.
4. Identify optimal hybrid shielding systems combining indigenous and imported materials.
5. Propose architectural envelope configurations that accommodate the material properties and thickness requirements of selected shielding systems.
6. Assess construction processes suitable for implementing these materials on the Moon and Mars.

5. RESEARCH QUESTIONS

Primary Research Questions :

1. Which materials provide optimal radiation shielding performance for lunar and Martian habitats when evaluated across shielding effectiveness, structural properties, and ISRU feasibility?
2. How can hybrid material systems balance radiation attenuation, structural performance, and construction feasibility?
3. What architectural envelope geometries support the implementation of these material systems.

Secondary Research Questions :

1. What performance differences exist between geopolymers, sintered regolith, and polymer composites?
2. What construction parameters affect additive manufacturing and sintering processes on planetary surfaces?

3. How do mission parameters influence optimal material selection?

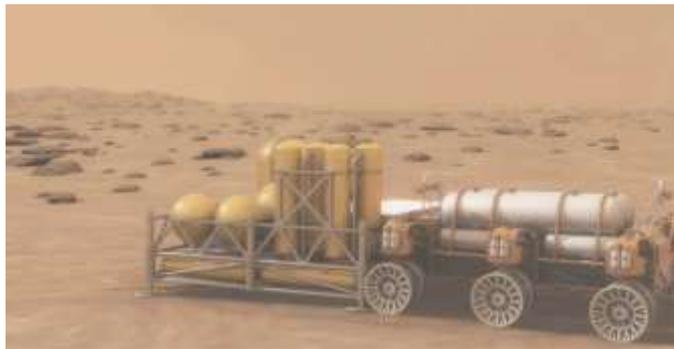


Fig 5. In-Situ Resource Utilization for Deep Space Exploration

6. HYPOTHESES

To radiation shielding Three hypotheses guide the research:

Hypothesis 1

Hybrid systems combining regolith-derived materials and hydrogen-rich polymers will outperform single-material shielding systems.

Hypothesis 2

Layer sequence in hybrid systems influences radiation attenuation performance.

Hypothesis 3

Domical and cellular envelope geometries improve constructability compared to cylindrical forms.

7. LITERATURE REVIEW

The literature reviewed in the dissertation spans nineteen primary sources including NASA technical reports, ESA research studies, and peer-reviewed journal publications. These studies focus on radiation physics, shielding materials, and extraterrestrial construction methods.

7.1 Radiation Shielding Principles

Radiation interactions with matter occur primarily through two processes:

1. Electronic stopping – energy loss through interaction with electrons.

2. Nuclear interactions – collisions with atomic nuclei that generate secondary particles.

Secondary neutron production is particularly important for high-energy cosmic radiation.

Table 1. Secondary radiation production processes

Primary Particle	Target Materials	Secondary Products	Biological Impact
Protons	High-Z materials	Neutrons and fragments	Increased biological dose
Alpha particles	Most materials	Helium fragments	Moderate dose contribution
Heavy ions	All materials	Fragmentation cascades	High biological effectiveness

These interactions explain why low-atomic-mass materials perform better in space radiation environments.

7.2 Hydrogen-Rich Materials

Hydrogen atoms effectively moderate neutrons through elastic scattering. Polyethylene contains 14.3% hydrogen by weight and approximately 7.9×10^{22} hydrogen atoms per cm^3 , making it one of the most effective solid shielding materials.

Studies comparing materials show strong performance differences.

Table 2. Example shielding performance values

Material	Dose at 20 g/cm ²
Liquid Hydrogen	~3 cSv/year
Polyethylene	~19 cSv/year
Water	~22 cSv/year

Lithium Hydride	~24 cSv/year
Aluminum	~36 cSv/year

These results demonstrate that hydrogen-rich materials reduce radiation dose more effectively than metals.

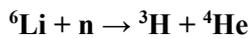
7.3 Geopolymers and Regolith Materials

Geopolymers are produced through alkali activation of aluminosilicate materials. Lunar regolith contains suitable precursors for geopolymer formation.

Typical properties include:

- Compressive strength: 20–100 MPa
- Thermal stability: above 800°C
- Moderate radiation attenuation

Lithium-activated geopolymers also absorb neutrons through the reaction:



This reaction improves shielding performance in neutron-rich environments.

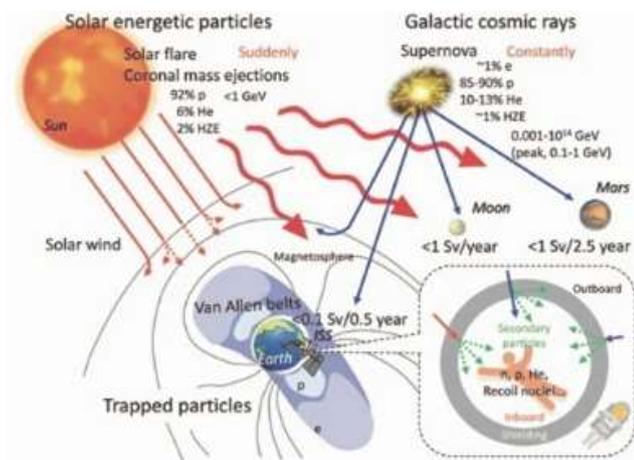


Fig 6. Components of the space radiation environment

8. ANALYTIC FRAMEWORK OF STUDY

The analytical framework of this research integrates three domains: radiation transport physics, material performance evaluation, and architectural system translation. The framework allows the study to move from raw scientific data toward design-relevant conclusions.

The dissertation adopts a multi-criteria comparative framework in which shielding materials are evaluated through a structured decision matrix. Each material is assessed across four main dimensions:

1. Radiation attenuation performance
2. Structural mechanical properties
3. In-situ resource utilization feasibility
4. Architectural constructability

This framework recognizes that radiation shielding cannot be evaluated purely through physical attenuation metrics. Materials must also support structural stability, construction practicality, and resource autonomy for extraterrestrial missions.

The analytical framework therefore operates in three stages.

8.1 Stage One: Radiation Shielding Evaluation

The first stage analyzes radiation attenuation performance for candidate materials. The analysis considers the two dominant radiation hazards present beyond Low Earth Orbit:

- Galactic Cosmic Rays (GCR)
- Solar Particle Events (SPE)

Galactic Cosmic Rays consist of high-energy ionized nuclei originating outside the solar system. Approximately:

- 85% protons
- 13% alpha particles
- 2% heavy ions (HZE particles)

Although heavy ions represent a small fraction of the total flux, they contribute disproportionately to biological damage due to their high linear energy transfer.

Solar Particle Events differ from GCR in that they occur sporadically but can deliver extremely high radiation doses over short time periods. Historical events illustrate the magnitude of this hazard.

Table 3. Radiation events discussed in the literature

Solar Event	Maximum Particle Energy	Estimated Dose in Free Space
August 1972 SPE	~4.11 Sv to blood-forming organs	Extremely hazardous

February 1956 event	~1 GeV proton energies	Major radiation event
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These radiation conditions establish the shielding requirements for lunar and Martian habitats.

The shielding performance of materials is measured through dose reduction relative to unshielded exposure.

For a given areal density m (g/cm^2), the effective dose behind shielding is expressed as:

$$D_{\text{shielded}} = D_0 \cdot e^{-\mu m}$$

Where:

D_0 = unshielded radiation dose

μ = attenuation coefficient

m = areal density of shielding material

Although this equation simplifies complex particle interactions, it captures the fundamental relationship between shielding mass and radiation attenuation.

However, space radiation shielding differs from conventional gamma radiation shielding because nuclear interactions generate secondary particles. High atomic number materials tend to produce neutron cascades that increase biological dose.

This observation forms one of the central theoretical foundations of the study.

8.2 Stage Two: Material Property Evaluation

The second stage evaluates candidate materials based on mechanical and structural properties. Radiation shielding materials must function as part of a pressurized habitat envelope, which introduces additional requirements beyond radiation attenuation.

Table 4. Structural requirements for extraterrestrial construction environments

Parameter	Earth	Moon	Mars
Surface gravity	9.81 m/s^2	1.62 m/s^2	3.71 m/s^2

Required compressive strength	~35 MPa	~6 MPa	~13 MPa
Atmospheric pressure	1 atm	vacuum	~0.6% Earth
Thermal cycling	moderate	extreme	moderate

Reduced gravity significantly lowers structural loads. A compressive strength of 6 MPa is sufficient for single-story structures on the Moon, while Martian structures require approximately 13 MPa compressive strength.

This difference allows certain materials that would be structurally inadequate on Earth to become viable building materials in extraterrestrial environments.

Material evaluation therefore includes the following mechanical parameters:

- Compressive strength
- Tensile strength
- Flexural strength
- Thermal stability
- Resistance to vacuum exposure

For example, lunar regolith geopolymers may achieve compressive strengths exceeding 30 MPa, which significantly exceeds lunar structural requirements.

These values demonstrate the structural feasibility of regolith-based construction systems.

8.3 Stage Three: ISRU Feasibility Assessment

The third stage examines the feasibility of producing construction materials using locally available resources.

In-situ resource utilization is critical for sustainable extraterrestrial construction. Transporting shielding mass from Earth becomes economically prohibitive.

The ISRU evaluation considers five factors:

- Availability of raw material feedstock
- Energy requirements for processing
- Water consumption
- Equipment complexity
- Recyclability of material systems

Table 5. Basic resource characteristics of lunar and Martian regolith

Parameter	Lunar Regolith	Martian Regolith
Dominant minerals	silicates, glass	basaltic minerals
SiO ₂ content	40–50%	high
Al ₂ O ₃ content	10–20%	moderate
Iron oxide	up to 18%	abundant
Water content	minimal	significant ice deposits

These compositions allow the production of geopolymer binders and sintered ceramic materials using planetary resources.

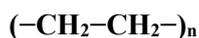
9. CANDIDATE MATERIAL SYSTEMS

The dissertation analyzes eighteen candidate materials divided into four groups.

9.1 Hydrogen-Rich Polymer Materials

Hydrogen-rich materials perform well as radiation shields because hydrogen atoms efficiently moderate neutrons and fragment heavy ions.

Polyethylene represents one of the most widely studied shielding materials. Its chemical structure is:



This structure contains approximately 14.3% hydrogen by weight and a hydrogen atom density of approximately:

$$7.9 \times 10^{22} \text{ atoms/cm}^3$$

This density approaches that of liquid water and provides strong neutron moderation capability.

Experimental and simulation studies consistently demonstrate strong shielding performance for polyethylene.

Table 6. Typical dose reduction performance

Material	Dose at 20 g/cm ² (cSv/year)
Liquid hydrogen	~3
Polyethylene	~19
Water	~22
Lithium hydride	~24
Lunar regolith	~33
Aluminum	~36

Hydrogen-rich materials outperform metals in space radiation environments.

However, polymers present structural limitations. Their tensile strength and thermal stability are often insufficient for use as primary structural materials in habitat envelopes.

9.2 Metal Hydrides

Metal hydrides store hydrogen atoms in solid form and therefore provide high volumetric hydrogen density.

Table 7. Hydrogen storage capacity of several hydrides

Compound	Hydrogen Content (wt%)	Density (g/cm ³)
Lithium hydride	12.6%	0.78
Lithium borohydride	18.5%	0.66
Magnesium hydride	7.7%	1.45
Beryllium hydride	18.2%	0.65

Lithium hydride demonstrates strong shielding performance, achieving 0.6 mSv dose equivalent at 15 g/cm² areal density.

Despite this performance, hydrides present several challenges:

- Chemical reactivity
- Brittleness
- Toxicity concerns for certain compounds

These limitations restrict their use in large-scale architectural systems.

9.3 Regolith-Derived Geopolymer Materials

Geopolymers represent one of the most promising material systems for extraterrestrial construction.

Geopolymers form through alkali activation of aluminosilicate minerals found in regolith. The reaction produces sodium aluminosilicate hydrate (N-A-S-H) gel structures.

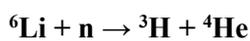
The geopolymerization process includes three stages:

1. Dissolution of aluminosilicate particles
2. Formation of reactive silicate and aluminate species
3. Polycondensation into a rigid network structure

The resulting material exhibits the following properties:

- Compressive strength between 20–100 MPa
- High thermal stability
- Moderate radiation attenuation due to mass shielding

Lithium-activated geopolymers provide additional neutron absorption capability through the reaction:



This reaction absorbs neutrons and produces alpha particles and tritium.

Experimental studies demonstrate that lithium-activated Martian geopolymers can achieve compressive strengths of approximately 30 MPa under optimized curing conditions.

9.4 Hybrid Material Systems

Because no single material satisfies all requirements, the research evaluates hybrid configurations that combine multiple material layers.

Hybrid systems aim to achieve:

- High radiation attenuation
- Structural stability
- Resource efficiency

The most promising configuration identified in the dissertation consists of:

1. Outer structural layer: regolith or geopolymer shell
2. Intermediate layer: polymer composite or hydride material
3. Inner layer: hydrogen-rich shielding layer near the crew environment

The sequencing of these layers affects radiation performance because secondary particle cascades generated in outer layers may be moderated by inner hydrogen-rich materials.

10. DECISION MATRIX AND RANKING

To compare candidate materials, the research develops a decision matrix that assigns weighted scores to each evaluation criterion.

The weighting scheme reflects the relative importance of each factor in extraterrestrial construction.

Table 8. Weighting distribution

Evaluation Criterion	Weight
Radiation attenuation	40%
Structural performance	25%
ISRU feasibility	25%
Architectural constructability	10%

Each material receives a score from 1 to 5 in each category.

The total performance score is calculated using the equation:

$$\text{Score}_{\text{total}} = \sum (w_i \times S_i)$$

w_i = weighting factor

S_i = material score in each category

This scoring method allows materials with different strengths to be compared within a unified framework.

11. ARCHITECTURAL TRANSLATION

The final stage of the dissertation translates material analysis into architectural design strategies. Material thickness requirements and structural characteristics influence the geometry of extraterrestrial habitats.

Three architectural envelope typologies emerge from the analysis.

11.1 Domicial Envelopes

Domicial forms distribute compressive stresses efficiently and reduce bending forces.

These geometries are well suited for regolith-based materials that perform best under compression.

Additional advantages include:

- Efficient structural behavior in low gravity
- Reduced material consumption
- Improved resistance to micrometeorite impacts

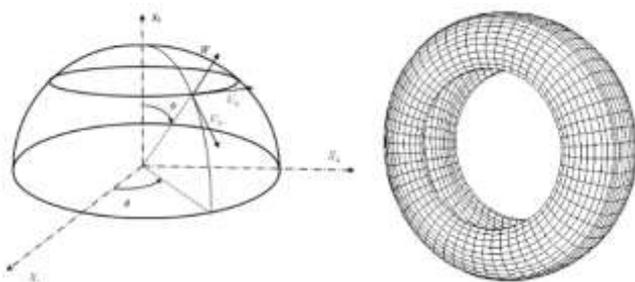


Fig 7. Spherical Shell geometry from domicial configuration

11.2 Cellular Modular Structures

Cellular habitats consist of interconnected modules forming a cluster of pressurized volumes.

This approach offers several advantages:

- Modular construction

- Redundancy in case of structural damage
- Scalability for expanding settlements

Cellular geometries also allow different material systems to be used for different modules depending on function.

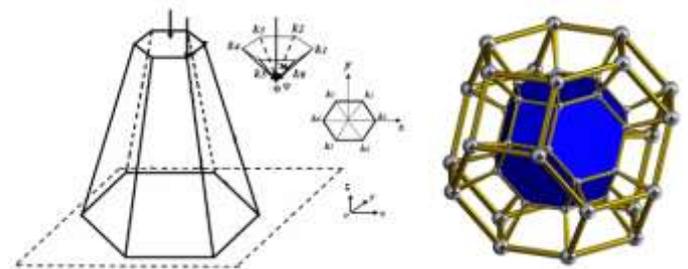


Fig 8. Hexagonal Prism geometry from cellular configuration

11.3 Layered Sectional Envelopes

Layered envelopes integrate multiple material systems within a single structural wall.

A typical cross-section may include:

- Outer regolith shell
- Polymer composite shielding layer
- Internal pressure vessel structure

This configuration allows the structure to combine the advantages of each material type.

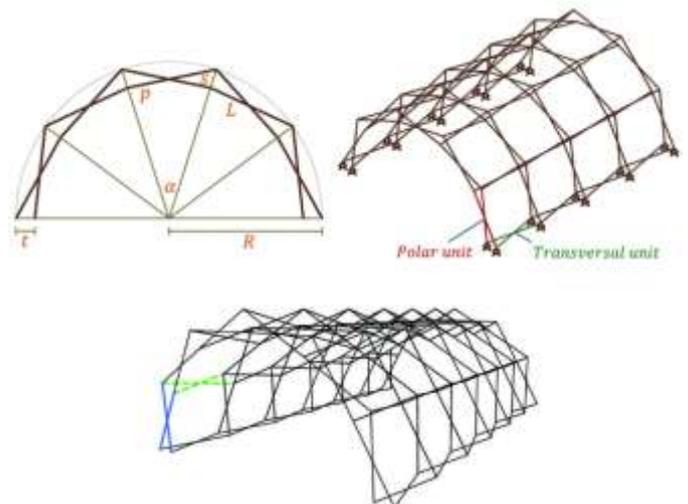


Fig 9. Barrel Vault geometry from sectional vault configuration

12. CONSTRUCTION METHODOLOGIES

The dissertation identifies three potential construction approaches for extraterrestrial habitats.

12.1 Regolith Sintering

Selective laser sintering can fuse regolith particles into solid structures.

Experimental studies demonstrate compressive strengths of approximately 1.5 MPa for sintered regolith bricks.

Although this strength is relatively low, sintered bricks may serve as protective shielding layers.

12.2 Geopolymer Additive Manufacturing

Additive manufacturing systems can extrude geopolymer mixtures to form structural shells.

Advantages include:

- Reduced construction labor
- Efficient use of local materials
- Adaptability to complex geometries

Urea extracted from human waste may serve as a superplasticizer, reducing water demand by 24–32%.

12.3 Hybrid Assembly Systems

Hybrid systems combine prefabricated modules with locally produced shielding materials.

For example:

- Inflatable habitat core
- External regolith shielding
- Internal polymer composite layers

This strategy reduces launch mass while maintaining structural reliability.

13. EXPECTED CONTRIBUTIONS

The research is expected to produce several contributions:

Material Database

A ranked dataset of candidate materials for extraterrestrial shielding.

Decision Framework

A replicable evaluation system for selecting shielding materials.

Architectural Prototypes

Envelope typologies compatible with hybrid shielding systems.

14. IMPLICATIONS

The results suggest that future extraterrestrial habitats will likely combine:

- Indigenous regolith structures
- Hydrogen-rich shielding materials
- Layered architectural envelopes

This integrated approach reduces launch mass while maintaining adequate radiation protection.

Three envelope typologies are also proposed:

Domical Structures

Advantages:

- Efficient compression distribution
- Suitable for geopolymer construction

Cellular Structures

Advantages:

- Modular construction
- Scalable expansion

Layered Sectional Envelopes

Advantages:

- Allows hybrid material layering
- Improves shielding efficiency

15. CONCLUSIONS

This research proposal addresses a central architectural challenge in extraterrestrial habitation: the development of construction materials and envelope systems capable of protecting human occupants from continuous space radiation exposure. Beyond Earth's protective atmosphere and magnetic field, astronauts are exposed to Galactic Cosmic Rays and Solar Particle Events that can produce annual radiation doses exceeding 500 mSv in unshielded conditions. These exposure levels exceed accepted safety thresholds for long-duration missions and therefore require integrated shielding strategies within habitat construction systems.

The analysis presented in this proposal demonstrates that conventional terrestrial approaches to radiation shielding cannot be directly applied to extraterrestrial

environments. Terrestrial shielding typically relies on dense materials such as lead, which attenuate gamma

radiation effectively. However, studies reviewed in the dissertation show that high atomic number materials perform poorly against high-energy cosmic radiation. Nuclear interactions between energetic particles and dense materials generate secondary neutron cascades, which may increase biological radiation dose behind the shield. Research cited in the dissertation reports that 20 g/cm² of lead shielding provides essentially no dose reduction against Galactic Cosmic Rays, while equivalent mass composed of hydrogen-rich materials significantly lowers radiation exposure.

This finding establishes a key principle for extraterrestrial shielding design: materials with lower atomic mass and higher hydrogen content generally provide better attenuation performance against high-energy particle radiation. Hydrogen-rich materials such as polyethylene, water, and lithium hydride show strong performance in comparative shielding studies because hydrogen nuclei effectively moderate neutrons and fragment heavy ions. For example, shielding simulations indicate that polyethylene at comparable areal density reduces radiation dose substantially more than aluminum or other structural metals.

However, the research also identifies significant limitations associated with these materials. Hydrogen-rich polymers generally exhibit low structural strength and may degrade under thermal cycling or prolonged radiation exposure. Metal hydrides, while offering high hydrogen density and strong shielding performance, present additional challenges related to chemical reactivity, brittleness, and handling requirements. These constraints limit their ability to function as primary structural materials within habitat envelopes.

At the same time, extraterrestrial construction must operate under strict mass constraints. Transporting large quantities of shielding materials from Earth would require extremely high launch mass. Estimates cited in the dissertation indicate that launching shielding mass to the lunar surface can cost more than \$10,000 per kilogram, and a single large habitat may require tens of metric tons of radiation shielding material.

Because of these constraints, future extraterrestrial construction systems must rely heavily on in-situ

resource utilization (ISRU). Both the Moon and Mars possess extensive regolith deposits that can potentially be used as construction feedstock. Lunar regolith contains significant concentrations of aluminosilicate minerals, while Martian regolith includes basaltic materials and

localized water ice deposits. These materials can support the production of geopolymer binders, sintered ceramic structures, and other regolith-based construction systems.

Geopolymers derived from aluminosilicate regolith represent one of the most promising material systems for extraterrestrial architecture. The geopolymerization process produces a rigid aluminosilicate network capable of achieving compressive strengths exceeding 30 MPa under optimized conditions, which exceeds the structural requirements for lunar and Martian surface structures.

Reduced gravity conditions further improve the feasibility of these materials. On the Moon, for example, a compressive strength of approximately 6 MPa is sufficient for single-story construction, meaning that regolith-derived geopolymers can easily satisfy structural requirements.

Although regolith-based materials provide structural stability and local availability, their radiation shielding performance remains lower than that of hydrogen-rich materials. Mass shielding from regolith can reduce radiation exposure, but thicker layers are required to achieve equivalent protection. As a result, relying solely on regolith materials for radiation protection may require large structural thicknesses that increase construction complexity.

The comparative analysis conducted in the dissertation therefore supports a key conclusion: no single material satisfies all requirements for extraterrestrial radiation shielding and construction simultaneously. Materials that perform well in radiation attenuation often lack structural capability, while structurally robust materials may produce secondary radiation effects that reduce shielding efficiency.

To resolve this conflict, the research proposes the use of hybrid material systems that combine the complementary advantages of different material classes. Hybrid configurations allow the structural mass of regolith-derived materials to provide mechanical

stability and bulk radiation attenuation, while hydrogen-rich materials can be incorporated within interior layers to moderate secondary radiation and improve shielding efficiency.

Layer sequencing plays an important role in the performance of hybrid shielding systems. High-density structural materials positioned on the exterior of a habitat may generate secondary particles through nuclear

interactions with incoming radiation. When hydrogen-rich materials are placed within inner layers of the wall assembly, these materials can moderate secondary neutrons and reduce the radiation dose reaching the interior environment. The dissertation suggests that such layered configurations may provide improved shielding performance compared with monolithic materials of equal mass.

Beyond material selection, the research also highlights the importance of architectural envelope geometry. Radiation shielding thickness requirements and material behavior influence the structural forms that can be constructed efficiently on planetary surfaces. Domatic structures distribute compressive forces effectively and therefore align well with the structural characteristics of geopolymer and regolith materials. Cellular modular systems offer advantages in scalability, redundancy, and phased construction. Layered sectional envelopes allow hybrid material systems to be integrated within structural wall assemblies.

Construction methodology represents another critical factor in the feasibility of extraterrestrial architecture. The dissertation identifies three primary construction strategies compatible with regolith-based materials: regolith sintering, geopolymer additive manufacturing, and hybrid assembly systems combining prefabricated components with locally produced shielding materials. Each method presents different trade-offs in terms of energy consumption, equipment requirements, and achievable mechanical properties. Additive manufacturing using geopolymer mixtures appears particularly promising because it allows structural shells to be fabricated directly from local materials while minimizing transportation mass.

Taken together, the findings of the research suggest that future extraterrestrial habitats will likely rely on integrated material systems and layered envelope architectures rather than single-material solutions.

Structural shells composed of regolith-derived geopolymers or sintered materials may provide the primary load-bearing framework, while hydrogen-rich polymers or composite materials may be incorporated into interior layers to improve radiation protection. Such hybrid systems allow the strengths of different material classes to be combined while mitigating their individual limitations.

The research also contributes to a methodological framework for evaluating shielding materials in

extraterrestrial architecture. By integrating radiation attenuation data, mechanical property analysis, and ISRU feasibility assessment within a multi-criteria decision matrix, the study provides a systematic approach for comparing candidate materials. This framework allows architects and engineers to evaluate shielding strategies according to mission-specific requirements such as crew size, mission duration, available resources, and energy constraints.

Although the research relies primarily on simulation studies and laboratory experiments using regolith simulants, the findings provide a foundation for future experimental work and habitat design development. Additional studies will be required to validate geopolymer curing processes under actual lunar and Martian environmental conditions, to investigate long-term material durability under radiation exposure, and to refine construction techniques suitable for robotic deployment.

Despite these limitations, the analysis demonstrates that architectural design, material science, and radiation physics must be addressed simultaneously when developing extraterrestrial habitation systems. Treating radiation shielding as an isolated engineering problem is insufficient for planetary surface habitats, where materials must perform multiple roles including structural support, environmental protection, and radiation attenuation.

The proposed framework therefore positions radiation shielding as a central design parameter in extraterrestrial architecture. By combining regolith-based construction systems with hydrogen-rich shielding materials in carefully designed hybrid envelopes, it may be possible to create habitats capable of supporting safe and sustainable human presence on the Moon and Mars.

This approach establishes a practical direction for future research and design development in space architecture. It suggests that sustainable extraterrestrial construction will depend not on a single optimal material but on integrated material systems, adaptive architectural forms, and efficient use of planetary resources.

17. ACKNOWLEDGEMENT

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