Radiations and micro-meteoroids protection for lunar infrastructures: regolith-filled voussoir dome

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Abstract

The next milestone of human exploration is to establish a permanent presence on the Moon, and many programs intend to develop infrastructures that will accommodate humans on the lunar surface. This objective sets different challenges such as protection against radiation and lunar environment, adapted technical solutions then need to be developed.

Current solutions for in-space radiation protection consist in using thick and heavy structures, which are viable solutions to an extent. Landing payload on the lunar surface requires lightweight structures, in-situ resource utilization is a judicious approach to address this matter. The lunar regolith is an abundant resource, offers good insulation, and protects from radiations and micro-meteoroids. Its usage drastically reduces the launch mass of a lunar infrastructure.

Several structural designs using lunar regolith in their architectures have been proposed over the past decades. Popular solutions include buried and underground habitats, while more original ideas present structures using processed regolith or complex equipment (e.g. 3D-printing). These solutions are difficult to implement due to the low technology readiness level.

A regolith-filled voussoir dome uses raw lunar regolith, in a simple and scalable concept. It is composed of multiple trapezium volumes, filled with lunar regolith, attached to one another, and forming a discretized half-sphere.
The independence of each prism makes the structure modular and facilitate the maintenance. This concept offers advantages in terms of cost and deployability compared to aforementioned systems.

Many challenges need to be addressed in order to build a lunar structure capable of accommodating humans and solutions are still under investigation. The regolith-filled voussoir dome concept intends to tackle radiation and space-environment problems in a reliable and scalable way, while enabling in-situ resource utilization to lower the overall launch mass.

Keywords: Dome, Moon, Regolith, Deployable, Radiation, Insulation

Nomenclature

α	Absorptivity of the body
ε	Emissivity of the body
λ	Thermal conductivity of the body [$W.m^{-1}.K^{-1}$]
σ	Stefan-Boltzmann constant [$W.m^{-2}.K^{-4}$]
e	Regolith layer thickness [m]
q_{out}	Heat load of the dome [$W.m^{-2}$]
q_{sun}	Sun flux [$W.m^{-2}$]
r	Dome base radius [m]
R	Thermal resistance of the dome [K/W]
T_i	Dome's interior temperature [K]
T_m	Moon surface temperature [K]
T_S	Dome's exterior temperature [K]

Acronyms/Abbreviations

BFO	Blood Forming Organs
ECLSS	Environmental Control and Life Support System
ESA	European Space Agency
GCR	Galactic Cosmic Ray
HERA	Human Exploration Research Analog
HLIS	Hybrid Lunar Inflatable Structure
ILMH	Inflatable Lunar/Mars Habitat
ISS	International Space Station
LOLA	Lunar Orbiter Laser Altimeter
MMOD	Micro-Meteoroid and Orbital Debris
NASA	National Aeronautics and Space Administration
SPE	Solar Particle Event
USA	United States of America

1. Introduction

The Moon is the only natural satellite orbiting around Earth, and it is the closest planetary-mass object from us. It does not possess any atmosphere and surface conditions are too extreme to host sustainable life without robotic enhancement. It has been of strong interest between 1962 and 1972, where the Apollo program from the USA sent several successful missions to the lunar surface, achieving the exploit of landing humans on the Moon for the first time. With the end of the Cold War, the activity on the lunar surface was greatly reduced for several years, only some robotic missions being sent.

However, recently we are witnessing a regain of interest towards exploring the Moon. An ambitious project such as NASA's Artemis program has inspired scientist and professors all over the world. There are numerous reasons for this: first of all, the Earth's satellite is a real open-air laboratory. At a time when the International Space Station is about to retire, the scientific community must find another way to conduct experiments in zero gravity and the Moon is the ideal playground. Moreover, contrary to what one might think, the Lunar soil is far from being without interest. The resources it contains are rare. There is for example Helium 3, very rare on Earth, but abundant on the Moon. It could be the fuel for future space mission, perfect for the nuclear fusion that we are trying to develop on Earth. Another important point but less abundant, the rare metals, with the many meteorites that hit the satellite, the Moon would have a small amount of rare metals. Behind these scientific reasons, the actors of the race to the Moon see above all the strategic and economic interest mainly thanks to its resources and the symbol that it represents. The first country to send men to the Moon in the 21st century will, as for the first step, make a technological demonstration to its opponents.
In an exploration aspect, thanks to its distance from Earth (around 385000 km away) and mean orbiting velocity of 3680.5 km/h [1], it is easier to launch an inhabited spaceship from the Moon, making it a major steppingstone towards Mars colonization. A habitable outpost for Moon and solar system exploration is the next major step in space engineering, this is the first time in history that humans plan to settle permanently on another celestial body. This paper is part of this Moon "colonization" and describe a concept of a voussoir dome as external shielding against lunar environment.

2. The Lunar environment

2.1. General considerations

The Lunar environment can be slightly different according to the geographic location. The Sun exposure is not the same everywhere and it has a non-negligible impact on the environment. In the frame of the Artemis program, the development of a moon base will be considered at the South pole, near the Shackleton crater. Those are the environmental conditions to consider for the voussoir dome design.

The lunar environment is hostile, without atmosphere and a small gravity (1.625 m/s^2), landing on the moon is a challenging task. In the Apollo missions, the propellant needed to land a system on the lunar surface is almost twice as heavy as the lander itself [2].
Contrary to the equatorial regions, temperatures at the South pole are less extreme. Thanks to the LOLA topography, its terrain is also well known. With a quasi-constant illumination on the crater rim (>90% of the year [3]), the average temperature in this region is 260K, with a minimum and maximum peak at 26K and 350K respectively [4].

2.2. Radiations and micrometeoroids

Without any atmosphere and magnetic field, the moon has a harsh radiative environment. Two sources must be studied for the shielding dimensioning: the galactic cosmic rays and the solar particle events.

Galactic Cosmic Ray (GCR): From outside the solar system, GCR irradiates with high energy particles GeV. The intensity of the GCR is directly linked with solar activity, during a maximum solar activity, CGR are minimum.

Solar Particle Event (SPE): The SPE are mainly composed of proton and alpha particles, and they originate from the sun, induced by solar flares. For the SPE, the energy is in MeV and varies following the sun cycle every 11 years. The maximum and minimum radiations exposures are before and after sunspot maximums. [5]

Micro-meteoroids impact on a precise location on the lunar surface has quite a low probability, but it has to be taken into account when designing a system accommodating humans.

2.3. Lunar Regolith properties

It is obvious that to gain mass, it is mandatory to use directly the lunar soil as a raw material. From analysis of different regolith samples, most grains size are from 45µm to 100µm. Those grains are the direct result of thousands of micrometeoroids impact on the moon. The density of the lunar regolith is about 1.5-1.7 g/cm^3 from 0 to 30 cm depth [6]. This property match for radiation shielding, avoiding the addition of heavy radiation shields like the structure on the ISS.

Lunar regolith is a very good insulation material thanks to his low thermal conductivity properties. Hemingway et al. [7] determined specific heats and thermal conductivity for lunar soil sample at a density of 1.3 g/cm^3.

Table 1. Thermal properties of a lunar soil at a density of 1.3 g/cm^3 [HEMINGWAY]

Temperature (°K)	Thermal conductivity (W.m^{-1}.K^{-1})	Specific Heat (J.kg^{-1}.K^{-1})
100	0.0007	275.7
150	0.0008	433.9
250	0.0011	672.4
300	0.0014	758.1
350	0.0017	848.9

3. State of the art

One of the biggest challenges of an extra-terrestrial structure aiming to shelter human life is to provide a reliable pressurized environment. In the case of a lunar system, the structure shall handle pressure difference, temperature variations, radiation, micro-meteoroids impact, and provide airtightness while accommodating airlock technologies.

In NASA’s Apollo program, the Lunar Module (LM) ascent stage, in which the astronauts resided, was primarily made of aluminum alloy, with titanium used for fitting and fasteners [2]. In addition, mylar sheets were used for thermal insulation, and an aluminum sheet for micro-meteoroids protection. Overall, the ascent stage dry mass was about 2 tons, and launched with a descent stage and propellant to land and return, the complete spacecraft launch mass was about 16 tons.

In a review of analog habitats for lunar and Martian habitats [8], C. Heinicke and M. Arnhof analyzed the different shell types of analog habitats on Earth. Depending on locations (desert, underwater...) and objectives of the structures, different choices were made. True pressure vessels like the underwater base Aquarius are made of welded steel plates, complying with the above requirements, but they are heavy and bulky. Other structures are imitated pressure vessels, meaning they cannot sustain high pressure differences. These structures are either unpressurized or simply air-tight or water-tight. Some of them aim to provide lightweight habitat solutions while facilitating manufacturing and transportation by introducing inflatable elements, such as HERA or ILMH.

This gives some insight regarding strategies to build and launch a sustainable lunar structure. The standard ways of coping with extreme conditions are to use heavy and resistant materials, however launching and landing on the lunar surface such structures is difficult and costly. Different approaches are considered such as lightweight materials or inflatable structures, but they do not sustain extreme conditions on the lunar surface.

To allow the establishment of a perennial human presence on the Moon, a performant structure combining high resistance, mass efficiency and deployment easiness must be designed. Numerous and various concepts have been proposed in the literature.

Among them, Malla & Chaudhuri [9] imagined a frame-membrane structure made of Kevlar membrane for pressurization, and aluminum frame that would be filled with regolith. The use of regolith here is an in-situ resource utilization that allows for a lighter system to launch, and provides good thermal insulation, radiation protection and micro-meteoroid protection. The finite element analysis performed enlightens good preliminary results for an efficient structure.

Mottaghi & Benaroya [10] proposed an igloo-shaped structure made of sand-casted magnesium using rapid manufacturing technologies, covered with regolith sandbags. In a detailed thermal analysis of the structure at the equator, and at the lunar South pole during night or noon, they concluded that a 3 meters regolith layer can dampen sufficiently the temperature variations between lunar day and night for the design of the thermal control system. Although regolith layers for lunar structures result in thicknesses from 30 cm to several meters depending on the studies, this shows that the use of regolith is pertinent and can be considered in the design of “Moon-deployed” systems.

This brief introduction to lunar structures and concepts underlines the main constraints to be considered: the lunar environment, the launch constraints and the deployment constraints. In an attempt to answer the need of new concepts for lunar structures, this study presents the design of an unpressurized voussoir dome concept, aiming to tackle the radiation, thermal and micro-meteoroids constraints while providing a lightweight deployable system by means of in-situ resource utilization.

4. Moon Voussoir Dome Conception Design

4.1. Radiation & MMOD analysis

The objective of this dome concept is to protect astronauts against the external lunar environment. The most dimensioning parameter to establish the thickness of the wall and then the quantity of regolith needed to fill the different elements is the maximum dose that can receive the astronauts on the moon. Without atmosphere and magnetic field, the moon surface is constantly bombarded by GCR and SPE.

The maximum radiative dose per year for Blood Forming Organs (BFO) shall be under 0.5Sv, and the dose limit for 30 days shall be under 0.25Sv (ESA's dose limits). According to the radiation study in the ESA's Moon Village report [11], the September 1859 Carrington and summer of October 1989 events are considered. The September 1859 Carrington event being extreme, only the summer of October 1989 event is considered, and a conservative value of around 50 g/cm2 of areal density is needed to comply with the 30 days dose limit. Using non-sintered regolith with a density of 1.5 g/cm3, a 40 cm layer is needed to protect against radiations (including a 20% margin).

If a system to sinter the regolith is designed, the amount of lunar soil can be divided by two. Since, the regolith is abundant and cost nothing, for a first study analysis, the regolith is not sintered in the different element of the structure.

In addition, regolith shielding also serves as a barrier against micro-meteoroids, that could threaten the life of astronauts by compromising the integrity of a lunar structure. Although there is a low occurrence rate of micro-meteoroid impact, such a shielding can be considered sufficient.

4.2. Structure

Architecture: A semi-spherical shape is chosen as structure. This geometry offers naturally multiple structural advantages and solves engineering issues like the strength and stability, the stresses on materials are inferior to 10% of their maximum strength. Furthermore, this architecture has a tremendous historical heritage, with the proof that against time, a dome can stand for centuries.

The most common dome architecture is with an assembly of triangles or hexagons. A frequency 4 geodesic dome (to fit perfectly with the ground) require 160 triangular faces of 5 different sizes. For the deployment and maintenance of the structure, a simpler architecture is mandatory. The voussoir dome is the solution, with an octagonal base profile, a complete structure only needs 33 elements, dispatched in five different sizes.

In more details, each component of the structure is a trapezium volume shape. Divided in five stages, from the base to the keystone, the size of the element decreases. In that sense, the heaviest part of the structure is at the base and lightest on the top offering a natural stability. The semi-sphere has a diameter of 5-meters, for a total volume of 33m^3.

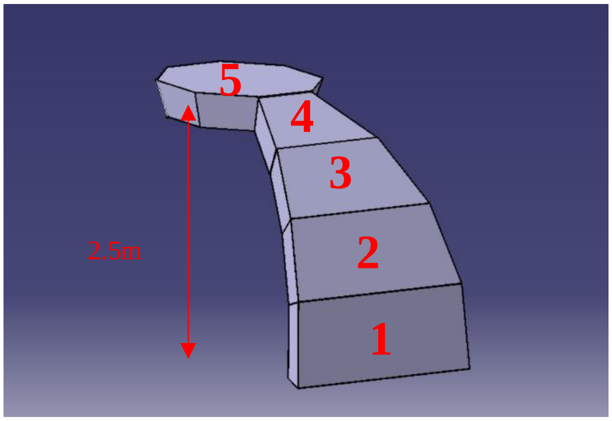

Figure 1: 1/8 Voussoir Dome skeleton (Catia)

Voussoir element design: As with an igloo, the principia is to build the dome block by block. The trapezoidal geometry offers a natural stability between each element [12]. Each block is linked with an attachment system by the teeth of a gear or dove tail. To assemble and remove the blocs, a grabbing stick is located on the back of the trapezium. The handle will be used as cork to seal the volume when it is filled with the regolith.

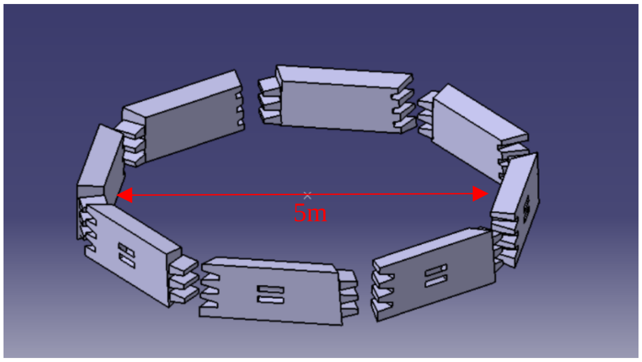

Figure 2: Voussoir Dome level 1 (Catia)

The material chosen for the envelop is aluminum with a density of 2700 kg/m^3. In the first iteration of the design, a thickness of 3 mm is considered for every boxes. With these assumptions, the biggest element in the level 1 has a mass (empty) of 47 kg for example.

4.3. Thermal analysis

A preliminary thermal analysis can be performed, only considering the radiative environment at the outer surface, and the 1-dimensional conductive fluxes within the structure. The Moon albedo and the Moon subsurface flux are neglected.

A worst case is considered, where the solar flux and Moon IR flux are received on all the outside surface with a full view factor. The solar flux received is 1361 W/m^2. The outside surface, assumed to be covered in white paint, has an emissivity of 0.91 and an absorptivity of 0.15. The radiative governing equation at the outside surface is as follows:

$$q_{out} = \sigma\varepsilon(T_S^4 - T_m^4) - \alpha q_{sun} \qquad (1)$$

Where q_{out} is the outgoing flux through a surface in W/m^2, σ is the Stefan-Boltzmann constant, ε is the emissivity of the dome, α is the absorptivity of the dome, q_{sun} is the sun flux received in W/m^2, T_S is the temperature of the outside surface of the dome and T_m is the temperature of the lunar surface.

Now considering the conduction through the dome:

$$q_{out} = \frac{T_i - T_S}{R} \qquad (2)$$

Where T_i is the inner surface temperature and R is the thermal resistance of the regolith layer. It can be defined as follows:

$$R = \frac{1}{4\pi\lambda}\left(\frac{1}{r} - \frac{1}{r+e}\right) \qquad (3)$$

Where λ is the thermal conductivity of the regolith (aluminum frame is neglected), r is the inner radius of the dome and e is the regolith layer thickness. In this case, assuming the dome is a half-sphere with a 5-meter inner diameter, R=2.583. As an example, it is assumed the inner surface is maintained at a temperature of T_i =299K. Combining and resolving equations (1) and (2) results in a surface temperature of T_S =255K.

These preliminary calculations show a good thermal insulation capability of the regolith shielding with a 46 Kelvin temperature gradient in the case of ambient temperature inside the dome.

5. Deployment

The key point of this concept is the deployment of the infrastructure. Referring to the state of the art, many technologies are already under investigation, but deployment strategies are not detailed.

Launcher integration: The main problem in the deployment of a habitable outpost on the moon is the mass that the launcher can carry to the moon and then the lander capacity to land on the lunar surface. In the concept of operation, the mass is one of the major points to consider. In the design of the voussoir dome before the deployment on the moon all the elements are empty and interlocked in in each other to limit the volume taken under the fairing, in this configuration one structure only takes 25m^3. According to the dimension of a Falcon Heavy's fairing size [13], it is possible to launch 8 domes to the moon.

Deployment on the moon: Made with aluminum the total mass to deploy on the Moon for one dome is less than 1.2 tons. With a structure light and robust, according to the future lander capacity, it is conceivable to land on the moon multiple dome structure in once. To unload the lander, not only for the structure but for every payload, a crane similar as the Canadarm on the ISS is mandatory. The idea is to use this already developed technology for the moon to gather every element of the dome. On the Moon, thanks to the low gravity, loads are less constraining, and every object weigh only 16.5% of their original mass on Earth. For the crane it means that the heaviest load to displace is equal to ~165 kg.

With 33 elements and a construction rate of 3 blocks per day, one dome is built in 11 days.

The number of equipment is limited on the moon, to perform multiple tasks with a minimum number of tools, modularity is essential. The crane used to displace the blocks is used to fill every element with the regolith. As explained in the trapezoidal volume description, one side of trapezium can be open and close, from this opening, the crane drops off the regolith inside the box. Only the extremity of the crane is modulable, then, one equipment is used for different operations. In all the concept envisaged for a moon base, the problematic of how to exploit the regolith arrives, a modulable crane is not only a solution for the voussoir dome presented in this paper, but a solution needed in every scenario.

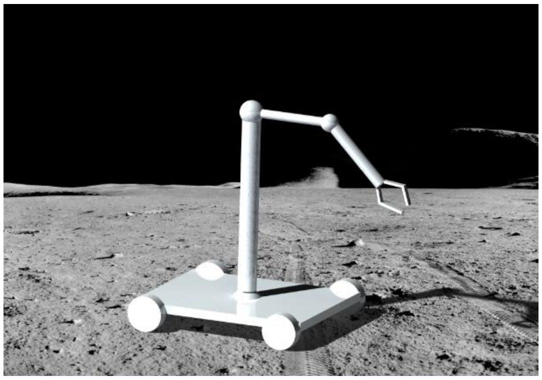

Figure 3: Crane Illustration with the grabbing hand (Catia)

6. Modules examples & adaptation

The modules on the Moon must reproduce a vital environment with ECLSS system like on the ISS. But as explained previously in the state of the art bringing a rigid and autonomous module like this one is too heavy and costly. Inflatable structures could be a solution, they are light and collapsible, easily integrable for transportation to the Moon. This is a well-known technology and industrials like BigeLow are experts in this domain. However, this kind of structure doesn't protect against radiations and micrometeoroids, or very lightly. In this context, the voussoir dome concept and an inflatable structure are complementary, one protects against external hazard (radiations, micrometeoroids), and the other one ensures habitable conditions for the astronauts.

Dronadula R. and Benaroya H. [14] proposed a concept of a Hybrid Lunar Inflatable Structure (HLIS), combining rigid elements and fabric. They put an emphasis on deployment and transportability: the structure can be folded during launch and autonomously deployed on the lunar surface, making it a mass-efficient system that answers the challenge of building a lunar outpost. The authors considered structural and deployment aspects taking into account a regolith shielding layer that is not detailed. The voussoir dome proposed in this paper can be a pertinent complementary solution with an appropriate scaling of the two systems, as it is also highly transportable and mass efficient.

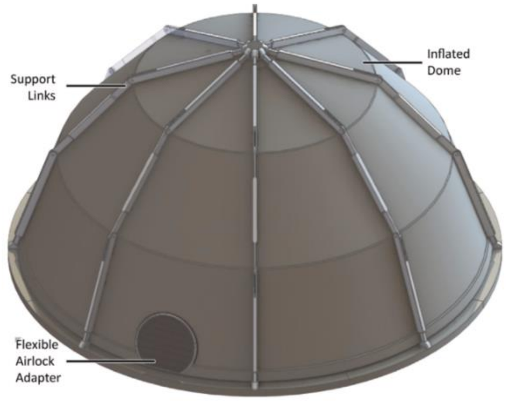

Figure 3: HLIS fully deployed with inflated and rigidized fabric dome [HYBRID]

7. Results

- Structural mass: **1234 kg**
  - Block 1: 47.16kg x 8
  - Block 2: 42.68kg x 8
  - Block 3: 34.47kg x 8
  - Block 4: 23.72kg x 8
  - Block 5: 49.87kg x 1
- Volume under the semi-sphere deployed: **33m^3**
- Volume at launch: 25m^3
- **8 domes** in one launch with a Falcon Heavy

8. Conclusions & Discussion

A regolith-filled voussoir dome structure is proposed in this paper as a conceptual solution for the radiation, MMOD and thermal constraints of a lunar building. This structure is composed of trapezoidal pieces to be filled and deployed with a robotic arm on the lunar surface.

In contrast with usual designs for space rated modules that use heavy and pre-built structures, this concept emphasizes transportability and deployability.

The thickness of 40 cm of the dome is determined by the radiative dose limits, also providing resistance to MMODs. With an octagonal base, the 5-meter diameter dome is composed of 33 elements of 5 different sizes, distributed on 5 different stages. Moreover, the low thermal conductivity of lunar regolith provides good insulation capabilities (a 46 kelvins gradient at ambient temperature inside). The deployment of the dome is made using a crane, that is used for filling the elements and assembling them remotely or autonomously, and such a structure can be combined with inflatable modules concepts.

There is a need for cost and mass efficient systems for future Moon exploration missions, and the use of in-situ resources such as non-sintered regolith helps in that regard. Contrary to 3D-printing, sand-casting, or digging concepts, this is a simpler and lightweight solution, although it needs a peculiar effort on the deployment strategy and reliability.

In this voussoir dome concept, the regolith dropped off inside the boxes doesn't need to be filtered. The lunar soil is not perfect and regular, a rock or the chemical composition of the sample collected for a 3D printing or thermal-chemical reaction can provoke failures. Without modification on the natural aspect of the regolith, a critical step in the construction is removed. Simplicity, reliability, and maintainability make this concept credible and feasible.

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