Stability Analysis and Construction of Resilient and Permanent Extra Terrestrial Habitat

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Abstract -*Years of analysis, development and research has caused the genesis of settlement on earth to a highest degree of sophistication. on the far side the protection of Earth's atmosphere, Astronomical explorers and colonists face new challenges ranging from the dearth of atmospheric pressure and element, temperature fluctuations, extraterrestrial body impacts and intense particle radiation. Countering these challenges to produce liveable conditions in extraterrestrial environments would require the foremost advanced applications of engineering and technology. So as to push possible and sustainable space exploration, these habitats are envisioned to be engineered either from satellite in situ resources or from materials on earth. The lunar lava tubes acts jointly of the key locations on the lunar surface for the development of habitats. These tubes give protection from extreme hazards like radiation, extraterrestrial body impacts and Temperature fluctuations. This subject is chosen to entails the practicableness of construction on the lunar surfaces and to debate the mode of construction utilized. This subject stress on the development of an appropriate surrounding for human habitation on the surface of the moon. The development, risks concerned, mode of exploration and numerous different factors is studied intimately and that they are appropriately analyzed in ANSYS for the practicableness and stability checks are mostly used to assess this work. These checks tested that the development of such a habitat is feasible on the lunar lava tubes within the lunar surface. We have developed the way for beginning the construction and analysis on the lunar surface for the resilient and permanent habitation of humans.*

KeyWords**: Analysis, Development, Extraterrestrial, Habitat, Resilient, Construction, Lunar**

1. INTRODUCTION

An astronomical body named Moon orbits the Earth as its only permanent natural satellite. From the beginning of humankind, there were dreams and aspiration to fabricate a habitat on the surface of other planet. This thought had a prime concern and people around the globe started working on it. On July 20, 1969, the first person stepped on the lunar surface[3]. This was a significant move contemplating the perspective of settlement of habitats in a broader way. The plan, erection and functioning of guarded and congenial livelihood is one of humanity's primordial activities. However, humanity is now fronting new challenges as we start to proceed afar the Earth surface and out into Space. In the circumstance of utmost conditions, there is much knowledge required in stretch of an approach to designing and erecting habitats that are resilient to interference, usually in the form of natural and manmade menace.

2. LITERATURE REVIEW

- GEOMETRY AND STRUCTURAL STABILITY OF LUNAR LAVA TUBES

The work done by **Theinat et al. (2018)** was reviewed. The erection of livable structures on the moon would be most effective if shielded against factors like radiation and meteoroid strikes. The paper hence majorly speaks about the geometry and structural stability of the lunar lava caves. The results of the analytical solutions presented in the paper supported the GRAIL observations that indicate the existence of large vacant substructures under the surface of the moon[2].

Geological and mechanical considerations concerning the formation of the lava tubes indicate that the sizes of the lava tubes of about 1 KM are possible. Hence the lava tubes with this size could provide potential habitats for the astronauts on the moon. Previous numerical simulations showed that the lava tubes as large as 4 km wide could remain stable with a roof thickness as small as ~40m[2]. More realistic assumptions regarding the tensile capacity of the overburden rock indicate that larger roof thickness might be necessary for the lava tube to remain stable or conversely a small overburden or small capacity of the rock in tension may require smaller sizes of the lava tubes to remain stable.

- HAZARD INVOLVED IN THE CONSTRUCTION

The work done by **H. Benaroyaet al.(2008)** was reviewed[4]. It provided a detailed investigation on the hazards involved in the lunar construction along with a brief glimpse of the structural and structural-related engineering issues for human habitation on the Moon.

Safety and reliability: Human safety and the minimization of risk to acceptable levels are always at the top of the list of considerations for any engineering project. Any structure on the moon will have six times the weight-bearing capacity as on the Earth. In order to increase the utility of ideas developed for lunar structural design, mass rather than weight-based criteria should be the approach of lunar structural engineers. The effect of radiation on the health of astronauts should also be in prime consideration. The true exposure of radiation in space may reach 7 times the Earth allowable. This radiation data brief that the regolith covering on a lunar habitat should probably be at least 50 cm to provide minimum protection. The next factor to be considered is the lunar micro and macro meteoroids. The moon surface is exposed to a stable flux of micrometeoroid particles in a range of sizes and densities. Vanzani, Mazari and Botto (2007) analyzed the NASA Long Duration Exposure Facility results to extrapolate the micrometeoroid flux hitting the lunar surface[2,10]. Their findings were dramatic. Their results predict that a lunar meteoroid flux two to three times larger than former estimates, indicating a larger risk of meteoroid impact and collision damage on the moon surface. The thermal cycling on the Moon take place in a 28 day cycle, with 14 days of intense sun and 14 days of deep, dark cold, has direct effect on the performance and quality of life for the human beings[2,10]. This cycle will affect the availability of power, and other functions in the darkness. This temperature stress suggests that the external materials for lunar habitats and bases must deliver a thermal buffer to protect the structural members from failure. This constant thermal cycling breaks regolith and rocks into smaller and smaller particles. Dust is perhaps the iniquitous problem on the moon, as it will tend to get in everywhere and to cover everything[2,10]. The lunar dust is highly abrasive, and can cause problems not only for thermal control emissive surfaces , but also for hatch seals and machines, EVA suits, and many other types of equipments.

- EXTRATERRESTRIAL CONSTRUCTION MATERIALS

The work done by **Naser (2019)** was reviewed[1]. The review aims at highlighting past and recent research efforts of non-terrestrial materials, together with their processing techniques and envisioned future research directions. Selection of material plays a key role while designing the inflatable structure. Magnesium is taken as the base material due to its availability on the lunar surface, it is abundantly available and it is the most easily machined metals and also have excellent cast ability, which enable the work easy with CNC (Computer Numerical Control) machines. Magnesium also exhibit high strength to weight ratio. As compared to aluminium and steel ,magnesium alloys have better mechanical properties. Due to its high strength and low weight the usage of magnesium is abundantly increasing. Due to the relative conductivities of aluminium and magnesium it is considered as the radiation shielding material for space applications. It also exhibits electromagnetic shielding properties due to its high conductivity and permeability. Here Kevlar 29 is used as a shielding material, as it has high strength to weight ratio, it can resist high speed impact. Elongation at break for Kevlar is considered as 3.6% so that it has high resistance to shape changes. It has a wide application in boats and the aerospace industry. It has more resistance to torque and tensile stress. Combined with other materials Kevlar is stable at higher temperature. It is more resistant to abrasion and impact damages, it is also used as fire resistant clothing and scratchproof gloves. It is an inevitable material in racing car petrol tanks. Kevlar plays a major role in reducing the weight of the vehicle and its flexibility resists the collision at high speed.

- OVERVIEW ON RESILIENT EXTRATERRESTRIAL HABITATS

The work done by **Dyke et al. (2018)** was reviewed[3]. It provided a brief overview of the view for and accomplishments to date towards the challenges of engineering permanent extraterrestrial habitats. The results of the studies were then integrated into a system resilience framework for permanent extraterrestrial habitats. This framework provides a systematic approach to designing of space structures considering their operational dependencies and disruptive/degrading conditions. Any human settlement in space will require excavation, construction and transportation of large masses of material from one place to another. Accomplishing these tasks in the Space environment, on nearly or completely airless bodies with less gravity than the Earth such as the Moon, Mars or asteroids is not beyond our current capabilities, but will require extensive planning combined with both theoretical and experimental studies long before we even begin to construct in situ pilot projects.

3. PROPOSED LOCATION

In Earth the basic natural need for habitation is availability of fresh water. Locations with extreme temperatures and climatic conditions such as deserts, polar region and volcanic mountains are not fit for settlement in Earth. Whereas in Moon, there is no atmosphere is present in it. Therefore a normal habitation is not possible in lunar surface. Extreme temperature fluctuations, solar radiations, meteoroid impacts are some of the other factors to be considered while selection of site. Topographic features of various locations on moon are:

- **THE POLES**

The two important reasons for considering poles for settlement are: First, as per the latest information, there is traces of water present in the poles of the moon. Second, there are regions such as Peary Crater in which Sun is visible throughout the year expect during lunar eclipse[7]. A potential constrain of these regions is that the inflow of solar wind can create an electrical charge on leeward side of Peary Crater rims. These may cause damage to the electrical equipment, change surface chemistry, erosion and rise of lunar dust.

- **THE EQUATORIAL REGION**

The equatorial region contains high concentration of Helium-3 which is rare on Earth surface[7]. Helium-3 is a potential fuel for nuclear fusion reactors. It is also ideal location for launching and landing of materials due to moon's slow rotation. Many probes have been landed in this region.

- **THE FAR SIDE OF THE MOON**

At far side of the moon no direct communication with Earth is possible. But with the help of communication satellite communication is possible. The far side is ideal location for radio telescope and other researches of outer space. But the far side of moon is fully exposed and thus should receive a huge amount of the ion stream

- **THE LUNAR LAVA CAVE**

The lunar lava is a tubular structure formed from path of hot, fluid, low viscosity basaltic magma which is now inactive in nature. The average size of lava cave ranges from 4.9m wide and 2.2m high to 8.6m wide and 3.8m high and extended up to tens of kilometers long[2,5]. Lunar lava tubes can act as shield from various above mentioned severe environment conditions of moon surface. This underground shelter would help to escape from the extreme temperature on the Moon's surface. In underground both in day and night the temperature would be around -23^{0}C and human can use ordinary heater[7,11].

After considering different regions in moon, the lunar lava cave should be an ideal place for the establishment of human colony. Marius Hills region of Oceanus Procellarum contains several number of lava tubes which are ideal location for constructing habitat[2,3,5]. The image of the lunar lava cave is shown below in Figure 1.

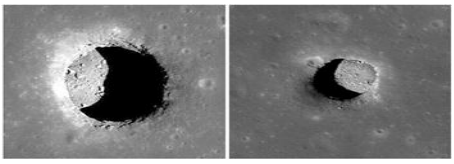

Fig. 1 Lunar lava cave (Mars Reconnaissance Orbiter, NASA, JPL, HiRISE-University of Arizona) [5]

4. ENVIRONMENTAL CONSTRAINTS OF THE LUNAR SURFACE

The constraints taken into concern are as follows:

- **Absence of atmosphere**

Lack of atmosphere is an important concern while designing the human habitat. Lunar structures must be stable enough to provide a better platform for the space travellers. It should be designed in such a way that it should sustain the catastrophic decompression. The pressure difference between the earth and the moon is the major concern. Lunar structure is a life supporting system. It provides a optimum internal pressure of 101 KPa that is earth atmospheric pressure [10].

- **Temperature fluctuations**

The surface exhibiting the extreme temperature variations such that the interior of habitat needs to be thermally isolated from the exterior environment. Extreme temperature variations may cause high fatigue stress with in the structural elements and connections due to the continuous expansion and contraction of materials [10]. So in order to prevent the loss, strong thermal protection system is needed.

- **Low gravity**

Lunar surface have gravity approx. 1/6 of that of earth's surface. Lack of gravity may reduce the self-weight of structural and non –structural members. The low gravity atmosphere is beneficial while designing the rigid and flexible members.

- **Excess radiation**

The radiation is in the form of charged ions from the solar and the cosmic sources [8]. The cosmic sources may include solar wind, solar flares, and galactic cosmic rays. Due to the lack of atmosphere the surface is bounded by harmful radiation. It can bring harm to humans and destroy the equipment. Therefore the lunar habitat outer wall must be strong enough to resist the penetration of these particles so that the infiltration can be within the permissible limit. The rate of infiltration can be reduced by proper selection of materials. Normally lunar regolith is such a material to prevent the radiation[10]. It can be used to give a surface cover on top of the structure. The comparison of radiation dosage is seen in Figure 2.

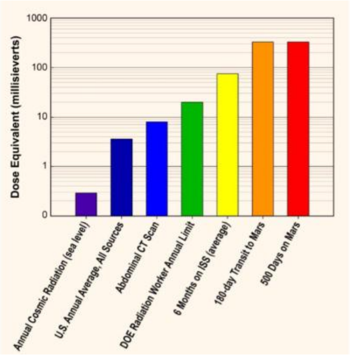

Fig. 2 Comparison of radiation dosage in different space and terrestrial environments[8]

5. MATERIALS USED

As discussed in the literature review section, there are many factors on which the material selection for our inflatable structure depend on for its selection. We have chosen an inflatable structure that is transported to the Moon and inflated there. For the foundation base upon which the inflatable will sit, we consider materials that are abundantly available on the Moon, and can be easily machined or prototyped on the Earth as well as the lunar surface, here we explore possible materials for the inflatable structure, and the foundation base that are available and feasible to build on lunar surface. The moon suface as a whole comprises of various materials that are native to its surface. They are altogether called as regolith. There are various materials in the lunar surface which can be used for the construction of future structures. The material extraction and commercial utilization seems to be the only problem looking at the Lunar soil/Regolith. Lunar regolith is the most common material available on the Moon. Relative density of regolith can be adjusted depending on the compactness of the soil particles, which is an added advantage.

Table 1 The Conventional Terms Of Relative Density[1]

Relative Density	**Description**
0-15	Extremely loose
15-35	Loose
35-65	Medium
65-85	Dense
85-100	Extremely Dense

Regolith is generally used for shielding structures from direct radiation, meteoroid impacts, and temperature variations. A minimum of 2.5 m of regolith cover is required to minimize the radiation levels[10]. Conventional terms of relative density is given in the table 1 and Average Composition of Major Materials on Lunar Surface in the table 2.

Table 2 Composition of Materials on Lunar Surface[1]

Element	O	Si	Mg	Fe	Ca	Al	Cr	Ti	Mn
Amount (wt%)	43.4	20.3	19.3	10.6	3.22	3.17	0.42	0.18	0.12

5.1. KEVLAR AS THE INFLATABLE MEMBERANE

Kevlar is a high-strength para-aramid synthetic fiber. It is developed by Kwolek at DuPont in 1965 and was first commercially used in racing tires[1]. Latterly Kevlar has become a foremost composite material used for a number of uses, from building canoes and aircraft parts, to making ballistic panels and bulletproof vests. While there are several grades of Kevlar, the most common types are Kevlar 29 and Kevlar 49.

Kevlar 29 is majorly used material for the ballistic applications. Since they have high strength to weight ratios,it can hold out against high speed collision making it a suitable material for our mode of application as we require materials with high penetration strength because of the likelihood of meteoroid strikes.

The elongation at break for Kevlar 29 is 3.6% and 2.4% for Kevlar 49, which indicates Kevlar 29 is more resistant to changing shapes[1].Kevlar 49 is used in boats and the aerospace industry. It has higher aversion to torque and tensile stresses. The properties of Kevlar 29 and Kevlar 49 are given in tables 3 and table .4.

Table 3 Properties of Kevlar 29[1]

Property	**Units**	**Kevlar 29**
Elongation at breakpoint	%	2.4
Tensile ultimate Strength	MPa	3600
Tensile Yield strength	MPa	3000
Poisson's ratio	-	0.36
Young's Modulus	MPa	112400
Density	g/cc	1.44

Table 4 Properties of Kevlar 49[1]

Property	**Units**	**Kevlar 49**
Elongation at breakpoint	%	3.6
Tensile ultimate Strength	MPa	3600

Tensile Yield strength	MPa	2920
Poission's ratio	-	0.36
Youngs's Modulus	MPa	70500
Density	g/cc	1.44

By the combination of Kevlar with other materials like a composite, it is very secure at high temperatures as it has a moderately negative coefficient of thermal expansion, like graphite. But far from graphite, Kevlar is very repellent to abrasion and impact damages. When Kevlar is combined with rubber it becomes more flexible and can be made even stronger during high-speed impacts. Kevlar is a light weight material. The disadvantage of Kevlar is that it is likely to absorb moisture and when compared with glass or graphite as it is more sensitive to the condition. To get the better of this, Kevlar is combined with moisture resistant materials. Even though it has high tensile strength, it has relatively poor compressive properties. It should be protected from direct sunlight, as it reacts badly to UV light. Kevlar undergoes some corrosion, when exposed to chlorine. Upon our assessment we have chosen Kevlar 29 as our standard of material for the use in our inflatable structure

5.2. MAGNESIUM AS BASE MATERIAL

The primary important factor for selecting the base material for foundation is that it should be copiously found on the lunar surface so that it can be contrived on the Moon after the first installation and material extraction is done. We know, magnesium is widely available in the moon surface. Magnesium is one of the most easily machined metals and has excellent cast ability, when it comes to machinability. Its alloys have high strength-to-weight ratios, particularly in alloys like AZ91, which performs better than steel[1]. With the current technological advancement, magnesium alloys have been proved to have stronger mechanical properties than aluminium and steel. Its usage in aerospace and automotive applications is increasing rapidly because of its reduced weight and high strength properties. Because of their relative conductivities of 0.36 and 0.61, respectively magnesium and aluminium are contemplated to be the radiation shielding materials for space applications[1]. Due to its conductivity and permeability, it displays strong electromagnetic shielding properties.

Magnesium is highly resistant to impact and also has 30 times the vibrational damping of aluminium, which is helpful during meteoroid impacts and moonquakes.

The main disadvantages of magnesium are; its highly reactive nature with water and oxygen. But, this is not a problem if magnesium is used on external surfaces as there is no atmosphere on the Moon. For the internal surfaces, we presume the entire magnesium structure is fastened from inside and also the alloys like AZ 91 which are more repellent to corrosion when comparing with other magnesium alloys.

Table 5 Properties of Magnesium Alloy[1]

Property	Units	Value
Tensile Yield Strength	MPa	150
Compressive Yield Strength	MPa	165
Ultimate Tensile Strength	MPa	230
Coefficient of Thermal Expansion,20°C	µm/m-°C	25
Density	g/cm³	1.81
Poisson's ratio	-	0.35
Young's Modulus	GPa	45

The lower tensile strength and fatigue strength of magnesium as compared to aluminium and other metals has fewer importance, as the Moon's gravity is only one-sixth of the Earth's gravity. The tensile strength of magnesium can be boosted by using stronger magnesium alloys. The refining of magnesium is expensive as the separation of MgO from Regolith is difficult. As there is no research focused on extraction of magnesium from lunar surface, we have only some proposed indirect methods for it. The risk of highly flammable property of magnesium and its alloys in the pure form is reduced due to the lack of atmosphere on the Moon. Properties of Magnesium Alloy is given in table 5.

5.4. ALUMINIUM AS THE INTERCONNECTOR PLATE

The inflatable membrane and the magnesium plate are connected with the help of a base plate that inter joints both the structures. It is then connected with the help of screws for further strength and stability through the plates. The properties of Aluminium plate are described in table 6. The plate thus helps in tying both the substances together thereby facilitating more stability for the structure.

Table 6 Properties of Aluminium Plate[1]

Property	Units	Value
Density	g/cm³	2.7
Tensile Yield Strength	MPa	276
Ultimate Tensile Strength	MPa	310
Coefficient of Thermal Expansion, linear 250°C	µm/m-°C	25.2
Young's Modulus	GPa	68.9
Poisson's Ratio	-	0.33

5.5. EPOXY AS THE FILLER

The Inflatable membrane is filled with epoxy to maintain puncture resistance throughout the structure. This is an important aspect as unlike air which can cause rapid depressurization and explosion Epoxy helps to contain and maintain the pressure even in the presence of small flaws which can then be rectified at the earliest. The properties of Epoxy are mentioned in table 7

Table 7 Properties of Epoxy[1]

Property	**Units**	**Value**
Young's Modulus	MPa	64.8
Tensile Yield Strength	MPa	50
Tensile Ultimate Strength	MPa	692
Density	Kg/m³	1250
Poisson's Ratio	-	0.3

6. STRUCTURAL DETAILING AND ANALYSIS

The chosen geometry of the structure is based on the Transhub concept[10]. The design is based on using Kevlar fabric for the inflatable membrane and Magnesium for the base of the structure[4]. The minimum habitable volume required per person is taken into consideration and then the model is built with an appropriate factor of safety. We have used AutoCAD and SOLIDWORKS for the design of the model. The analysis of the structure is completed using the Finite Element Software ANSYS Workbench. This is to make sure that the structure can withstand the impact of the environmental loads on the lunar surface.

6.1. ANALYSIS OF THE STRUCTURE

The literature review of this project emphasized the selection of an inflatable structure due to its High strength-to-weight ratio and also the impact of the transportation costs. The design consist of two parts namely the upper inflatable part for storage and the foundation base for the living area. The prime motive was to design the structure and hence the interior and its specified designing were kept at bay. We have used a combination of Inflatable and rigid structure. The base may be fabricated on the surface of the earth for the initial phase and once the settlement is complete it can by fabricated on-site via 3D printing.

6.2. HABITABLE VOLUME PER PERSON

The parameters defined in MARS DRM 5.0 and research trail blazed at NASA, the minimum habitable volume is 25 m^3 per person. The structure has hence taken this into account and has been suitably designed for 6 inhabitants. Considering the cost and building potentiality on the lunar surface we have concluded by finalizing the volume to be about 200m^3. That is a dome like structure with a foundation base of radius 4.5m thus providing 200m^3 of habitable after the whole structure has been completed

6.3. INFLATABLE STRUCTURE

The Inflatable structures have many advantages over the traditional rigid structures. They posses high strength to weight ratios and hence are more economical and easy to transport from the earth to the Moon. The structure designed possesses a double layered Hemispherical inflatable structure with a radius of 4.5m and the total height of the structure is supposed to by 3.3m. The design has been optimized to provide symmetry so that the stresses induced can provide equal magnitude of distribution. Although there are a very few areas with high stress concentration, this eventually doesn't affect the entire structure. Also the two layers (0.048m) with a gap (0.048m) between them which helps to hold the structure intact and rigid when inflated. Inflating the structure with air was an option but it required the use of various layers within the structure to puncture resist and strong hold the air pressure. This seemed to be expensive and impractical. Hence we chose to fill the gap of 0.048m using Epoxy as it becomes rigid once applied and can act as a puncture resistant.

6.4. BASE STRUCTURE

The Kevlar fabric has been used for the inflatable, hence we don't want to insert doorways in the fabric that will result in a high stress concentration area. Also it would be difficult to sustain the internal pressure with repeated openings of the door. Either we can make it on Earth and transport it to the Moon, which indeed will increase the cost of transportation. Else we can propose to make the magnesium support base on the lunar surface assuming we have necessary machinery available for the excavation. Ideally, we are able to send autonomous 3D printing robots that can extract and process the surface magnesium and create the base for the inflatable portion of the habitat in the coming future. The base has the same dimension as inflatable of 30 ft. diameter with a total height of 9.6 ft. (116 in). This base has the doorway for exit to the lunar surface, and a portion of step like structure/elevator by which the top inflatable can be accessed. It can also be used as a storage compartment as it has a volume of 5024 ft^3 (1532m^3).

6.5. REGOLITH SHIELDING

The designing the structure has begun by considering the extreme temperatures and radiation levels on the Moon. In order to protect the astronauts from those radiation levels and extreme temperature the lunar regolith (which is abundantly available on lunar surface) has been placed around and on top of the surface of the structure. The shielding regolith layer around the structure should be thick enough to not let the extreme temperatures touch the Kevlar fabric.

Previous studies suggest that a 2 m (6.56 ft.) or 3 m (9.84 ft.) thick regolith layer can protect the module against the extreme temperatures of about 253 °F at day and -243 °F at night [11]. Thus a 3 m thick regolith layers is provided for the initial calculations and then modify the thickness, if necessary, depending upon the results obtained from finite element analysis.

6.6. ALUMINIUM PLATE

The two parts of the structure has been modeled below. Now the challenge of fitting them together is the next task. The bolt cannot be directly screwed down the fabric to the magnesium base as it creates a high stress concentration factor and may result in tearing the fabric apart. In order to fit them together we consider using an aluminum plate where the Kevlar is tucked in between the plate and base. Also, the fabric is made in such a way that it has gaps for the bolts. Aluminum was chosen as fastener material as the regular carbon alloy fasteners might react with magnesium creating the galvanizing effect. Figure 3 presents the arrangement of plate in the interior of structure.

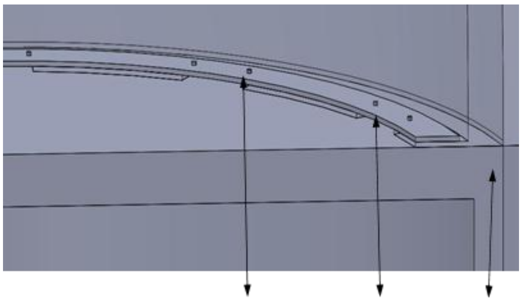

Fig. 3 Image depicting internal arrangement of aluminum plate

6.7. CAD DRAWINGS AND MODEL

SOLIDWORKS was used to draw the parts and then, the assembly feature is used to assemble multiple parts into one solid model. As discussed, the base is drawn with a radius of 4.57 m (180 in) and a wall thickness of 0.04ft (2 in). This is essentially a thin walled pressure vessel (t/r ≤ 0.1).

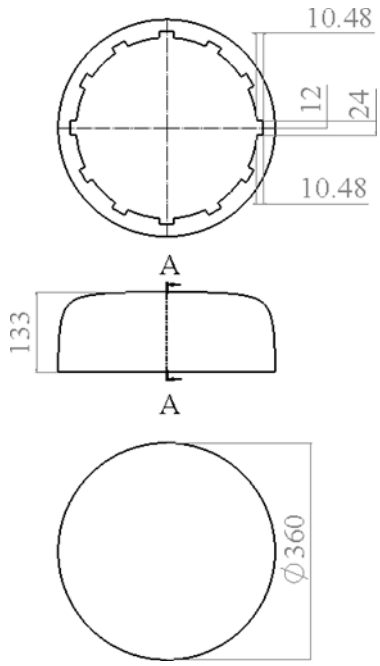

Fig. 4 CAD drawings of the structure

The thin walls in tension are more resistant to bending. The entire dimensions of the base and fabric, and the engineering drawing, are presented in Figures. All dimensions are in inches. The CAD model of the structure can be seen in Figure 4 and 5 The solid model is represented in Figure 6.

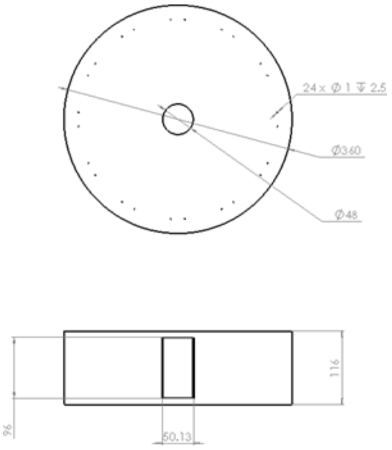

Fig. 5 Dimensions of Inflatable structure and base

Fig. 6 SOLID model of Structure

6.7. FINITE ELEMENT ANALYSIS

ANSYS Workbench (student version) is used for the finite element analysis. The analysis begun by considering the lunar structure to be fixed to the lunar surface. All interior surfaces of the Kevlar inflatable structure are subjected to a uniform internal pressure of101.35 KPa (14.7 psi). The 3 m regolith shielding placed on the structure has a bulk density of 1500 kg/m^3, which results in a uniform downward pressure of 44.05 KPa (6.39 psi). A negative acceleration of 1.63 m/s^2 (1/6th of Earth's gravitational force) is taken for the lunar gravitational force. The properties of Kevlar and magnesium are given as discussed in the materials section. Static Structural analysis in ANSYS academic version is used to run the load simulations. A triangular mesh was generated with 132,653 nodes and 88,453 elements. The generated elements are SOLID 187 and SOLID 186 type.

SOLID 187:

SOLID 187 element is a 3D, 10-node element. This element is capable of modeling plasticity, hyper elasticity, creep, stress stiffening, large deflection and large strain. It is well suited for modeling irregular meshes and has a quadratic displacement behavior.

SOLID 186:

SOLID 186 is a 3D, 20-node element. It has the same capabilities as of SOLID 187 element and has a quadratic displacement behavior. It is suitable for modeling irregular meshes.

6.8. ANALYTICAL CALCULATIONS

From figure 8 The maximum equivalent stress of 12.35 MPa acting on the structure, which is calculated by using ANSYS. The order of magnitude of stress acting on the structure is analytically calculated in order to be confident with the ANSYS results. Our inflatable structure is designed in the shape of a hemisphere, and for a hemisphere the stress acting in every direction is the same. The stress is approximated by Eq 6.1 to calculate stress acting on hemisphere

$$\sigma = \frac{P \times D}{4t}$$, Where ...Eq 6.1

D = Internal diameter of structure = 348 in

P = internal pressure = 14.7 psi

t = Wall thickness = 4 in

σ = Allowable stress

σ = 319.725 psi = 2.20 MPa

The calculated theoretical stress of 2.2 MPa, and the respective stress of 12.35 MPa results from the ANSYS simulation

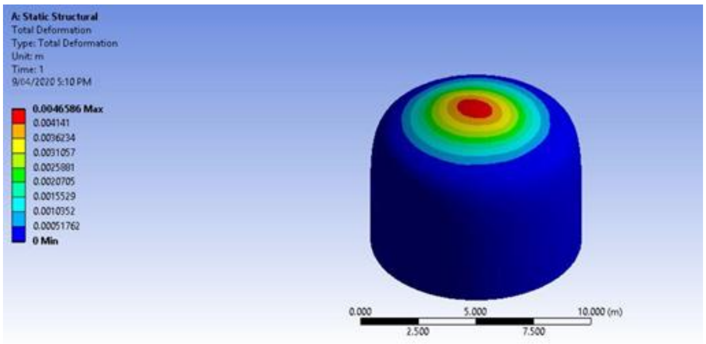

Fig. 7 Total Deformation occurring on structure

From Figures 7 and 8, we observe that the maximum deformation of the structure is 4.6 mm, which is almost negligible when compared to the strength of the material. Also, the maximum equivalent stress acting on the structure is 12.37 MPa, which is much lower than the yield strength of Kevlar at 2920 MPa.

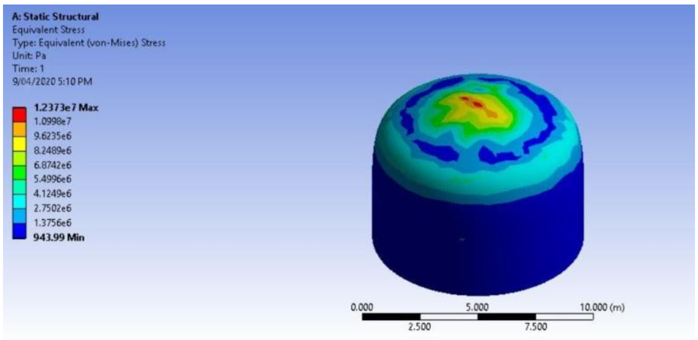

Fig. 8 Equivalent Stress acting on the structure

From the analytical calculations in Section 6.8, we can see that the maximum stress is 2.2 MPa, which is an order of magnitude smaller than the maximum stress obtained from ANSYS simulations. While the very simplified stress equation does not adequately represent the actual stress, it does give us some confidence in the simulation results.

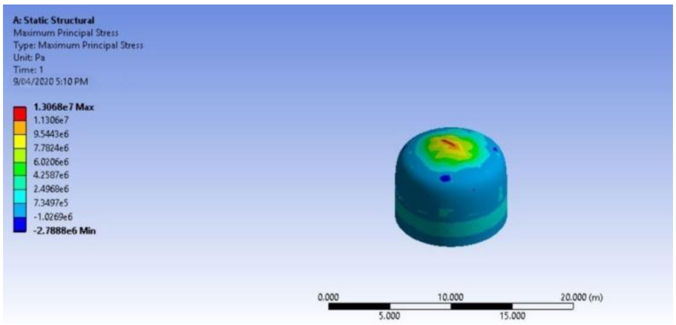

Fig. 9 Maximum Principal stress acting on structure

The maximum principal stress on the structure can be obtained from figure 9. The stress obtained is within the limit. Thus this goes in accordance with our Analysis hence proving that the structure is stable in the lunar lava cave.The Issue of the meteoroid strikes is solved to maximum of extend as we wish to place the structure inside the lunar lava cave for its habitation process. Although the structure is safe from the Meteoroid strikes, we are conducting a stability analysis for this cause to be sure in case of a meteoroid strike. Meteoroids usually travel at a speed of 26-72Km/s, but due to the pulverization of material starting at speed of km/s, we only consider the speed to be less than 6 km/s. Also, meteoroid densities range from 0.5 g/cc to 7.8 g/cc, depending on meteoroid composition. As most meteoroids are made of rocks, and also the large meteoroids are very rare, we consider meteoroids of density 1.5 g/cc. The analysis of deformation of impact of meteoroids is depicted in figure 10.

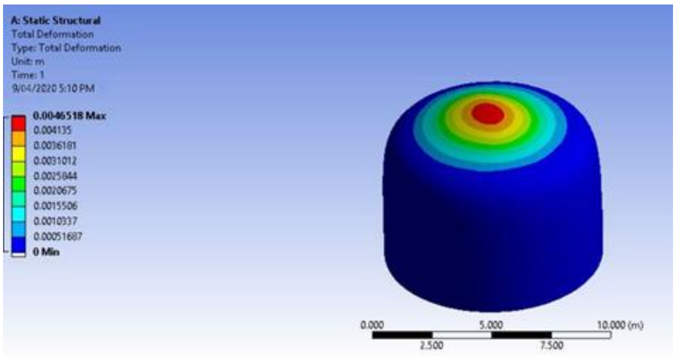

Fig. 10 Total deformation due to meteoroid impacts

The maximum size of the meteoroid our structure can sustain has a radius of approximately 250mm. This number is, of course, very approximate.

we can see that the maximum total deformation of the structure is 4.65 mm, which is almost negligible.

This impact can easily be taken by the structure as we are also providing regolith shielding for our structure. Hence it is analyzed against the impact by meteoroids is very low since we are placing the structure inside the lunar lava tube.

7.0 ENERGY REQUIREMENTS FOR HABITAT AND STORAGE

For the construction of settlement and extraction of minerals alternate power source and storage facilities are required. Many sources of energy are identified in Moon's surface such as solar energy, nuclear energy and energy derived from ISRU techniques. The major power sources and storage facilities are:

7.1. NUCLEAR POWER

A nuclear fission station can generate around 40 kilowatts of steady power which is equivalent to the energy requirement of eight houses on Earth[9]. This power plant should be buried below the lunar surface for protecting it from the meteoroid strikes and radiations. In situ resource such as Helium-3 can be used instead tritium for the potential production of fusion power.

7.2. SOLAR ENERGY

Solar energy would be less hazardous and renewable source of energy comparing to nuclear power. Many of the raw materials such as panel can be obtained from lunar surface itself. By storing energy produced can be used for long lunar night or install solar panel in places where sun available throughout the year such as Peary Crater or leave the panels in orbit and beam the power down as microwaves. The extraction of various elements from lunar surface material by focused heat technology can be done.

7.3. ENERGY STORAGE

It is difficult to store the energy than to generate. Fuel cells are being used in Space Shuttles which can be operated reliably for up to 17 earth days at a time. Therefore, fuel cell can be used for lunar night which is only 14 ¾ days. The byproduct of fuel cell is water. PEM (Proton Exchange Membrane) is the current fuel cell technology proposed by NASA because it produces considerably less heat and is lighter than the usual fuel cells[6]. Thus, PEMs would be more economical to transport from Earth. PEMs have not yet been tested in lunar surface conditions. Combining fuel cell with electrolysis would be an ideal source for electricity. Even if solar panels are installed at locations with continuous source of solar energy, they would still need fuel cell or any other alternate source to sustain during lunar eclipses and emergency situations.

8. CONCLUSIONS

The technology involved and the composite materials required for construction practices are discussed and the stability of the structure is analyzed. Based on that, various conclusions were drawn:

- A modular structure involving Hybrid Frame membrane can be sent to the moon in parts and it can be mobilized and connected together. This should have the strength and capability to withstand the extreme temperature and radiation effects.

- The placing of the structure can either be inside the lunar lava tubes or outside on the surface. If it is placed on the surface extra care has to be taken as after the long day(14 Earth days) there comes the long night(14 earth days) due to the extreme temperature it can affect the durability of the structure if not properly protected . Due to this extreme situation, a structure inside the lunar lava cave is more favourable.

- From the literature on lunar habitats, especially inflatable concepts, we have developed a new concept for a hybrid-inflatable structural habitat for the lunar surface. We have considered the choice of materials for the inflatable part of the hybrid structure, as well as the foundation base for the structure. We have developed the concept for the connection between the solid and the Kevlar. This is a challenge when working with inflatable structures.

- From our analysis, we observe that the maximum deformation of the structure is 4.65 mm, which is almost negligible when compared to the strength of the material. Also, the maximum equivalent stress acting on the structure is 12.37 MPa, which is much lower than the yield strength of Kevlar at 2920 MPa.

- From the analytical calculations in Section 6.8, we can see that the maximum stress is 2.2 MPa, which is an order of magnitude smaller than the maximum stress obtained from ANSYS simulations. Hence the structure is stable. While the very simplified stress equation does not adequately represent the actual stress, it does give us some confidence in the simulation results.

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