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Demonstration of concept for fabrication of lunar physical assets utilizing lunar regolith simulant and a geothermite reaction

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ABSTRACT

NASA's anticipated return to the Moon by 2020 and subsequent establishment of a lunar base will necessitate the development of methods to utilize lunar resources for various construction and resource extraction applications. In this study the design of a lunar physical asset utilizing in-situ resources available at the lunar surface was examined. The design incorporated a voussoir dome type of architecture that has been in use for centuries on Earth. Production of the desired dome elements was accomplished by initiating a geothermite reaction in a mixture of lunar regolith simulant and aluminum powder. Shaping of voussoir elements was accomplished during the reaction using a custom fabricated silica-slip crucible to contain the geothermite reactant mixture. The product of the reaction retained the shape of the crucible.

1. Introduction

The Constellation program of NASA intends to return humans to the Moon by 2020 [1]. Many challenges will be encountered in the lunar environment due to its vast differences from that of Earth. The atmosphere of the Moon has a pressure of $\sim 10^{-12}$ Torr, while Earth's atmosphere is 760 Torr [2]. Cosmic rays, solar wind, and meteoroids impact the lunar surface in far greater quantities than experienced on Earth due to the negligible lunar atmosphere. Utilization of in-situ lunar resources for construction and mining applications will reduce transport costs and increase the efficiency of lunar operations. Learning how to utilize in-situ resources on the Moon is critical to expanding the presence of the human race to Mars, across the solar system, and beyond.

Prior research by Faierson and Logan [3] has shown that a geothermite reaction can occur between JSC-1AF lunar regolith simulant and aluminum powder. A geothermite reaction is a reaction between minerals and a reducing agent, which exhibits a thermite-type of reaction behavior. The geothermite reaction process involves oxidation-reduction reactions between the constituents of the reactant mixture. A ceramic-composite material was produced from the reaction between regolith simulant and aluminum. Some of the major chemical species identified within the reaction product synthesized in a standard Earth atmosphere included Si^0, Al_2O_3 (corundum), $CaAl_4O_7$ (grossite), and $MgAl_2O_4$ (spinel). In addition, extensive whisker networks composed of aluminum nitrides, aluminum oxides, and/or aluminum oxynitrides were observed.

This study investigated the design of a voussoir dome type of structure for use on the lunar surface, which utilizes a geothermite reaction between lunar regolith simulant and aluminum to fabricate near net shape voussoir dome structural elements. The lunar regolith

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simulant used in this study was mined from a volcanic ash deposit in Arizona [4,5]. Two different particle size distributions of regolith simulant were used: JSC-1AF and JSC-1A. The JSC-1AF regolith simulant had an average particle size of $\sim$25 μm, and the JSC-1A simulant had an average particle size of $\sim$185 μm. Regolith simulant is composed of minerals and glass. The primary mineral component is the plagioclase solid solution series; olivine and pyroxene minerals are also present.

Many studies have been performed to develop methods to use lunar regolith as a construction material. Prior research by Toutanji et al. [6] was conducted in the synthesis of a thermoplastic material, which incorporated sulfur and was loosely termed sulfur concrete. A mixture of 65% JSC-1 lunar regolith simulant and 35% sulfur by mass was heated to 145 °C and cast into a two inch cube. Little or no chemical reactions occurred between the constituents, unlike typical concrete. The ultimate compressive strength of the material was found to be $\sim$2500 psi. Further research was conducted by Grugel and Toutanji [7] who investigated the effects of simulated lunar conditions on thermoplastic regolith simulant material. Lunar equatorial temperatures range from -180 to 123 °C, while polar temperatures range from -220 to -60 °C. Typical atmospheric pressure on the Moon is $\sim 10^{-12}$ Torr. For simulation of lunar conditions, samples were exposed to a vacuum of $\sim 10^{-6}$ Torr for 60 days. Samples were kept at room temperature and weighed periodically during the time period. Over the 60 day period samples were observed to lose 0.3 mg of mass per 1 mm^2 of surface area due to sulfur sublimation. An increase in temperature would cause a significant increase in sublimation. It was estimated that total sublimation of a 1 cm layer of pure sulfur in a 10^{-12} Torr environment would occur in 1.63 h at 120 °C and 3.7 years at 15 °C.

Melting of regolith simulant was investigated by Tucker et al. [8] for the purpose of drawing the melt and making fiberglass. The drawn glass fibers and rods would be used to reinforce lunar concrete that was made without using water, from sulfur and regolith simulant. Fibers were synthesized with diameters as small as three microns, and rods synthesized as large as $\sim$0.95 cm (3/8 in) in diameter. The glass fibers and rods were shown to increase the strength of the concrete, provided that the glass fibers were isolated from the moisture found in Earth's atmosphere. Allen et al. investigated sintering of regolith simulant using radiant and microwave heating at temperatures of 1100 °C [9]. Two different simulants were used, MLS-1 and JSC-1. The MLS-1 simulant is a titanium-rich crystalline basalt, which was processed to a particle size ranging from 1 mm to <10 μm. JSC-1 is basaltic ash that has high concentrations of glass and is similar in composition to lunar mare regions. Particles passing through a 1.168 mm sieve were used in the experiments. Hand tamping, uniaxial compaction at $\sim$310 MPa (45,000 psi), and vibrational methods (80 Hz, 3 g max acceleration over 5 min) were used to densify the MLS-1 mixture. The densification methods yielded sample porosities of 30–31%, 23–24%, and 30% respectively. Unprocessed MLS-1 had a porosity of around 40%. Inconel and porous fused silica were used as crucibles during the heating process. Thermal cracking induced by uneven heating caused by the insulating characteristics of the simulants was observed. It was found that the glass content of JSC-1 assisted in allowing more uniform sintering when compared with crystalline MLS-1. Microwave heating was found to be more difficult to control than radiant heating in controlled sintering applications due to difficulty in maintaining the sample temperature just below its melting point.

In-situ materials have been used in fabrication of terrestrial structures since the beginning of recorded history. Availability of stone materials led to development of voussoir arch and dome construction, which reached its climax during the Baroque period. A good source of information for voussoir arches and domes can be found in *The Stone Skeleton*, by Jacques Heyman. Numerous magnificent structures remain intact today even after exposure to shifting foundations, severe storms, earthquakes, and damage from wars. It has been stated that if a dome stands for 20 years, it will stand for 500 years [10]. Voussoir dome architecture was chosen for use in this study due to its historically robust structural performance and incorporation of in-situ materials. Structural elements of the dome would be comprised of regolith-derived masonry produced by a geothermite reaction. Masonry dome architecture can be used to solve engineering issues such as strength and stability, and would need to be used in conjunction with a material capable of being hermetically sealed. The masonry architecture would also provide protection from micrometeoroids and particles accelerated by launches and landings from the lunar surface. The masonry structure is not sensitive to dust and is not affected by accumulation of particles and debris over time.

Voussoir arch or dome construction typically produces stresses on materials that are less than 10% of their ultimate strength [10]. The arches and domes are compression-stabilized and can be analyzed as rigid elements relying only upon structural stability, not structural strength, as the defining design criteria. Joints can be made without mortar or other cement. Cracks do not affect their stability, evidenced by the number of cracks in historical structures.

Since the design of voussoir arches and domes relies upon static stability rather than material strength, the typical modern tools of stress analysis have limited applicability [10]. The structure and integrity of a dome is based upon force analysis and stability criteria. Stability is based upon linear geometric proportions resulting in linear scaling laws. Due to the linear relationship between stability and length scale, stable sub-scale models can be used to prove the stability of the full-scale structure. The design of voussoir domes utilizes three fundamental assumptions for classical masonry construction: masonry has no tensile strength, stresses are low enough that the masonry can be considered to possess infinite compressive strength, and failure by sliding does not occur [10,11].

Voussoir dome construction can potentially be achieved with material derived from a regolith simulant-aluminum geothermite reaction for a number of reasons:

1. Relatively low strength materials can be utilized to produce a strong, stable structure.
2. Assembly of large structures can be accomplished using small elements (blocks).
3. Blocks can simply be stacked in the correct order to build a stable structure.

2. Experimental

The most simple dome geometry having a semi-spherical shape and uniform wall thickness was analyzed within this study. It is possible that more complex dome shapes are superior in form and/or function; however, the intent was to show feasibility of the voussoir dome construction method.

Variations in regolith composition on the lunar surface may result in variations in mechanical properties of the geothermite reaction product. An analysis was performed to determine sensitivity of the structure to variations in material strength, as well as assembly under conditions of lunar gravity. Reaction loads at the base of the dome were also determined for a candidate structure. A numerical analysis demonstrated design feasibility.

A representative dome structure was designed, and geometries of voussoir elements were determined. Since each level of the assembly required a unique voussoir shape, the demonstration structure was limited to five levels. The dome was approximated by an octagonal shape; and a total of 33 voussoir elements were needed for a complete model structure. Details such as intersecting vaults for ingress/egress were eliminated for simplicity. The resulting structure and voussoir elements are shown in Figs. 1 and 2, respectively.

A silica crucible was developed for level V1 and was used to fabricate net shape voussoirs. A mock-up model of a voussoir element was created from wood. Polyvinyl chloride (PVC) was vacuum molded to form a negative shape of the wood voussoir element. The PVC closely reproduced the wood block geometry during molding as shown in Fig. 3. The shaped PVC mold was then used to create a Plaster of Paris mold for use in slip casting the crucible. The fired silica crucible is shown in Fig. 4.

A mixture of 67 wt% regolith simulant and 33 wt% aluminum with a total mass of 250 g was created. The aluminum powder used for the reaction had a particle size of -325 mesh. The mixture of regolith simulant and aluminum was poured into the silica crucible. Reactions were performed with JSC-1AF and JSC-1A regolith simulant; and NiCr wire lengths of ~66 cm (26 in) and ~86 cm (34 in) were used to initiate the reactions. The NiCr wire

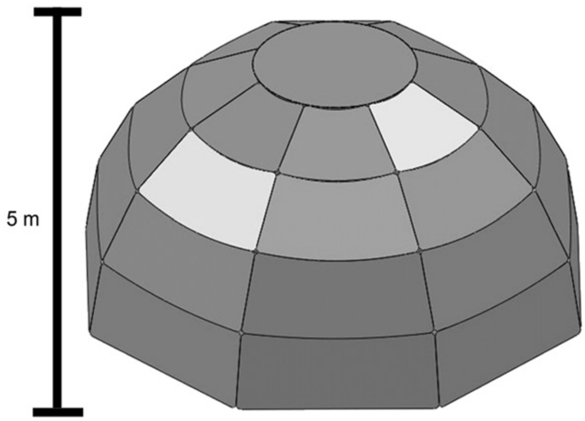

Fig. 1. Voissoir structure.

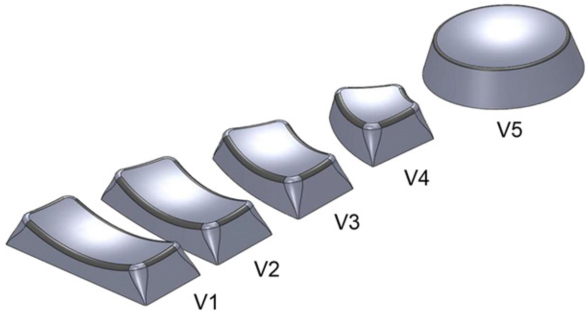

Fig. 2. Voissoir elements.

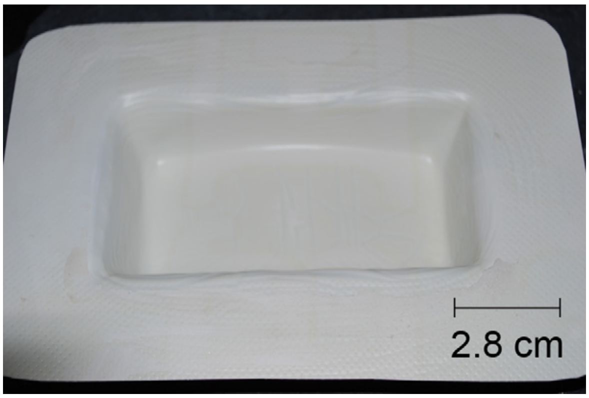

Fig. 3. Vacuum molded PVC shape used for creating the Plaster of Paris mold.

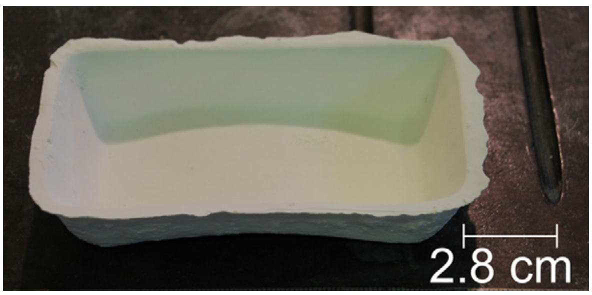

Fig. 4. Silica-slip crucible after firing at 1200 °C.

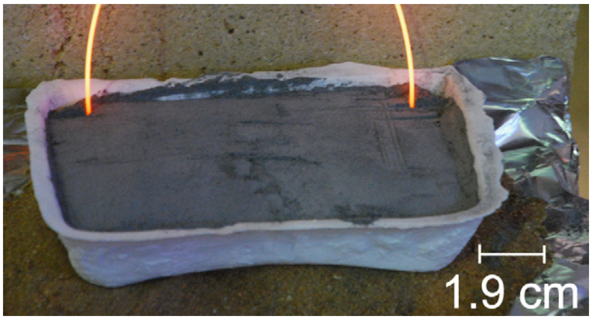

Fig. 5. Heating of regolith simulant and aluminum powder mixture contained in a fused silica crucible.

was folded in a waffle pattern and immersed in the mixture. The surface of the reactant mixture was smoothed prior to application of electric current. The ends of the NiCr wire were connected to a Variac power supply that was used to induce current flow within the wire. The electrical current was increased gradually to the final current setting over a period of 7–12 min (see Fig. 5). The electric current supplied at reaction initiation ranged from ~18 to 24 A; and reaction initiation occurred between 7 and 15 min after the initial application of current. Reactions were performed in a standard atmosphere.

In order to measure compressive strength of the geothermite reaction product, cylindrical samples were fabricated utilizing a cylindrical crucible made from aluminum foil. The cylinders had dimensions of ~5 cm in height and ~2.5 cm in diameter. The ends of the reaction product were leveled using a ceramic tile saw with a diamond blade. An Instron 4468 with a 50 kN load cell was used to perform compressive strength testing. Platen displacement was set to a rate of 1 mm/min.

3. Results and discussion

The three fundamental assumptions used in the design of voussoir domes were discussed earlier. The assumptions were that masonry has no tensile strength, stresses were low enough that the masonry was considered to possess an infinite compressive strength, and that sliding failure did not occur.

The first assumption, while slightly conservative, is consistent with stone construction with or without mortar. Cracking occurs under tension; and evidence abounds regarding cracked, yet fully functional masonry structures. Design of the proposed structure assumes that no mortar would be used in the joints.

The assumption of strength was checked by determining the height by which a vertical column would be crushed under its own weight. Experimental data from compressive strength tests indicated that ultimate strengths typically ranged from ~10 to 18 MPa, depending on the particle size of the regolith simulant and the proportions of aluminum and regolith simulant used in the synthesis process. A hypothetical regolith-derived element with compressive strength of 13.8 MPa at the lunar equator was used in the subsequent equation: (See Appendix A: Nomenclature for variable definitions.)

$$\sigma = \frac{P}{A} = \frac{\rho g_l V}{A} = \frac{\rho g_l \cancel{A} h}{\cancel{A}} = \rho g_l h \tag{1}$$

Solving for the limiting height h,

$$h = \frac{\sigma}{\rho g_l} = \frac{13.8 \times 10^6 \frac{N}{m^2}}{\left(2000 \frac{\mathrm{kg}}{\mathrm{m}^3}\right)\left(1.62 \frac{\mathrm{m}}{\mathrm{s}^2}\right)} = 4259\,\mathrm{m} \tag{2}$$

Eq. (2) indicates that structures up to 4259 m in height could support their own weight using the product of the geothermite reaction as construction material. It is presumed that most structures would be less than 10 m in height, representing a compressive stress less than 0.2% of the regolith bricks. Validity of the second assumption was demonstrated in the equations above, and also shows masonry regolith construction is tolerant of wide variations in material strength of the geothermite reaction product. Acceptance testing of individual voussoir elements is straightforward, and allows for latitude in numerous processing variables.

The third assumption relies upon friction to lock the elements together. In a terrestrial environment, the gravity of Earth is usually sufficient to lock the elements and stabilize a stone structure. Since lunar gravity is ~1/6 that of Earth's, it is likely that a supplemental form of locking elements, such as notches or lips will be needed to prevent slippage. If a net shape can be produced; then locking features can be easily formed.

It is apparent that the strength of the elements will not be a limiting factor. However, the supported weight, combined with the force equilibrium at the base will require a horizontal reaction force to insure the stones remain loaded in compression and are constrained on the outer boundary. The load of the structural elements can be followed from the top of the dome down to the base by visualizing an imaginary slice of the dome, called a lune, shown in Fig. 6.

At the base of the lune, both vertical and horizontal reaction forces must exist for equilibrium. For a spherical, constant thickness lune, the horizontal thrust required

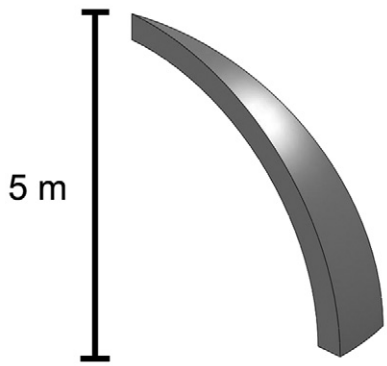

Fig. 6. Lune geometry.

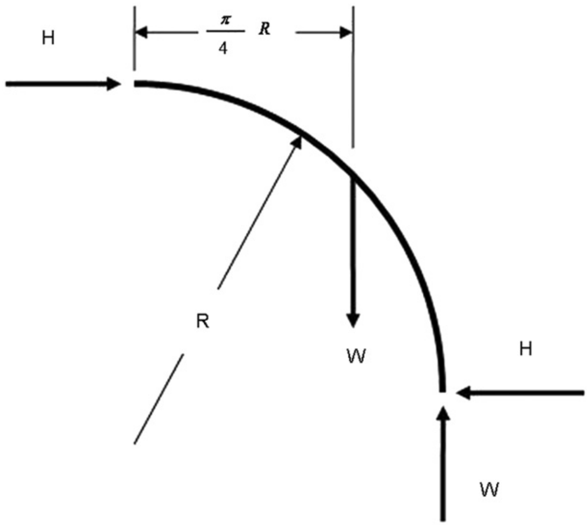

Fig. 7. Derivation of horizontal thrust from static equilibrium.

can be derived by static equilibrium along a centerline, as shown in Fig. 7.

By summing moments for equilibrium, it can be shown that:

$$H = \left(1 - \frac{\pi}{4}\right) W_v \tag{3}$$

The horizontal thrust must be counteracted by an abutment structure, or by a tension element. An abutment structure requires significant mass as well as a path to transfer the load to the lunar bedrock. Using an abutment structure is likely to be impractical since it would require large amounts of material to be moved—something that the regolith masonry approach seeks to avoid. A structural path to stable terrain also requires elements such as foundations, piles, etc., and is heavily dependent upon local site conditions. It is more likely that a tension ring be applied. Calculations of mass, weight and reaction loads for a simple dome are shown below:

Consider a spherical dome with:

$$h = 5\,\text{m}$$

$$R = 5\,\text{m}$$

$$t/R = 0.10$$

$$\rho = 2000\,\frac{\text{kg}}{\text{m}^3}$$

$$R_o = 5\,\text{m}, \quad R_i = 5\,\text{m}(1-0.1) = 4.5\,\text{m} \tag{4}$$

Enclosed volume,

$$V_{enc} = \frac{2}{3}\pi R_i^3 = 190.9\,\text{m}^3 \tag{5}$$

Voussoir volume:

$$V_V = \frac{2}{3}\pi(R_o^3 - R_i^3) = 70.9\,\text{m}^3 \tag{6}$$

Dome weight:

$$W = \rho V_V g_l = \left(2000\,\frac{\text{kg}}{\text{m}^3}\right)(70.9\,\text{m}^3)\left(1.62\,\frac{\text{m}}{\text{s}^2}\right) = 229.7\,\text{kN} \tag{7}$$

Figs. 8 and 9 show the vertical and radial loads of the dome structure.

Distributed loads at the boundary:

Dome distributed vertical load:

$$W' = \frac{W}{2\pi R_i} = \frac{229.7\,\text{kN}}{2\pi(0.45\,\text{m})} = 81.2\,\frac{\text{kN}}{\text{m}} \tag{8}$$

Dome distributed pressure load:

$$W'' = \frac{W'}{t} = \frac{81.2\,\frac{\text{kN}}{\text{m}}}{0.45\,\text{m}} = 0.18\,\text{MPa} \tag{9}$$

The loading is very low, representing a very small fraction of the chosen regolith product strength of 13.8 MPa.

Dome distributed radial load:

$$H' = \frac{H}{2\pi R_i} = \frac{\left(1-\frac{\pi}{4}\right)W}{2\pi R_i} = 1744\,\text{N} \tag{10}$$

The distributed horizontal load is counteracted by a tension element under hoop stress. For a distributed line load, the restraint is related to the cross-sectional area of the restraining "band" around the periphery. For illustration purposes, the band was assumed to have a

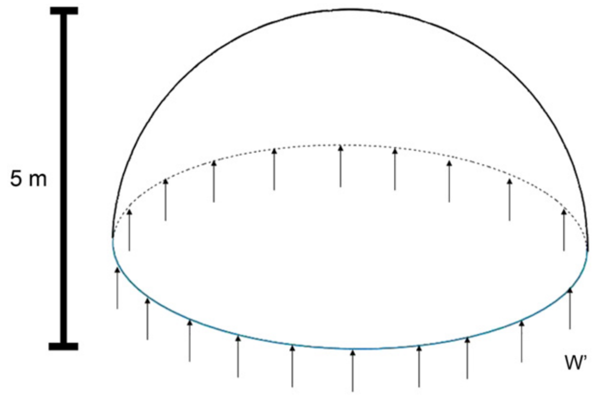

Fig. 8. Distributed vertical loads of the dome.

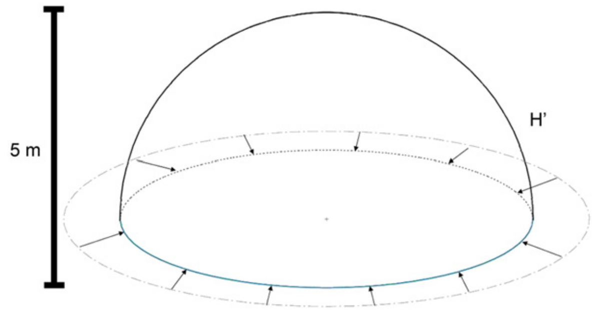

Fig. 9. Distributed radial loads of the dome.

rectangular cross-section 0.20 m high by 0.01 m wide. The hoop stress within such an element is given by,

$$\sigma_h = \frac{W' R_o}{A_{ring}} = \frac{\left(1744\frac{\mathrm{N}}{\mathrm{m}}\right)(5\,\mathrm{m})}{(0.2\,\mathrm{m})(0.01\,\mathrm{m})} = 4.36\,\mathrm{MPa} \qquad (11)$$

6061-T6 aluminum can have a yield strength up to 290 MPa [12]. Therefore, hoop stresses generated within a constraining band would be less than 2% of the yield strength. Environmental conditions such as temperature, abrasion resistance, etc. are more important design factors for the restraining band than tensile strength. The numerical example above demonstrates that the proposed 5 m radius domed structure would not only be feasible, but indicates even larger domes are structurally feasible.

It should be noted that a thickness ratio of 10% is large for terrestrial structures. More elaborate structural and stability analyses in reduced lunar gravity, along with experimentation will be necessary to determine optimal thickness and other configuration variables. In addition, random events such as meteoroid impacts need to be considered.

In regard to fabrication of voussoir elements using a geothermite reaction, the electric current supplied at reaction initiation and the time of reaction initiation depended on the length of NiCr wire used and the type of regolith simulant used. The reactions performed with the JSC-1A simulant required more time to initiate than reactions performed with the JSC-1AF. Reactions performed with the JSC-1A simulant tended to have small amounts of residual unreacted mixture at the edges of the reaction product. The JSC-1AF reaction products tended to have little to no unreacted mixture at the edges. Smaller particle sizes allowed more surface area for reactions, promoting more extensive reaction propagation. The larger particle size of JSC-1A simulant combined with the thermal loss through the crucible likely inhibited the reaction at the outermost sample edges. The uppermost surface (the only surface not in contact with the crucible walls) of the JSC-1AF reaction products (Fig. 10) was observed to have more deformation and cracking than JSC-1A reaction products (Fig. 11). Larger quantities of outgassing were observed during the JSC-1AF reaction process. It is likely that the surface cracking and deformation of the JSC-1AF reaction product is a result of increased outgassing. An example of a near-net shaped reaction product with double-curved surfaces and angled sides is shown in Fig. 12.

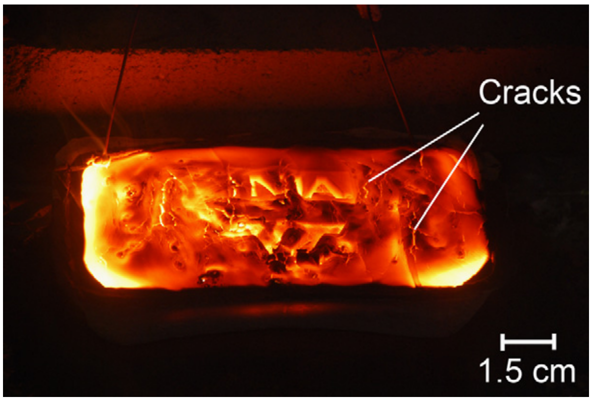

Fig. 10. Geothermite reaction propagation using JSC-1AF regolith stimulant.

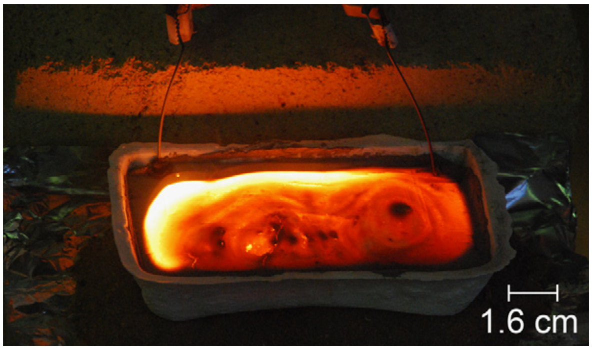

Fig. 11. Geothermite reaction propagation using JSC-1A regolith stimulant.

Fig. 12. Near net shaped voissoir element.

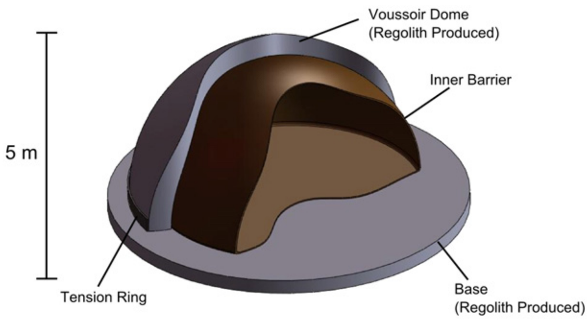

Fig. 13. Cross-section of habitat architecture.

Production of an entire structure, even at a reduced scale, would require appreciable amounts of regolith simulant. As a result, only a few net shape articles representative of V1 elements were produced. While the masonry dome concept would suffice for structural integrity it is likely that barrier materials will be needed for atmosphere containment and other purposes. Integration of barrier materials into a large structure is paramount and a possible solution and assembly scheme is shown in Fig. 13.

Assembly procedure:

1. Install base stones. These are similar to paver materials—Produced by the geothermite reaction.
2. Install and inflate inner barrier. This would likely be a tough membrane that would resist punctures and would serve as the environmental seal—Transported from Earth.
3. Erect the voussoir dome—Produced by the geothermite reaction.
4. Install tension ring. Assemble the ring from components—Transported from Earth.

Although stabilization of completed voussoir domes is not necessary, the inflated inner membrane would serve as a support structure until the dome construction is completed. Elements such as vaults and doors for ingress/egress would require a more detailed design to provide the required resistance to pressure loads as well as proper sealing of the dome. Elements such as doors would need to be transported during flight, and would require integration with the lander to minimize launch mass. Careful design could allow components to be used in both the lander and the voussoir dome assembly.

Since structure height is insensitive to material strength, it is possible to construct very large structures with or without environmental barrier films. For example, it may be useful to have large storage structures for items and materials that are not sensitive to vacuum, but may be sensitive to dust. Very large, simple structures could be erected by combining a barrel vault with two half-domes. Ingress/egress could be accomplished by an intersecting vault with a non-sealing door.

The ability to fabricate discrete elements of various sizes, with ingress/egress elements, would lead to possible modular arrangements including co-joined, and separate domed and large-scale structures. An illustrative arrangement of a lunar base is shown below. While there are numerous potential configurations, Fig. 14 illustrates some of the performance and safety features of such an arrangement.

Safety could be attained by a careful balance of co-joined and standalone elements. Fig. 14 shows a habitat module with direct egress to the lunar surface and a power module at an extreme node. Domed modules are 5 m high, with storage structures shown to illustrate the range of structure scales possible. The modular architecture allows for a sequential assembly of a growing base, with allowance for construction using numerous flights and crews.

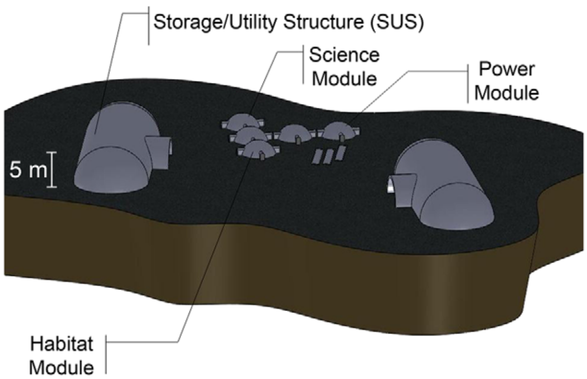

Fig. 14. Concept for lunar base layout.

4. Conclusion

The analyses presented in this study show that a regolith-derived voussoir dome type of structure is feasible from a structural standpoint. The combination of voussoir dome elements with specialized barrier materials allows flexibility in function and scalability. The voussoir dome elements show tremendous promise and allow for significant variation in regolith composition. The geothermite reactions using both JSC-1AF and JSC-1A lunar regolith simulant can be used to produce near net shape voussoir elements that would be adequate to assemble a voussoir dome.

Acknowledgments

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Appendix A. Nomenclature

A	area, m^2
A_{ring}	cross-sectional area of ring, m^2
g_l	lunar acceleration due to gravity, m/s^2
H	horizontal thrust, kN
h	height, m
H'	dome distributed radial load, N
P	force, N
R	radius, m
R_o	outer dome radius, m
R_i	inner dome radius, m
t	dome wall thickness
V	volume, m^3
V_{enc}	enclosed volume, m^3
V_V	voussoir volume, m^3
W	dome weight, kN
W'	dome distributed vertical load, kN/m
W''	dome distributed pressure load, MPa
σ	compressive strength, MPa
σ_h	hoop stress, MPa
ρ	density, kg/m^3

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