LUNARCRETE

A Novel Approach to Extraterrestrial Construction

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ABSTRACT

A novel approach to construction of lunar structures is presented. This approach uses mostly indigenous raw materials with little or no processing and is based on an existing terrestrial technology used in the refractories industry. The main features of the current lunar concrete proposal are: placement and curing can be accomplished without the use of water or the control of ambient temperatures; raw materials are abundant and therefore inexpensive; completed structures contain air at least as effectively as a metal shell; and monolithic structures can be prepared from lunarcrete quickly and easily.

INTRODUCTION- BACKGROUND

During the earliest stages of the industrialization of space, a permanent settlement on the Moon is likely to be required to produce oxygen-- "the gasoline of space"-- and material feedstocks for expanding space industries. The earliest lunar miners may be teleoperated robots, but eventually human miners will probably be required to obtain a diversity of materials. Perhaps for other reasons such as astronomy, human settlements will be established on the Moon.

The early lunar pioneers will need to build habitable structures that utilize the maximum amount of indigenous raw materials and the minimum amount of imported materials. So far several approaches to construction of lunar buildings are being studied.

One approach under study at the Jet Propulsion Laboratory is to send a robot processing plant to the Moon in advance of the human settlers.[1] This plant would produce building bricks for use in the construction of structures once the settlers arrive. A large plastic bag would be used to line this type of building to prevent atmospheric seepage through the joints and/or porosity of the bricks.

A second approach under development for construction of lunar buildings is the use of conventional concrete to prepare wall sections that are joined together.[1] However, the extreme ambient temperature conditions of the Moon (as discussed below) require that this construction be done inside of a climate controlled enclosure. For this reason, the conventional concrete approach will not be used for the first few buildings to be placed on the Moon.

A simple and obvious approach is to take along a metal pressure shell which would be covered with lunar soil upon arrival to shield the settlers from solar flares and cosmic radiation. (Based on the analysis of O'Neill[2], a six foot wall appears to be necessary for shielding and will be used as the appropriate thickness throughout the current paper). Each new structure of this design must be imported at the considerable expense of earth launch cost.

The present paper will describe a novel approach to construction of lunar habitats using a minimum amount of imported materials and as much indigenous raw material-- the lunar regolith-- as possible. Many, theoretically an infinite, number of structures can be produced using this technique without significant resupply of components.

Table I lists the requirements for a concrete-like construction material to be used in the lunar enviornment. Obviously the material must be able to withstand loads especially the pressure exerted by the internal atmosphere with no significant loss of atmosphere over extended periods of time. The material should be abundant so that it is also inexpensive. For the first structures the material must be easily and quickly prepared and placed. The structure must not fail catastrophically without warning and must be structurally stable, enviornmentally inert, and impervious to external and internal stresses. The concrete material must not require strict control of environmental conditions during placement or curing.

As mentioned above, the extreme ambient temperatures of minus 200°C to plus 250°C on the Moon prevent the use of water in the concrete material. Also the high cost of water during early settlement would preclude its use.

The novel approach to be discussed in the current paper meets all of the above requirements and differs in many ways from conventional concrete. So to avoid confusion while discussing the concept, the term "lunarcrete" has been adopted to describe this unique material and process.

The lunarcrete process was adapted directly from the terrestrial refractories industry where it is known as the dry, vibratable concrete process and has been used to line induction furnaces, blast furnace troughs and run-

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ners, steel ladles, and other vessels for over twenty years.[3] Only a few modifications in the process are required to make it viable for construction of lunar buildings.

DESCRIPTION OF THE PROCESS

Initial Lunar Structures

The first lunar pioneers could utilize the resources of the moon together with their own physical strength and a small amount of imported materials to build many structures to live and work within on the Moon. The construction of lunarcrete buildings could start with the launch from Earth of a rigid form, or mold, aboard the space shuttle. A form designed to construct a building of the size of a conventional single family dwelling could weigh as much as 37 tons depending on the thickness and grade of steel used. If aluminum or another low density material is found to be acceptable, the forms could weigh much less. Regardless, the 37 ton form could be lifted into orbit by one or two shuttle flights.

Next the form would be transported to the Moon along with a construction crew. A ten man construction crew was used for the estimate of construction time, but any size crew could be used as long as sufficient manpower or equipment is available to put the pieces of the mold together.

The first order of business upon arrival on the Moon would be to assemble the inner form which would serve as living quarters for the crew until completion of the first and subsequent buildings. The form could consist of a two section mold set composed of an inner mold cavity, or mandrel, and an outer mold section. The mold could consist of triangular shaped pieces that fit together along any of the edges so different sizes and shapes could be formed from them. Future supply missions could bring additional plates increasing the size and/or number of structures that could be made at any one time. The form could be made to fit tightly together with lap joints to prevent leakage of atmosphere and eliminate need for a sealant to caulk the mold joints.

TABLE I

REQUIREMENTS FOR A LUNARCRETE

- SUPPORT LOADS-ATMOSPHERE
- CONTAIN ATMOSPHERE-NO LOSS
- ABUNDANT: INEXPENSIVE
- EASILY AND QUICKLY PREPARED AND PLACED
- NO CONTROL OF AMBIENT TEMPERATURES
- CONTAIN NO WATER
- NO CATASTROPHIC FAILURE WITHOUT WARNING
- STRUCTURALLY STABLE
- ENVIRONMENTALLY INERT
- IMPERVIOUS TO INTERNAL AND EXTERNAL STRESSES

A fine-grained mortar of excess fines from the lunar soil could be used if a mold sealant is required. Under tension from the internal atmosphere, the mold would be "stretched" to its limit. Under compression from the shrinkage of the sintering rock, the mold pieces could be made to slide together somewhat to relieve the strain on the lunarcrete structure.

The external form could be erected surrounding the internal cavity. Loose lunar soil could be graded by hand and blended into the proper size distribution to form a dry vibratable powder. Further research may indicate that 'as-mined' lunar soil is suitable to form the initial crude structures.

After a powder of proper particle size is obtained, it is poured carefully using a specially designed funnel to prevent segregation during filling of the form. A time consuming de-airing step that requires additional care in filling the forms in terrestrial applications can be eliminated due to lunar vacuum. Some additional care must be taken to insure that the material fills properly around and under door and window channels, anchor supports, prestressing cable channels, and any other inserts. Manual labor using shovels, wheel barrows, and other hand tools could be used to carry out this mold filling step.

Next, the entire form is vibrated using pneumatically or electrically driven external vibrators such as the Martin vibrator. As the powder densifies, additional material can be added to the top of the mold. A lunarcrete structure can probably be prepared to the fully vibrated stage at the same rate as construction of dry vibratable refractory installations: $37ft^3$/hr/man[8]. While de-airing is unnecessary and there should be no problem with the amount of work space around the structure, both of which can significantly slow the installation on Earth, other factors such as the low gravity or the cohesive nature of the lunar soil might slow the rate of installation to that of terrestrial experience. It is unlikely that external factors could slow the installation much below the terrestrial rate, and, concievably, the installation rate could be much faster.

Vibratory compaction is essentially an air removal process which means that compaction of lunar soils could be achieved more quickly and to a higher degree of theoretical density. The vibration technique will probably require adjustments of increased frequency and decreased force or amplitude under conditions of one-sixth gravity.[4] Table II shows the rate at which a typical house and a typical pilot plant can be compacted using dry vibration. Ten people could easily inhabit a 2300 square foot house for several weeks until additional structures could be erected.

TABLE II

CONSTRUCTION TIME OF BUILDING USING LUNARCRETE PROCESS

CONSTRUCTION TYPE	PLACEMENT RATE* (FT^3/HR/MAN)	TOTAL MATERIAL VOLUME (FT^3)	TOTAL PLACEMENT TIME (DAYS)
INDUCTION FURNACE LINING	37	NA	NA
TYPICAL HOUSE† (2300 FT^2)	37	34,000	9**
TYPICAL PILOT• PLANT (40,000 FT^2)	37	507,000	137**

NOTE: NA= NOT AVAILABLE

* USING EXTERNAL VIBRATORS LIKE THE MARTIN VIBRATOR (7.5 FT^3/HR/MAN USING IMPACT VIBRATORS LIKE THE BOSCH VIBRATOR)

** TEN HOURS DAYS BY TEN MEN = 10 MAN-HOURS/DAY

† HEMISPHERICAL SHELL- 27 FOOT INNER RADIUS AND SIX FOOT WALL THICKNESS

• HEMISHERICAL SHELL- 113 FOOT INNER RADIUS AND SIX FOOT WALL THICKNESS

After three days of filling and vibration are completed, the structure may require moderate preheating to sinter the powder sufficently to support its own weight when the forms are removed. This step may prove to be unnecessary due to the lunar vacuum and low gravity. A low temperature binder could be synthesized from lunar iron, silica, and other materials if it is found to be necessary. The inner form will remain in the structure to hold the atmosphere until sufficent strength is obtained in the lunarcrete.

After removal of the external forms, the exterior of the structure would be heated by focusing mirrors, electric heaters, oxygen/aluminum burners, microwave radiation, or other heat sources to a very high temperature (over 1000°C or 1800°F). The resulting microstructure will be discussed below. The structure will consist of a completely enclosed living area and will be a single piece of lunarcrete.

The finished lunarcrete structure would resemble glazed concrete in appearance and would be much stronger. This structure would be resistant to chemical attack, water damage or corrosion, fire, explosion, and impact. Ultrasonic testing could pinpoint weak areas that require attention during construction and use stages.

To even out thermal loads on the structure the exterior could be coated with a fiberous or foamed insulating material. Fiberglass can be readily made from basalt similar to lunar soil.[5] This insulation would need more periodic repair than the glazed surface of the structure due to micrometeorite bombardment but the insulation would be easier and less expensive to repair. If considerable damage is to be repaired, the soft insulation could be mechanically cut and shaped with much greater ease than the hard glazed surface. The insulation would also protect the glazed surface from microcracking that could lead to crack propagation and rupture.

Later Structures

One major improvement possible during the later stages of the settlement would be the use of lunar-derived nickel-iron alloy, aluminum, and other metallic cables to prestress the lunarcrete. Prestressed lunarcrete would have even higher strength and impact resistance and a greater degree of safety due to the compression of the concrete by the stressed cables. The formula for prestressed concrete calls for about 90% concrete and 10% steel[6], so the amount of highly processed material-- the metal-- would be small.

TECHNICAL DETAILS

Lunar Soil Properties vs. Material Requirements for Lunarcrete

At this point, it is appropriate to compare the lunar soils to the material requirements of lunarcrete and discuss the engineering details of a lunarcrete structure. The following analyses are not rigorous and are based on a combination of standard engineering design practice and personal experience of the author.

Table III shows the particle size similarity between typical lunar soils and a typical dry vibratable powder. These dry vibratable powders have been used in terrestrial refractories for about twenty years to line various vessels of complex shape including channel induction furnaces. The main difference between the conventional dry vibratables and lunar soil is the higher level of fines (minus 100 mesh) in the lunar soils. As mentioned before, these excess fines could be used to make a fine powder to act as mortar for sealing cracks and joints.

The lunar soil is composed of a basaltic material in the mare and a high titania material in the highlands. The lunar basaltic soils resemble typical terrestrial basalts[5] in chemical composition except for a lower alkali content as indicated in Table IV. A terrestrial fused basaltic product (chemistry shown in the third column) has been used for refractory, pipe linings, chemically resistant vessel linings, glass fibers, and limited structural applications for many years.[8] Note the similar chemistry to the lunar soils. Basalt ceramics are currently widely used in Eastern Europe for abrasion and chemically resistant fixtures for the construction and chemical in-

TABLE III

COMPARISON OF PARTICLE SIZE DISTRIBUTIONS

PARTICLE SIZE (MICRONS)	TYLER MESH SIZE	TYPICAL DRY VIBRATABLE*	RANGE OF TYPICAL LUNAR BASALT SOIL*
+3360	+6	3	1 to 19
-3660+595	-6+28	27	6 to 13
-595+149	-28+100	29	15 to 24
-149+53	-100+270	12	22 to 28
-53	-270	19	31 to 51

*BY WEIGHT PERCENT

TABLE IV

COMPARISON OF CHEMICAL COMPOSITION OF LUNAR AND TERRESTRIAL BASALTS

CHEM ANAL (WT%)	RANGE OF TYPICAL LUNAR BASALTS*,12	RANGE OF TYPICAL TERRESTRIAL BASALTS[5]	TERRESTRIAL FUSED BASALTIC PRODUCT[8]
SiO_2	42.0-50.9	44.7-52.6	45.9
TiO_2	0.4-7.6	0.6-3.6	---
Al_2O_3	8.8-27.5	11.7-16.6	18.4
Fe_2O_3	4.5-20.8	10.9-14.2	12.2
MgO	5.3-9.7	5.3-13.3	6.1
CaO	9.7-15.6	8.6-13.0	13.3
Na_2O	0.4-0.6	2.4-3.8	4.1
K_2O	0.1-0.5	0.5-2.9	TOTAL ALKALIES
BaO	0.2-0.6	---	---
P_2O_5	0.12-0.4	0.2-0.6	---
Cr_2O_3	0.12-0.4	---	---

dustries. Basalts have been used for many years as trap rock-- a filler in concrete and blacktop-- and as an aggregate material in road beds and water filtration systems by the terrestrial construction industry.

The compressive and flexural strengths of this fused basaltic product and other fused basalts are more than sufficent for use as structural materials as shown in Table V. Fused basaltic compressive strengths greater than 10,000 pounds per square inch (psi) are much higher than 1000 to 8000 psi strengths of conventional concrete. Some basaltic glass-ceramics have flexural strengths as high as 50,000 psi.

The lunar soils also have physical properties similar to terrestrial basalts (Table VI). Note the similarities between the melting points and the thermal expansion coefficents of the lunar soils and the terrestrial basaltic materials. Calculations of thermal expansion coefficents based on chemical analysis[10] of these terrestrial materials were within reasonable error of the actual measured values. Thus the calculated thermal expansion coefficent of the lunar soils should be fairly close to the actual values. The thermal conductivity of the lunar soils appears to be much lower than terrestrial basalts but this difference is probably because of the differences in test conditions. Despite this difference and based on similarities in other physical properties, it is apparent that lunar soil could be used as a building material on the Moon.

Microstructural Design of Lunarcrete Walls

A completed lunarcrete structure could be designed through the appropriate heating and cooling cycles to produce the idealized structure shown in Figure 1. The upper half of this figure is a sketch of a lunarcrete macrostructure showing that three distinct zones could be formed. The circles at the bottom represent possible grain structures after heating has ceased. Rapid heating and proper cooling could produce a structure that is under compressive stress from the glazed exterior. This zone could be glassy in microstructure or could be crystallized into a glass-ceramic as shown in the bottom right hand circle magnified by 53,000 times. This fine-grained glass-ceramic would be pore free and could be designed to produce large compressive stresses an the order of 100,000 psi on the internal load-bearing region. This compression would increase the strength of the structure to such a high level that failure would be unlikely. To further insure against failure, pretensioned metal cables might be used in later structures to prestress the lunarcrete during compaction and sintering.[6] Lunar-derived aluminum or nickel-iron alloy could be used for these cables.

TABLE V

COMPARISON OF STRENGTHS OF FUSED BASALTS AND CONVENTIONAL CONCRETES

MATERIAL	COMPRESSIVE STRENGTH, PSI	FLEXURAL STRENGTH, PSI
TERRESTRIAL FUSED BASALTIC PRODUCT[8]	11,000 TO 71,000	2500 TO 3500
TYPICAL TERRESTRIAL BASALT*	14,000 TO 19,000	--------- ----------
BASALT GLASS-CERAMIC	---------	10,000* TO 50,000*
RANGE FOR TYPICAL TERRESTRIAL CONCRETE	1000 TO 8000	300 TO 2500
RANGE FOR TYPICAL TERRESTRIAL PRESTRESSED CONCRETE	**	25,000 TO 160,000

* GLASS MELTED FOR 6 HOURS AT 2640 °F (1450 °C); 55% APPROXIMATE CRYSTALLIZATION[8]
** SIMILAR TO RANGE FOR CONVENTIONAL CONCRETES; STEEL ADDS SOME

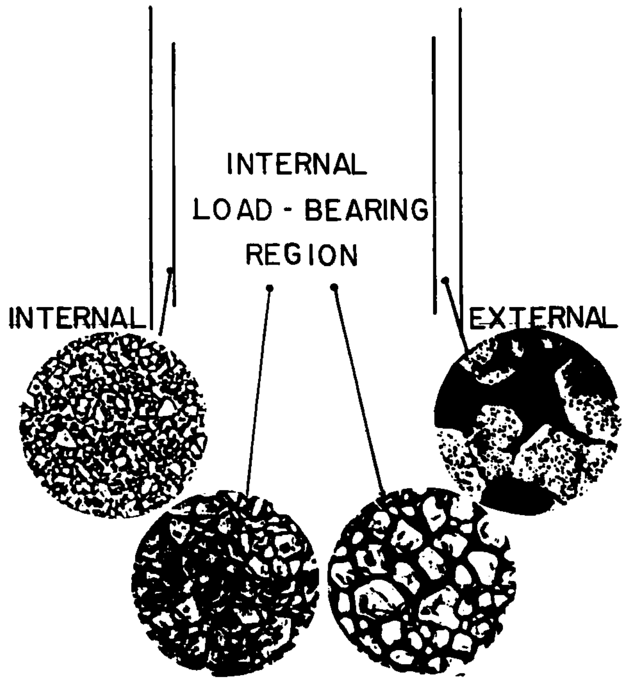
TABLE VI

COMPARISON OF SOME PHYSICAL PROPERTIES OF LUNAR AND TERRESTRIAL BASALTS

PROPERTY	TYPICAL LUNAR BASALT	TYPICAL TERRESTRIAL BASALT* [8]	TERRESTRIAL FUSED BASALTIC PRODUCT[8]
MELTING POINT			
°C	1350 TO 1500*	1450	1260
°F	2460 TO 2730	2640	2300
THERMAL EXPANSION COEFFICIENT PER °C	4.9*10-* (CALC)	7.3*10-*	5.9*10-*
THERMAL CONDUCTIVITY, BTU/FT^2/HR/IN/°F	0.00943** [11]	----------	7.24***
W/M/°K	0.00136	----------	1.044
CAL/CM/SEC/°C	0.00000325	----------	0.00249

* GLASSES MELTED FOR 6 HOURS AT 2640 °F (1435 °C); APPROXIMATELY 55% CRYSTALLIZATION[8]
** FOR LOOSE MATERIAL (BULK DENSITY = 81 PCF) IN A VACUUM (10-* TORR)[8]
*** FULLY DENSIFIED (BULK DENSITY = 178 PCF) IN AIR AT ROOM TEMPERATURE[8]

FIGURE I



MacKenzie[9], CuKierman et al[12], and others have shown that lunar soils can be made to crystallize into glass-ceramics probably due to iron oxide as a nucleating agent. However, terrestrial basalts that have been crystallized into glass-ceramics in reducing atmospheres using iron oxide nucleating agents have shown very coarse, irregular microstructures and weak physical strengths.[5] Additions of fine-grained rutile (TiO_2) have resulted in formation of strong, finely crystallized glass-ceramics. The titania combines with iron oxide to form ulvospinel (Fe_2TiO_4) that becomes a very good nucleating agent in reducing atmospheres.[5] As mentioned previously, the lunar highlands are composed of ilmenite, an iron-titania spinel mineral essentially the same mineral as ulvospinel. The small black spots in the right-hand micrograph are titania crystals. Rutile is a well-known nucleating agent for glass-ceramics even in systems containing large amounts of alumina.[13] The iron-titania spinel would be distributed in a similar manner and could act as excellent nucleating sites in a vacuum to form glass-ceramics.

The bulk of the microstructure of the wall which would support most of the loads on the structure would be carried to the final stage of sintering. This region would gradually change from a glass to a low and isolated porosity solid bonded with considerable glassy matrix and at solid-solid contact points. The microstructure would gradually increase in porosity toward the interior from 0% to about 10-20%.

The interior wall would be lightly sintered with little glassy matrix and grains bonded only at contact points or by narrow necks formed between grains during heating. The high porosity (15-25%) in this zone will absorb crack energies caused by moderate internal stresses before significant propagation through the structure can occur. Cracks and flaws originating in the interior of the structure would have to propagate into regions of increasing compressive stress and decreasing tensile stresses so continued propagation through the structure leading to failure is very unlikely.

The glassy or glass-ceramic exterior and the zero porosity crystalline phase region would have very low permeability and slow chemical diffusivity. Atmospheric losses through the ceramic structure would be very minimal. Oxygen diffusion coefficients at lunar temperatures range from 10^{-55} to 10^{-10} cm^2/sec for a typical silica glass and from 10^{-81} to 10^{-14} cm^2/sec for nitrogen in the same glass.[14] Order of magnitude calculations indicate atmospheric losses by diffusion through a one-inch thick zone of zero porosity glass of about 10^{-11} psi/year from a 27 foot diameter hemisphere at one atmosphere internal pressure.

Since the zero porosity regions are likely to be on the order of three to six inches thick, no appreciable loss of atmosphere will occur by permeation through the walls. Most atmospheric losses will be through air locks and by adsorption onto space suits and other objects such as tools routinely taken in and out of the building.

Structural Strength vs. Stress Analysis

The strength of a ceramic in tension is commonly known to be much lower than its compressive strength. On Earth, a concrete structure is compressed by the force of gravity and atmospheric pressure balances the internal pressure. On the Moon, the low gravity and zero atmosphere require treatment of any structure as a pressure vessel. Concrete pressure vessels are used for nuclear applications in the United States but usually contain a metal membrane liner internally and are produced from prestressed concrete. In Europe, prestressed concrete vessels are used in many pressure vessel applications with, and sometimes without, metal liners. Conventional concrete is very porous and permeable so a metal liner is generally required to prevent loss of pressure through the vessel walls.

Application of conventional, unstressed concrete as a pressure vessel is rarely if ever done. As the lunarcrete structure is designed with a glassy or glass-ceramic exterior, it would behave more like a glass pressure vessel. It has already been demonstrated that little loss of atmosphere will occur through the lunarcrete walls and it now remains to be shown that a lunarcrete structure is strong enough to withstand the tensile stress of the atmosphere. Although surface compression of the glassy layer by thermal tempering or of the glass-ceramic by chemical tempering or phase transition can be used to balance the tensile stress due to atmosphere, it will be shown that sufficient strength can be attained without the benefit of a compressive surface layer.

First the tensile strength of the ceramic must be obtained from experimental results. Most ceramics are tested for transverse strength by a three point bend test called a modulus of rupture. The modulus-of-rupture test is not a true tensile stress test but the following relationship from reference 15 can be used to estimate tensile strength:

$$\sigma_T = \sigma_{MOR}/(2(m+1)^2)^{1/2} \quad (1)$$

where m is the Weibull modulus ~10 for most ceramics, σ_{MOR} is the modulus-of-rupture strength, σ_T is the tensile strength of the material. This correction factor reduces the measured strength value by almost 50%.

The measured fracture strength is determined on a very small sample usually on the order of 0.03 cubic feet. Since the strength of ceramics can be described by the weakest link hypothesis where fracture occurs at the weakest point-- usually at the largest flaw under uniform stress, larger samples have a statistically higher probability of containing a large flaw that has a critical radius where stress can be highly concentrated and lead to crack propagation. The variation in strength as a function of sample size can be calculated from:

$$\sigma_L = \sigma_S(V_S/V_L)^{1/m} \quad (2)$$

where the subscript L refers to the larger sample and the subscript S refers to the smaller sample, V is the sample volume, σ is the sample strength, and m is again the Weibull modulus on the order of 10.[16]

The final strength reduction estimate comes from the loss of strength of ceramics with time due to stress corrosion. This effect is related to a chemical corrosion of the crack tip caused by moisture. There is also an intrinsic material loss of strength with time that has so far not been adequately explained nor modeled, but it is much less significant than stress corrosion. Because the lunar environment contains no moisture and moisture from the inside will only permeate to part of the structure due to its low porosity, an intermediate value between the two extreme types of behavior was chosen for this simple analysis. The relationship used to calculate the minimum structure strength after 30 years is:

$$\sigma_{30} = \sigma_{TEST}(t_{TEST}/t_{30})^{1/n} \qquad (3)$$

where t is the time in seconds, σ is the strength in psi, and n is an empirical constant taken as 55 (an average of 10 and 100 for the two types of strength loss).[17] The test time was estimated as one second.

The progressive nature of the strength reductions are summarized in Table VII. The minimum allowable thickness and the maximum allowable stress can be calculated from the ASME Code equation for a hemispherical shell:

$$h = PR/(2SE-0.2P) \qquad (4a)$$

$$SE = (PR/2h)+0.1P \qquad (4b)$$

where h is the minimum allowable thickness in inches, P is the maximum allowable internal pressure in psi, R is the inside radius of the shell in inches, S is the maximum allowable stress in psi, and E is a fractional measure of joint efficiency taken as 1.00 for a shell with no welded joints.[18] The pressure was taken as 15 psi or about one atmosphere for the house and as 5 psi for the pilot plant.

Low pressure work areas may provide some benefits in processing and should have no long term effects on the workers. Changing from different pressure environments when space suits are also considered may cause problems and will at least take considerable time. If necessary, the workers could wear pressure suits while working or, more favorably, the structure could be designed to hold higher atmospheric pressure if required.

The strength of the structure is obviously sufficient to hold the atmosphere and still withstand significant stress without failure. As previously discussed, compressive stresses up to 100,000 psi, or about 15 million pounds per square foot can be applied to the structure by thermal or chemical tempering or by phase transition to a glass-ceramic at the exterior. Also, the 3000 psi modulus-of-rupture strength chosen for this analysis is probably a conservative value for an average for the entire structure (see Table V).

If this value for modulus of rupture is for a porosity of 3%, the strength of the material as a function of porosity and, therefore, depth into the structure can be calculated from:

$$\sigma = \sigma_0 \exp(-n'P) \qquad (5)$$

where σ is the strength for a given porosity P, P is the volume fraction of porosity, σ_0 is the strength at zero porosity, and n' is an empirical constant between 4 and 7.[19] For an average n'=5.5, the strength reduction in Table VIII was calculated from equation (5). The low value of 900 psi strength at 25% porosity corresponds to the inner surface of the structure where the tensile stress is a maximum and the volume and the compressive stresses are at a minimum. Nevertheless, this strength is sufficent to withstand the atmospheric pressure without rupturing in the current house design. A more rigorous future treatment of stresses would consider this porosity effect and all other listed effects. All these effects would then best be treated by simultaneuosly integrating the differential equations from which equations (1) through (5) were derived over infinitesimal volume elements of the structure.

The simplified current treatment does indicate that the proposed lunarcrete structure is feasible with appropriate design techniques. After construction and during use, the structure can be regularly tested using ultrasonic techniques for overall soundness and for a propagation profile of the severest cracks or flaws with time. This profile will enable proper calculation of the constant n in equation (3). The life expectancy of the structure can be calculated from this data and can be continuously monitored by following the progress of the most severe flaws.

Table VII

Effective Strength and Wall Thickness Requirements of Lunarcrete Structures

	House	Pilot Plant
Modulus of Rupture	3000psi	3000psi
Tensile Strength	1730psi	1730psi
Material Strength of Structure	62,000 lb/ft^2	47,000 lb/ft^2
30 Year Fracture Strength of Structure	42,000 lb/ft^2	32,000 lb/ft^2
Minimum Allowable Thickness*	8 Inches	15 Inches
Stress Due to Atmospheric Pressure for 6 Foot Thick Walls	5100 lb/ft^2	6800 lb/ft^2
Atmospheric Stress vs. Erected Material Strength	8%	15%
Atmospheric Stress vs. 30 Year Strength	12%	21%

* For a 30 year lifetime.

TABLE VIII

EFFECT OF POROSITY
ON STRENGTH OF MATERIAL

(%) POROSITY	MODULUS of RUPTURE
0	3540
5	3000
5	2690
10	2040
15	1550
20	1180
25	900

SUMMARY AND CONCLUSIONS

A novel approach to construction of lunar structures was found to be feasible using a maximum amount of lunar regolith as building material. Many structures can be produced from a relatively small amount of initial equipment with only a minimal resupply required. Placement and curing of the lunarcrete can be carried out within the extremes of the lunar environment. The structures will be concrete-like in properties and may have a design lifetime of at least thirty years.

Future applications of this concept not only include construction of lunar structures but also include structures on Mars, in Earth orbit, or anywhere else in the solar system where a fine-grained soil and a source of sufficent energy to sinter it co-exist.

FUTURE RESEARCH AREAS

The current paper has surveyed the concept of lunarcrete and found it to have interesting possibilities. Much future research is required, however, to develop material and engineering constants that will enable improved design estimates. More rigorous design analysis is also required. Some of the areas of anticipated future research have been summarized in Table IX. This summary is far from exhaustive. The author would welcome suggestions for additional areas of research as well as any help in studying these areas in a coordinated manner.

TABLE IX

FUTURE RESEARCH AREAS

- SINTERING STUDIES
- HEAT FLOW ANALYSES
- COMPACTION VS. VIBRATION STUDIES AT LUNAR GRAVITY
- EXTERIOR INSULATION REQUIREMENTS
- EFFECT OF PRETENSIONED CABLES ON VIBRATION / COMPACTION
- BUILDING DESIGN • STRENGTH, DURABILITY, AESTHETICS
- DESIGN OF FORMS
- PREHEATING AND LOW TEMPERATURE BINDER REQUIREMENTS
- PLACEMENT ON LUNAR SOIL OR SOLID ROCK

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