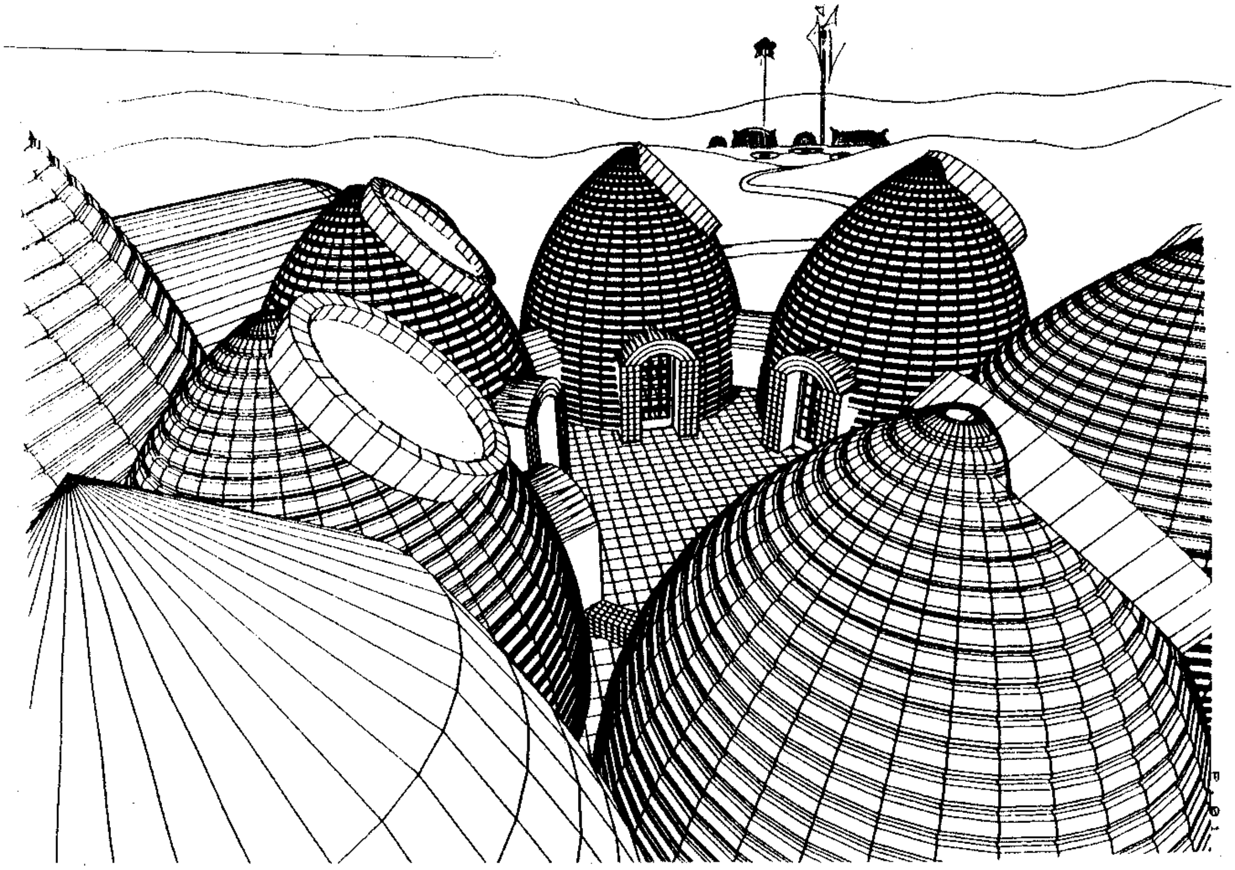
WORKSHOP ON USING *IN SITU* RESOURCES FOR CONSTRUCTION OF PLANETARY OUTPOSTS



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WORKSHOP ON
USING *IN SITU* RESOURCES FOR
CONSTRUCTION OF PLANETARY OUTPOSTS

Edited by

M. B. Duke

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Preface

The Workshop on Using *In Situ* Resources for Construction of Planetary Outposts was held in Albuquerque, New Mexico, April 30–May 1, 1998. The principal purpose of the workshop was to examine whether there are any high-priority, near-term applications of *in situ* planetary resources that could lower the cost of constructing human outposts on the Moon and Mars. Inevitably, there is also a great interest in the topic of building human settlements on other worlds. Whereas there is virtually no argument that using indigenous materials will be important for the latter case, no compelling argument has been made for the use of indigenous material for the initial stages of planetary outpost installation.

The workshop examined the potential uses of indigenous materials on the Moon and Mars, other than those uses associated with the production of propellants for space transportation. The use of indigenous propellants has become an accepted requirement for human exploration missions to Mars and in building permanent outposts on the Moon. The papers presented in the workshop concerned the needs for construction, based on analysis of the current NASA Mars Reference Mission and past studies of lunar outposts; the availability of materials on the Moon and Mars; construction techniques that make use of the natural environment; materials production and fabrication techniques based on indigenous materials; and new technologies that could promote the use of indigenous materials in construction.

One of the failings of many previous studies of indigenous planetary resources has been the lack of a demonstrated need; that is, there are many good ideas for how to use the natural materials, but no strong program applications that demand them. In order to advance from concepts into a technology development stage, the applications need to be defined and quantified. It is necessary to show explicitly that each proposed application is cost-effective within the context of the need. This workshop brought together both technologists and mission designers. People interested in planetary construction technology were provided with an update of NASA planning. In turn, they discussed ideas of potential interest to space mission planners. Future workshops should continue to explore the interface between technology innovators and mission designers, expand the database of applications, and promote the consideration of *in situ* resource technology in the human exploration and development of space.

This report contains abstracts of papers submitted to the workshop. In some cases, additional charts and figures have been included with the abstracts. In other cases, an edited version of the presentation made at the workshop has been included. Workshop participants and readers of this report are invited to provide commentary and feedback to the editor, Michael B. Duke, at the Lunar and Planetary Institute (duke@lpi.jsc.nasa.gov).

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ABSTRACTS

SPECIAL PRESENTATIONS

Abstracts

BRICKS AND CERAMICS. C. C. Allen, Lockheed Martin Space Mission Systems and Services, 2400 NASA Road 1, Houston TX 77058, USA.

Introduction: A lunar base will require large amounts of dense, strong construction material for thermal and dust control, as well as for radiation protection. Sintered lunar soil, a fine-grained mixture of crushed rock and glass, has been proposed to meet this need [1]. Our research effort [2,3] has focused on practical methods of sintering to produce lunar "bricks." We report here the results of two investigations of the sintering of simulated lunar soil. Radiant heating under carefully controlled conditions can reproducibly yield large, strong bricks. Hybrid microwave sintering, using a combination of microwave and radiant heating, is also shown to give promising results.

Starting Materials: We conducted sintering experiments on two lunar soil simulants. MLS-1 (Minnesota lunar simulant) is a high-titanium crystalline basalt with a chemical composition which approximates Apollo 11 soil [4]. The rock was ground and sieved to a size distribution close to that of lunar soil sample 10084 over a size range from approximately 1 mm to <10 µm [5]. JSC-1 is a glass-rich basaltic ash with a composition similar to lunar mare soil [6]. JSC-1 was also prepared with a grain size distribution close to that of the lunar regolith.

Radiant Heating: All radiant heating experiments were conducted in a Lindbergh Model 51333 laboratory furnace, equipped with a controlled atmosphere retort. The retort was heated from above and below. Experiments were run at temperatures of 1000º–1125°C for 0.5–3 hr. The basic experiment consisted of heating lunar soil simulant in a brick-shaped, fused silica mold. This material was chosen for its combination of low density and extremely low thermal conductivity.

Strong, uniform "bricks" of MLS-1 basalt were produced in three experiments by sintering in the fused silica mold on a steel base plate. The resulting bricks, measuring 7.9 (l) × 5.5 (w) × 3.6 cm (h), were sintered for 2 hr at 1100°C. The MLS-1 bricks heated in this manner are crack-free, with the exception of minor expansion cracking near the top surface. The dimensions of the bricks did not change during sintering, indicating no significant increases in density.

Larger bricks were made from the glass-rich JSC-1 simulant, heated to 1100°C in two experiments. The simulant was initially com-pacted in the mold by vibration for 5 min to a density of 2.45 g/cm^3. The samples were sintered for 2.5 hr in a fused silica mold. A silica fabric liner was inserted to prevent the rock from sintering to the mold.

Hybrid Microwave Sintering: The sintering of geological samples by microwave heating was initially investigated by Meek et al. [7]. We have run a series of investigations into the sintering of crushed basalt in a laboratory microwave furnace. The CEM MDS-81 furnace operates at a frequency of 2.45 GHz and delivers approximately 600 W of microwave energy to the sample.

Each sample of crushed MLS-1 basalt was placed in a cylindrical graphite mold 3.6 cm in diameter and 3.2 cm high. The powder was hand tamped to achieve a porosity of approximately 30%. The mold was capped with a graphite lid 0.26 cm thick. All heating was done in air. However, the graphite mold served as an O "getter," somewhat reducing the effective O fugacity of the sample.

Controlled, even sintering of rock powder by direct microwave heating proved impossible due to the combined effects of thermal runaway [8] and self-insulation. The microwave coupling efficiencies of the minerals in MLS-1 rise dramatically with sample temperature. As a result, initial heating is slow, but becomes increasingly rapid at temperatures above approximately 400°C. Microwaves penetrate the sample, and heating occurs throughout its volume. However, the center is well insulated by surrounding material and heats faster than the outside. Typically, samples sintered strongly or melted in the centers but remained unsintered on the edges.

To achieve uniform sintering we developed a hybrid heating technique, combining microwave and radiant heating. We surrounded the sample crucible with seven SiC blocks in a "picket fence" arrangement. The SiC converted part of the microwave energy to heat. Our samples were heated at full power for periods of up to 2 hr and then allowed to cool slowly in the mold under reduced microwave power.

Sintered samples were closely examined for evidence of cracking and delamination. All samples were weighed and measured prior to and after sintering to determine changes in density. The compressive strengths of several samples were determined in accordance with the standard test method used for concrete [9].

Sixty-three experiments were conducted in an attempt to reproducibly sinter MLS-1. We achieved optimum results by heating at full power for 85 min, with the sample held at 980°C for 35 min. At the end of this time the sample was carefully cooled by ramping down the microwave power over a period of several hours. The cylindrical samples were uniformly sintered and crack-free. Sample density increased by an average of 11%. Compressive strengths near 1100 psi were measured.

Discussion: Sintering of small test samples of lunar simulant basalt has been studied in detail but "scaling up" to the size of a brick has proved extremely challenging. Crushed rock is an effective thermal insulator, which often leads to uneven heating and thermal cracking. The wide range of grain sizes typical of lunar soil can produce inefficient sintering and localized stress concentrations. Minimizing precompaction limited the number of grain-to-grain contacts available for sintering.

These drawbacks have been overcome by a combination of strategies. Thermal cracking has been minimized by relatively long heating and cooling periods, coupled with the use of fused silica molds with extremely low thermal conductivity. Temperature control has proven to be critical — a mere 25°C can span the difference between minimal sintering and near-total melting. The JSC-1 lunar soil simulant, with its glassy component, sinters significantly more uniformly than the totally crystalline MLS-1. Finally, vibratory compaction provides a relatively low-energy method of increasing grain-to-grain contact and improving sintering performance.

Crushed rock can be heated to the melting point in a microwave furnace, but sintering requires careful control of a number of factors. Thermal runaway, combined with the low thermal conductivity of crushed basalt, makes uniform sintering just below the sample's melting point extremely difficult. Once sintering has occurred, the sample must be carefully cooled in order to minimize thermal stresses that lead to cracking.

A hybrid system using internal microwave heating combined with external radiant heating was effective for sintering MLS-1. The optimum heating time proved to be 85 min, including heatup, followed by a slow cooldown. These factors represent a delicate balance between microwave and radiant heating, in a material prone to thermal runaway. Thus, any microwave sintering method is likely to be very sensitive to changes in sample composition, size, and configuration.

References: [1] Shirley F. et al. (1989) *A Preliminary Design Concept for a Lunar Sintered Regolith Production Facility*, Battelle, Columbus, Ohio. [2] Allen C. C. et al. (1992) in *Engineering, Construction, and Operations in Space III* (W. Z. Sadeh et al., eds.), pp. 1209–1218, American Society of Civil Engineers, New York. [3] Allen C. C. et al. (1994) in *Engineering, Construction, and Operations in Space IV* (R. S. Galloway and S. Lokaj, eds.), pp. 1220–1229, American Society of Civil Engineers, New York. [4] Goldich S. S. (1970) *Science, 171,* 1245. [5] Weiblen P. W. et al. (1990) in *Engineering, Construction and Operations in Space II,* pp. 428–435, American Society of Civil Engineers, New York. [6] McKay D. S. et al. (1994) in *Engineering, Construction, and Operations in Space IV* (R. S. Galloway and S. Lokaj, eds.), pp. 857–866, American Society of Civil Engineers, New York. [7] Meek T. T. et al. (1985) in *Lunar Bases and Space Activities of the 21st Century,* pp. 479–486, Lunar and Planetary Institute, Houston. [8] Kenkre V.M. et al. (1991) *Journal of Materials Science, 26,* 2483–2489. [9] ASTM (1986) *Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens; Standard C 39-86*, American Society for Testing and Materials, Philadelphia, 6 pp.

IN SITU RESOURCES FOR LUNAR BASE APPLICATIONS.

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Lunar resources have been cited in two ways within the context of lunar (and Mars) development. The first is that lunar resources are an economic incentive for lunar development. In other words, there are bountiful natural resources on the Moon that could economically justify a return to the Moon. The other context is that lunar resources could be very useful in creating and maintaining a lunar settlement.

There is abundant O; about 45% of the weight of lunar rocks and soils is chemically bound O. These materials also contain considerable Si, Fe, Ca, Al, Mg, and Ti, which can be extracted as a byproduct of O extraction. In addition, He, H, N, and C can be found in the lunar regolith. All this suggests that many important components can be extracted, resulting in O and H-based rocket fuels that could be used both for Earth-Moon operations and for ships going to Mars. Various metallic ores also suggest other uses. The potentially brightest spot of lunar resources is ^{3}He, a light isotope of He and a potential fuel for nuclear fusion reactors. Unfortunately, these reactors have not been engineered yet. A guess of when they may be on line is in three decades, but that was before Congress cut off funds for the Princeton Tokamak research facility.

From the perspective of lunar base construction, one can envision that regolith could be fused into building blocks for lunar structures and into a material that can be used for roads and foundations. In principle, if one assumes the above constituent elements can be extracted efficiently from the regolith, then it is possible that many of the artifacts of an industrial society could be manufactured on the Moon. For example, Fe, Al, and Ti are the building blocks of many structural systems. Silicon is the heart of our computer-based society, affecting computation, control, robotics, etc.

A taxonomy for understanding building system needs for the Moon or any extraterrestrial body has been developed. The framework is larger than that which would focus solely on *in situ* resource utilization, but it provides the larger picture. This could be of value to those planning and constructing planetary outposts. This taxonomy is included at the end of this volume.

NEAR-EARTH ASTEROID PROSPECTOR AND THE COMMERCIAL DEVELOPMENT OF SPACE RESOURCES.

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With the recent bad news that there may be little or no budget money for NASA to continue funding programs aimed at the human exploration of space beyond Earth's orbit, it becomes even more important for other initiatives to be considered. SpaceDev is the world's first commercial space exploration company, and enjoys the strong support of Dan Goldin, Wes Huntress, Carl Pilcher, Alan Ladwig, and others at NASA headquarters. SpaceDev is also supported by such scientists as Jim Arnold, Paul Coleman, John Lewis, Steve Ostro, and many others. Taxpayers cannot be expected to carry the entire burden of exploration, construction, and settlement. The private sector must be involved, and the SpaceDev Near Earth Asteroid Prospector (NEAP) venture may provide a good example of how governments and the private sector can cooperate to accomplish these goals. SpaceDev believes that the utilization of *in situ* resources will take place on near-Earth asteroids before the Moon or Mars because many NEOs are energetically closer than the Moon or Mars and have a highly concentrated composition. SpaceDev currently expects to perform the following three missions: NEAP (science data gathering); NEAP 2, near-Earth asteroid or short-term comet sample return mission; and NEAP 3, *in situ* fuel production or resource extraction and utilization. These missions could pioneer the way for *in situ* resources for construction.

CONSTRUCTION OF PLANETARY HABITATION TUNNELS USING A ROCK-MELT-KERFING TUNNEL-BORING MACHINE POWERED BY A BIMODAL HEAT PIPE REACTOR.

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Significant manned exploration and support activities over extended periods on planetary surfaces such as the Moon or Mars will require space radiation shielding of habitats and laboratories. As habitat volumes grow, it will soon become cost effective in structural mass import and extravehicular activity (EVA) time to construct habitable volumes directly underground in the form of gas-tight tunnels incorporating many meters of overburden shielding. We have previously proposed [1] that an effective concept for constructing such tunnels is a tunnel-boring machine (TBM) design that combines conventional rotary (auger) cutters with rock-melting kerf heaters, the latter to control the tunnel gauge dimension in poorly consolidated rock and provide support for the opening. Advantages of this approach are (1) no fluids are needed to transport cuttings and (2) tunnel support in the form of a strong, impermeable glass lining is automatically formed as the TBM advances. The kerf heaters melt poorly cemented regolith rock on the tunnel boundary and consolidate the glass into a formed-in-place lining that, once cooled, is very strong [2] and orders of magnitude less permeable; residual cooling cracks in the glass are sealed with indigenous metals using an integrated plasma spray gun. The resulting tunnel is sufficiently strong and gas-tight to allow normal pressurization for habitation, and is constructed entirely of *in situ* materials.

A key technology needed to make the TBM design practical for space use is a robust, low-mass power supply. Recent design of a heat pipe-cooled, bimodal (thermal and electric power) fission-reactor power system [3] (HPS) is well matched to this application. The core of the HPS is cooled by passive Li metal heat pipes that can deliver 100–1000 kW thermal power at 1800 K to the kerf-melting bodies of the TBM (recently, a Mo/Li heat pipe HPS module was fabricated and performed well in electrically heated tests to 1400 K with multiple restarts). Using one of a number of possible conversion methods, a portion of the reactor heat can also be used to generate several tens kW of electrical power for the rotary cutters and muck conveyors. Residual waste heat after electrical conversion is disposed of in the cuttings that are conveyed out of the tunnel. We project that a mostly automated, melt-kerfing TBM with this power system can produce sealed habitation tunnels, 3–5 m in diameter, in planetary regolith materials at a rate of about 8 m length per day. A 3-m-diameter habitat would require a reactor generating power of about 500 kWt and 25 kWe. Additional features of the HPS are that it can be asymmetrically cooled to provide a TBM steering mechanism by asymmetric kerf heating, and it can be completely proof-tested using only resistance heaters.

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OBTAINING AND UTILIZING EXTRATERRESTRIAL WATER.

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As an *in situ* resource, water has no rival in terms of sheer usefulness for space operations. It can be used for life support, propulsion, radiation shielding, and structure. This paper describes a low-cost system for transporting water back from water-bearing bodies such as extinct short-period comets, carbonaceous asteroids, or possibly the moons of Mars. It is likely that water will be of most benefit initially as a propellant feedstock in low Earth orbit. Several ways to use the water are discussed, including a space-based stage to assist in putting mass into orbit and a propellant ladder for lifting mass higher in the Sun’s gravity well. A composite material of ice and fiberglass is discussed as a possible load-bearing structural material. A preliminary analysis of the economics of the water extraction/transportation system suggests it may be economically viable in the near-term. An initial system would require about 70 T of equipment and propellant be lifted into low Earth orbit.

The main element of the NEO-Earth water-transportation system is a lightweight tanker based in Earth orbit. The tanker would rendezvous with an incoming package of water by matching its orbit, transferring the water aboard, then aerocapturing it into orbit. The tanker’s heat shield would use a reflective overcoat to reflect most of the radiative heating[1], transpiration cooling to block convective heating, and the thermal mass of the water payload to absorb what is not otherwise rejected. Calculations show that a 1200-kg vehicle can aerocapture 50 T of water approaching at a Vinf of 6 km/s using less than 4% of the water for transpiration cooling. This approach allows the utility of expensive equipment to be maximized. Since only inexpensive water containers make the trip back from the NEO, the extraction equipment can run continuously, launching the water packages in batches with nuclear or solar thermal propulsion during the Earth return launch windows, and the same tanker can be used to catch many water packages. The system is basically split into two parts, one in Earth orbit and one at the water mine site. From a NEO in an orbit attractive for transportation, it can return water to Earth orbit at 60% efficiency (60% of the water extracted from the body arrives in Earth orbit; the rest is used for propulsion, tanker rendezvous, transporting the empty package back to the NEO, and transpiration during aerocapture). The tanker can also be used to aerocapture nonwater payloads, as long as they are sent along with a package of water.

A method for using extraterrestrial water to lower the cost of lifting material into orbit is proposed. The propellant (LOX/LH2) is manufactured out of water in an orbiting facility. Instead of lifting all of the propellant required for orbit from below, some is brought down from above. Two stages are used — an Earth-based stage and a space-based stage. The space-based stage is powered by propellant manufactured from extraterrestrial water. The Earth-based stage provides a portion of the Δ-V required for orbit, releases the payload on a suborbital trajectory, and prepares to reenter the atmosphere. Meanwhile, the space-based stage has slowed to match the final speed of the payload, either by using its engine or by aerobraking by skipping into the atmosphere and flying out. It intercepts the payload, attaches to it, and accelerates into orbit. It is like having a refueling station on the way to orbit, at 120 km and ~5.5 km/s. The orbital lifetime of a base in such an orbit is very short, of course; it is just put in place on a temporary (~60 s) basis. No propellant is transferred from one stage to the other; the space-based stage just starts its engine once it has made a mechanical connection with the payload. From a ground-operations standpoint, the system appears to be SSTO, but without the difficult SSTO mass-fraction requirements. Using this approach, the size of both stages combined is about one-sixth the size of a rocket that only uses propellant from Earth.

A method for lifting mass out of a gravity well using propellant brought down from higher in the well or outside the well is described. It uses a “propellant ladder,” which consists of propellant lowered to bases at various depths in the well. Although systems like this have been proposed with propellant lifted from Earth [2], it becomes very interesting when the propellant is supplied from a point higher in the gravity well. The bases (equipment to manufacture LOX and LH2 from water and store it) are in eccentric elliptical orbits with a common periapsis. To lift a mass higher in the well, starting in the lowest-energy circular orbit, a booster only needs enough propellant to accelerate to the next base. As the first propellant base reaches periapsis and is about to pass, the stage does a burn to accelerate to the velocity of the next base orbit. It docks with the base (the propellant base orbits would be synchronized so a base from each orbit would all reach periapsis at about the same time, with the slowest base arriving first) and takes on more propellant. It then repeats the process for each of the next bases as they pass by. The bases can be thought of as being in a series of Hohmann transfer orbits, each one transferring to a higher point in the well. The ship does not ride up any of the orbits until it has reached the last one. Using this method, the propellant required becomes an essentially linear function of total Δ-V instead of exponential. For a solar ladder, the bases would be arranged so on a certain day of the year a base from the 3-yr orbit and the 5-yr orbit (8 total) would pass within 24 hr of each other, the slower one first. This method could also be used to lift mass out of very deep gravity wells, such as Jupiter's.

Humans have historically constructed shelters out of the most readily available materials. If water turns out to be the material most easily obtainable in space, it may become widely used for construction, despite the difficulties it poses. Ice has many nice features: it can be formed into any shape and is an excellent radiation shield. In addition, reasonably sized structures can easily hold one atmosphere of pressure and be rotated to provide artificial gravity, as proposed by Zuppero [3]. The flexural strength of normal ice is around 2 MPa at temperatures just below freezing; this increases at lower temperatures. Russian studies of ice reinforced with glass fiber have shown it to be a few times stronger, about 8 MPa (2% fiber by volume, –20°C) [4]. Although a considerable mass of fiberglass would be required for a large structure, asteroidal material could be used as a glass feedstock. The obvious problem with using ice is that it must be insulated from the warm temperatures inside the structure, at least for human and plant habitats, and it will probably require some type of active cooling such as cold gas circulating between the ice wall and the insulation. However, with active cooling comes the possibility of a cooling-system malfunction, which must be taken very seriously if the structural integrity of the station depends on it. This can be dealt with using a series of measures: first, by installing redundant cooling systems; second, by having repair crews and spare parts available; third, by designing the wall to be sound at –5°C but keeping it normally at –140°C with the cooling system so that it will take a while to warm up; and fourth, as a last resort, by lowering the temperature and pressure inside the station. Although the strength of fiber reinforced ice at very low temperatures has not been measured, it may be surprisingly high. The structure would be shaded from the Sun. Built onsite at a comet or asteroid, large habitats could be constructed quite cheaply. Internal structures could be made from *in situ* resin/fiber composites manufactured from hydrocarbons or metal. Stations could be built at a water-bearing body and moved with nuclear thermal propulsion into a cycling orbit between Earth and Mars, Jupiter, or the asteroid belt.

A preliminary analysis of the economics of returning water from a NEO or a martian moon is given. It is difficult to justify a privately financed system without assuming an increase in space spending if the system costs $3 billion to develop and launch. It has an advantage over other systems for returning water in that half the investment is in a LOX/LH2 transportation infrastructure in LEO, which is useful by itself. Also, some of the money goes into developing a low-power nuclear thermal steam rocket that would have other space applications. Two options are analyzed: launching the extraction equipment directly and launching the LOX/LH2 infrastructure and then using it to launch the extraction equipment from LEO. Assuming a functioning space-based stage system is created (the LOX/LH2 infrastructure plus two 2-T stages), revenue from the first shipment of water is estimated at $2.4 billion the first year. It breaks down to 20% for LEO-GEO transport, 40% for launching other firms mining equipment to the asteroids, 30% for propellant for a space-based stage system, 5% for station keeping and life support, and 5% for launching scientific probes. It is assumed that the first shipment of water is more than can be sold in the first year, with the remainder being sold in subsequent years. The price of water in orbit should fall year by year as more extraction equipment is put in place, dropping to an ultimate level determined by the cost of the equipment time used to extract it, put it on an Earth-return orbit, and capture it into orbit, which may be as low as $6000 per ton of water.

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BALLISTIC TRANSPORT OF LUNAR CONSTRUCTION MATERIALS.

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Moving lunar regolith materials will be necessary for both construction and resource extraction. Most illustrations show bulldozers, draglines, clamshell buckets, and other similar devices being used for this purpose. However, the Moon's gravity and its vacuum environment suggest another possibility: namely, ballistic transport such as is used on Earth in threshing machines, street sweepers, snow blowers, and ice-rink resurfacers. During the Apollo 15 mission, astronauts maneuvered the lunar rover in such a way that its spinning, bouncing, and skidding wheels threw up sizable "rooster tails" of Moon dirt, showing the ballistic transport possibility. Now what is needed is some effort to find out more about this process, so that it can be determined whether or not it should be considered seriously for lunar construction and resource operations. Simple experiments in 1 *g* and air, using a drill motor and various wire brushes, show some characteristics of the plume of sand that can be thrown. However, the results are of no quantitative value because of air drag and the wind induced by the wire wheel itself. To get a better handle on the real physics of the process, and to understand whether it would be useful on the Moon, more quantitative experiments are needed. To this end, a small model has been designed to illustrate and possibly to test the process, first in laboratory vacuum and then in vacuum in 1/6-*g* aircraft flight.

MARTIAN (AND COLD REGION LUNAR) SOIL MECHANICS CONSIDERATIONS.

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The exploration of Mars has generated a lot of interest in recent years. With the completion of the Pathfinder Mission and the commencement of detailed mapping by Mars Global Surveyor, the possibility of an inhabited outpost on the planet is becoming more realistic. In spite of the upbeat mood, human exploration of Mars is still many years in the future. Additionally, the earliest return of any martian soil samples will probably not be until 2008. So why the discussion about martian soil mechanics when there are no returned soil samples on hand to examine? In view of the lack of samples, the basis of this or any discussion at this time must necessarily be one that involves conjecture, but not without the advantage of our knowledge of regolith mechanics of the Moon and soil mechanics on Earth.

Because of the generally freezing environment on Mars, our basis of conjecturing the soil mechanics of martian soil would be drawn upon our knowledge of engineering in cold regions on Earth. In another recent development, it appears that there may be water-ice in some craters near the poles of the Moon. While there is much dissimilarity in color between lunar regolith and martian soil, they are nevertheless predominantly fine-grained silty soils. It is therefore reasonable to assume that there may be some characteristics of martian soils that can be learned from tests performed with freezing/frozen lunar soil simulants. Some preliminary tests were performed by the authors on slightly moist frozen lunar soil simulant JSC-1 and the results are presented here (JSC-1 is a lunar soil simulant manufactured for and distributed by the Johnson Space Center).

The objective of this presentation/discussion is fourfold: (1) Review some basic engineering-related information about Mars that may be of interest to engineers, and scientists — including characteristics of water and CO_2 at low temperature; (2) review and bring together principles of soil mechanics pertinent to studying and predicting how martian soil may behave, including the morphology and physical characteristics of coarse-grained and fine-grained soils (including clays), the characteristics of collapsing soils, potentials and factors that affect migration of water in unfrozen and freezing/frozen soils, and the strength and stiffness characteristics of soils at cold temperatures; (3) discuss some preliminary results of engineering experiments performed with frozen lunar soil simulants, JSC-1, in the laboratory that show the response to temperature change with and without water, effects of water on the strength and stiffness at ambient and at below freezing temperatures; and (4) discuss engineering studies that could be performed prior to human exploration and engineering research to be performed alongside future scientific missions to that planet.

HUMAN EXPLORATION OF MARS: THE REFERENCE MISSION OF THE NASA MARS EXPLORATION STUDY TEAM.

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The Reference Mission was developed over a period of several years and was published in NASA Special Publication 6107 in July 1997. The purpose of the Reference Mission was to provide a workable model for the human exploration of Mars, which is described in enough detail that alternative strategies and implementations can be compared and evaluated. NASA is continuing to develop the Reference Mission and expects to update this report in the near future. It was the purpose of the Reference Mission to develop scenarios based on the needs of scientists and explorers who want to conduct research on Mars; however, more work on the surface-mission aspects of the Reference Mission is required and is getting under way. Some aspects of the Reference Mission that are important for the consideration of the surface mission definition include (a) a split mission strategy, which arrives at the surface two years before the arrival of the first crew; (b) three missions to the outpost site over a 6-yr period; (c) a plant capable of producing rocket propellant for lifting off Mars and caches of water, O, and inert gases for the life-support system; (d) a hybrid physico-chemical/bioregenerative life-support system, which emphasizes the bioregenerative system more in later parts of the scenario; (e) a nuclear reactor power supply, which provides enough power for all operations, including the operation of a bioregenerative life-support system as well as the propellant and consumable plant; (f) capability for at least two people to be outside the habitat each day of the surface stay; (g) telerobotic and human-operated transportation vehicles, including a pressurized rover capable of supporting trips of several days' duration from the habitat; (h) crew stay times of 500 d on the surface, with six-person crews; and (i) multiple functional redundancies to reduce risks to the crews on the surface. New concepts are being sought that would reduce the overall cost for this exploration program and reducing the risks that are indigenous to Mars exploration. Among those areas being explored are alternative space propulsion approaches, solar vs. nuclear power, and reductions in the size of crews.

HABITAT CONSTRUCTION REQUIREMENTS.

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Human-occupied habitats on either the Moon or Mars will need to make the maximum practical use of *in situ* resources for reasons of overall mission economy and because of transportation limitations. How the *in situ* resources can best be used, and to what extent they may be used, will depend on several factors, including the basic structural demands of the habitat, the maturity of the habitat and associated mission, manufacturing and construction support needed to use the material, and the degree the habitat use of such material fits with base capabilities to process such *in situ* material for other base and mission requirements.

Habitats on either the Moon or Mars must contain, with minimum leakage and a high level of reliability, a life-supporting artificial atmosphere that allows its human occupants, along with plants and other living components of its life support and food system, to survive and thrive. In the reduced gravity environment of either site, the internal pressure of the needed atmospheric gases will dominate the structural loading of the operational habitat, even if a several-meters-thick layer of mass shielding is placed atop the habitat. However, the habitat must be designed with the deployment/construction operation in mind, including the placement of mass shielding, the outfitting of the habitat, and possible planned or accidental depressurization of part or all of the habitat interior.

The practical uses of *in situ* materials will change as the base and its habitats progress through maturity steps that may be described as exploratory, pioneering, outpost, settlement, colony, and beyond. More processing, forming and manufacturing, and applications become possible as capabilities and activities of the base expand. Proposed and planned *in situ* material uses need to be associated with a level of base maturity in describing what uses are practical.

The net savings of imported mass also needs to be considered — the mass of imported processing and construction/handling equipment and any additional crew (and their support) or robotic resources needed to utilize *in situ* materials will act to partially offset savings in imported structural and other product mass. The practical availability of glass, metals, and other products derived from lunar or martian minerals, ores, and other raw materials will depend on how processing equipment can be miniaturized and operated with minimal energy and other resource needs.

Uses for *in situ* materials include (a) structural portions and shielding for the habitat, (b) habitat interior gases, (c) associate base infrastructure features, and (d) energy and other support systems.

Depending on the construction scheme, loose granular, bagged, sintered, or other minimally processed material can be used for shielding — for radiation, micrometeorites, and thermal stabilization. The use of many such materials, along with concretes, can be limited by their low tensile strengths for the pressure-containing core of the habitat. For the first several levels of base maturity, *in situ* material use will supplement imported structural habitat cores (rigid and/or inflatable). Lunar glass, metals, and other refined products for use as reinforcement and post-tensioning, as well as for interior structure, may become practical at fairly high base maturity levels. Even then, high value and specialty items will need to be imported.

Habitat interior gases can represent a sizable fraction of total base and habitat mass needs, and use of *in situ* resources, including water, to obtain O and other atmospheric components promises significant savings over an all-imported scenario. The availability of the needed Ar, Ni, C, and other elements necessary for plant growth and for an atmospheric composition with acceptable flammability and pressure characteristics is different, and generally more favorable, on Mars than on the Moon.

Granular material obtained by screening planetary regolith and the use of the sand and gravel-sized fractions of this material to surface and thus improve roadways (i.e., provide dust control and a smooth, firm surface) and to armor space port areas and active surfaces represents a potentially large, if unglamorous, use of *in situ* materials. The use of formed paving blocks for even higher quality surfaces may be the first practical use of lunar/martian concrete and sintered material. These *in situ* materials may also be formed into containers. Later, glasses and metals derived from *in situ* materials may be used for tanks and other routine equipment. Energy generation and storage for nighttime use will be a major operational challenge — *in situ* materials can serve as insulating and heat sink masses, perhaps in association with heat pumps. Fabrication of solar cells using processed *in situ* Si and other materials may prove practical. At some stage of maturity, portions of the construction equipment and tools needed for habitat expansion and base operation may be made from refined local resources.

This overview paper has the objectives of (1) giving a broad view of the overall requirements and challenges of utilizing *in situ* materials in human-occupied habitats and supporting base facilities, and (2) to survey several types of uses that the author considers most practical. Planning for future habitats must include the maximum practical use of *in situ* materials. What uses are feasible and economical will depend upon base maturity, enabling technologies available for material processing, the resource investment needed to process *in situ* materials into the desired final product (imported mass of equipment, energy needs, human resources), and base mission, including any *in situ* products. The planning of *in situ* material use must consider both the development of specific applications and the overall base/habitat human, energy, and technological needs and resources.

SEMICONDUCTORS: *IN SITU* PROCESSING OF PHOTOVOLTAIC DEVICES.

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Current proposals for developing an extended human presence on the Moon and Mars increasingly consider the processing of nonterrestrial materials essential for keeping the Earth launch burden reasonable. Utilization of *in situ* resources for construction of lunar and Mars bases will initially require assessment of resource availability followed by the development of economically acceptable and technically feasible extraction processes. In regard to materials processing and fabrication, the lower gravity level on the Moon (0.125 g) and Mars (0.367 g) will dramatically change the presently accepted hierarchy of materials in terms of specific properties, a factor that must be understood and exploited. Furthermore, significant changes are expected in the behavior of liquid materials during processing. In casting, for example, mold filling and associated solidification processes have to be reevaluated. Finally, microstructural development, and therefore material properties, presently being documented through ongoing research in microgravity science and applications, need to be understood and scaled to the reduced gravity environments.

One of the most important elements of a human planetary base is power production. Lunar samples and geophysical measurements returned by the Apollo missions provide detailed data on the composition and physical characteristics of the lunar materials and environment. Based on this knowledge and extrapolations of terrestrial industrial experience, it is clear that several types of solar-to-electric converters can be manufactured on the Moon. It is conceivable that well over 90% of a solar-to-electric power system could be made from lunar materials. Production and utilization of photovoltaic devices for solar energy production on Earth is primarily driven by the market economy. On Earth a production plant for photovoltaic devices is intimately linked to the planet's massive industrial base. A selection of off-the-shelf refined materials is available, as is cheap, fast transportation on demand. The processes take place (except for the few seconds' reprieve in shot towers, etc.) under one gravity, with solar radiation significantly modulated by weather, and under conditions where the atmosphere is free and high vacuum is cumbersome and expensive. Off Earth, on lunar or Mars bases, the cost of photovoltaic power is driven by transport costs — Earth launch, deep space transport, landing on the planetary surface. Thus there is a premium for processes that are materials self-sufficient or for closed-loop *in situ* processes. The lack of differentiated ores on the Moon and lack of explored minerals on Mars and interplanetary space give a premium to universal/non-ore-specific mineral extractive processes. Initially a semiconductor/photovoltaic production facility will be built without a local industrial base, further increasing the premium on closed-loop self-sufficient processes. The lack of a preexisting industrial base beyond Earth also provides an opportunity to integrate the architecture for propulsion, transport, power, and materials processing to achieve long-range materials/energy self-sufficiency. Such self-sufficiency can enable an economically positive permanent human presence on Moon and Mars. An example of such synergism might be a Solar Electric Propulsion (SEP) cargo vessel that converts to a Solar Power Satellite (SPS) on reaching Mars orbit. The SEP might eventually be built utilizing lunar materials, reducing transportation costs by an order of magnitude. On a lunar or Mars base, the cost to install capital equipment will be high. Thus, there will be a premium on "organic" technologies that can grow or "bootstrap." The most practical approach could well be *in situ* human-in-the-loop self-replicating facilities. Such a facility would start small and achieve better than linear growth until the desired production rate or energy output is reached. Thus, materials-processing issues could be quite critical to the establishment of a permanent human presence on the Moon and Mars in an economically feasible manner.

OPPORTUNITIES FOR ISRU APPLICATIONS IN THE MARS REFERENCE MISSION.

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The NASA Mars Exploration Reference Mission envisions sending three crews of six astronauts to Mars, each for 500-day stays on the surface. ISRU has been baselined for the production of propellant for crews leaving the surface, as well as to create reservoirs of water and life-support consumables. These applications improve performance (by reducing the mass of hardware and supplies that must be brought to Mars for the propulsion system) and reduce risk (by creating consumables as backups to stores brought from Earth). Similar applications of other types of ISRU-derived materials should be sought and selected if they similarly improve performance or reduce risk. Some possible concepts for consideration, based on a review of the components included in the Reference Mission, include (1) emplacement of a hardened landing pad; (2) construction of a roadway for transporting the nuclear power system to a safe distance from the habitat; (3) radiation shielding for inflatable structures; (4) tanks and plumbing for bioregenerative life-support system; (5) drilling rig; (6) additional access structures for equipment and personnel and unpressurized structures for vehicle storage; (7) utilitarian manufactured products (e.g., stools and benches) for habitat and laboratory; (8) thermal radiators; (9) photovoltaic devices and support structures; and (10) external structures for storage and preservation of Mars samples. These may be viewed principally as mission- enhancing concepts for the Reference Mission. Selection would require a clear rationale for performance improvement or risk reduction and a demonstration that the cost of developing and transporting the needed equipment would be recovered within the budget for the program. Additional work is also necessary to ascertain whether early applications of ISRU for these types of purposes could lead to the modification of later missions, allowing the replacement of infrastructure payloads currently envisioned for the Reference Mission with science or technology payloads (improving performance). This class of ISRU use can be tested on the Moon before sending people to Mars and much of the production and assembly could be done robotically. The technology developed would lead to the capability for expansion of the outpost beyond the Reference Mission, with diminished need for materials from Earth.

MATERIALS TRANSPORTATION.

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The movement of materials on planetary surfaces is seen to be a challenge for all stages of developing a permanent facility. The unloading of cargo spacecraft, the deployment of cargo and materials to construction sites, and the movement of large amounts of material needed for some scenarios where *in situ* resources are to be recovered are all situations requiring equipment development.

Adaptations of many terrestrial technologies can be expected as designers meet these challenges. Large vehicles, tracked or wheeled, tractor trains, and maglev rail systems might form the basis of a mobile vehicular approach. Pipelines, cableways, and conveyor systems are likely to be adapted for large-scale, continuous materials-delivery roles.

Difficulty of large-scale transportation may force a "mobile factory" approach wherein the processing facility moves over the source fields, lifting, processing, and then depositing wastes behind its track. On the other hand, large power requirements may dictate a stationary facility and hence force delivery of material resources for long distances over rugged terrain. Even in the case of large vehicles, power is likely to be provided by onboard fuel cells or batteries. The weight of these systems will decrease the effective payload of the vehicle. This will influence the results of trade-off studies where integrated systems designs are compared.

In some situations a small processing facility may be served by a series of robotic bulldozers that continuously scrape the resource material toward the fixed plant. Again, power demands and the condition of the resource material will drive the design of the transportation system. Providing simple, rugged, and reliable materials-transportation systems will be the goal of designers.

REQUIREMENTS FOR PLANETARY OUTPOST LIFE-SUPPORT SYSTEMS AND THE POSSIBLE USE OF *IN SITU* RESOURCES.

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If humans are ever to live and work on the Moon or Mars for extended periods of time, the operation of regenerative life-support systems at the planetary outposts will be a critical requirement. The substantial amount of materials consumed by humans (Table 1) and the inevitable waste products make open-loop life-support systems and resupply missions (as used in Space Shuttle and Mir operations) impractical and expensive. Natural resources found on the Moon and Mars (Table 2) could be used in conjunction with regenerative life-support systems to further reduce the amount of material that would need to be delivered from Earth.

There have been numerous studies and experiments conducted on the production of O from regolith materials on the Moon [2] and from the atmosphere of Mars [3]. One or several of these processes could undoubtedly be used to produce the O required by the crews at planetary outposts. Water is required in the greatest quantities, primarily for tasks such as personal hygiene and clothes washing, and it will be the most precious consumable. Again, several process have been described to produce water on the Moon using solar-wind-implanted H and O [2], and if water ice can be found and mined at the lunar poles, another source of water may be available. On Mars, water ice exists as polar deposits, and it is thought that permafrost

TABLE 1. Estimated total mass of consumable materials required to sustain one person for one year at a planetary outpost [1].

Consumables	Mass (kg/yr)	% of Total
Water	10,423	86.1
Oxygen	305	2.5
Food (dry)	265	2.2
Crew supplies (e.g., soap, paper, plastic)	253	2.1
Gases lost to space (e.g., oxygen, nitrogen)	257	2.1
System maintenance	606	5.0
Total	12,109	100

TABLE 2. General life-support system requirements and possible *in situ* resource utilization applications.

Requirement	Lunar Resources	Martian Resources
Air (e.g., oxygen, nitrogen)	oxides in regolith solar wind volatiles	atmosphere water
Water	oxides in regolith, solar wind hydrogen, polar ice?	polar ice, hydrated minerals, permafrost? liquid water at depth?
Food production	regolith substrate	regolith substrate carbon dioxide atmosphere
Environmental protection (e.g. radiation, temperature)	bulk soil shielding sintered/cast regolith underground cavities	bulk soil shielding sintered/cast regolith underground cavities
Storage tanks	cast regolith	cast regolith
Piping	cast regolith	cast regolith

may exist at high latitudes and that liquid water may exist 1–2 km below the martian surface [4]. Even though the idea of regenerative life-support systems is to recycle and reuse all consumables, there are always inefficiencies and losses (e.g., residual airlock gases) that will require the replenishment of O, N, and water.

The regoliths on the Moon and Mars can be used as a solid support substrate for growing food crops. It has been estimated that approximately 32 m^2 of plant growing area is required for the food production and waste regeneration to maintain one human [5]. This far exceeds the 4 m^2 and 14 m^2 of plant growth area needed for water and O production, respectively. Assuming a planting depth of 10 cm, approximately 3.2 m^3 of bulk regolith per person would need to be excavated and moved into a plant growth chamber. However, the regoliths on the Moon and Mars lack essential plant growth nutrients, and would need to be amended with slow-release fertilizers and composted organic wastes [6,7].

Protection from the extreme thermal and radiation environments and from micrometeoroid impacts should be mentioned when discussing life support and the health of the crews at planetary outposts. Protection can be provided by using bulk regolith or sintered/cast materials as shielding, or by locating the outposts in underground cavities, such as caves or lava tubes [2].

Life-support systems require reservoirs to contain consumables such as water or plant-growth nutrient solutions, provide for storage and composting of wastes, and house components such as bioreactors. Also, large habitat structures for living and plant growth areas will be needed as outposts expand in capability. These structures, reservoirs (or tanks), and associated piping could be cast from molten regolith materials, as has been proposed for lunar habitat structures [8,9]. Cast-basalt technology has already been in use in Europe for several decades.

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FISSION POWER SYSTEMS FOR SURFACE OUTPOSTS.

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Space-fission power systems can potentially enhance or enable ambitious lunar and martian surface missions. Research into space fission power systems has been ongoing (at various levels) since the 1950s, but to date the U.S. has flown only one space-fission system (SNAP-10A in 1965). Cost and development time have been significant reasons that space-fission systems have not been used by the U.S.

High cost and long development time are not inherent to the use of space-fission power. However, high cost and long development time are inherent to any program that tries to do too much at one time. Nearly all U.S. space-fission power programs have attempted to field systems capable of high power, even though more modest systems had not yet been flown. All of these programs have failed to fly a space-fission system.

Relatively low-power (10–100 kWe) fission systems may be useful for near-term lunar and martian surface missions, including missions in which *in situ* resource utilization is a priority. These systems can be significantly less expensive to develop than high-power systems. Experience gained in the development of low-power space fission systems can then be used to enable cost-effective development of high-power (>1000 kWe) fission systems.

For a space fission concept to have the potential of having a short development schedule and a low development cost, it should have the following 10 attributes:

Safety. The systems should be designed to remain subcritical during all credible launch accidents, preferably without using in-core shutdown rods. Passive subcriticality can be ensured by designing the systems to have a high radial reflector worth and by using resonance absorbers in the core. The systems should also passively remove decay heat and be virtually nonradioactive at launch (no Pu in the system).

Reliability. The systems should have no single-point failures. If single-point failures exist, they should only be with components that can easily demonstrate a high reliability, or for those for which a high reliability has already been demonstrated.

Lifetime. Materials and fuels should be chosen to ensure adequate lifetime without requiring an extensive development program.

Modularity. The system should be modular, with little interdependence between modules. Development of modules is generally less expensive and time consuming than development of a nonmodular system that must be fully integrated before meaningful data can be obtained.

Testability. It should be possible to perform full-power system tests on the actual flight unit without the use of fission-generated heat. After the full-power tests, very few operations should be required to ready the system for launch. Flight qualification should be feasible with nonfission system tests and zero-power criticals. No ground nuclear power test should be required, although it may be requested by the sponsor.

Versatility. The system should be capable of using a variety of fuel forms, structural materials, and power converters. Maximum advantage of other programs must be taken.

Simplicity. System integration is often the most challenging aspect of space fission system design; thus, system integration issues should be minimized.

Fabricability. Complex, hermetically sealed components should be avoided, bonds between dissimilar metals minimized, and general system fabrication kept as straightforward as possible.

Storability. The system should be designed so that the fuel can be stored and transported separately from the system until shortly before launch. This capability will reduce storage and transportation costs significantly.

Acceptable performance. The system must have adequate power capability and adequate specific power for potential missions of interest.

For the past three years, Los Alamos National Laboratory has been developing a design approach that would help enable the use of near-term, low-cost space fission systems. As part of that work a modular system concept has been developed and a prototypic module (1/12 core) has been successfully tested. The module has operated at prototypic conditions and has undergone nine startup/shutdown cycles. Additional tests of the module are planned in 1998.

Significant mass savings can be achieved if regolith is used to provide radiation shielding for surface fission power supplies on the Moon or Mars. A regolith shield 2–3 m thick will provide adequate shielding for most applications. In addition, fuel for future systems could be obtained from the lunar or martian soil.

CAST BASALT, MINERAL WOOL, AND OXYGEN PRODUCTION: EARLY INDUSTRIES FOR PLANETARY (LUNAR) OUTPOSTS.

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In the terrestrial environment, transportation cost is the basic limitation on the use of building materials such as sand, cement, gravel, and stones. Because of transport cost, local materials are preferred over imported, higher-quality materials. This is apparently the case for lunar and martian outposts as well, and this fact is augmented by the need to transport as little technological equipment as possible. In order to optimize the energy that will be available at planetary outposts, it is suggested that the production of cast-basalt building bricks, isolation materials such as mineral wool, and O should be achieved contemporaneously.

There is a long history of cast-basalt production in Europe. The first attempts were made in Germany and France (e.g., the French Compagne General du Basalt was founded in 1924) and numerous processes were patented. In the Czech Republic, a glass-making factory was converted into a basalt-casting factory in the late 1940s. Recently, a company named Eutite (Stara Voda near Marianske Lazne) has been a major European supplier of cast-basalt products, with a production rate of about 40,000 tons a year. The company produces tiles, pipes, sewage, and industrial pipe inlays. The data presented below are based on the experience gained through Eutite.

The major (and only) raw material that is used is olivine alkaline basalt of Cenozoic (Oligocene) age. It is fine-grained basalt, containing olivine, clinopyroxene, magnetite, plagioclase, and nepheline plus a small proportion of glass. The chemical composition of this basalt is SiO_2 43.5–47.0, TiO_2 2.0–3.5, Al_2O_3 11.0–13.0, Fe_2O_3 4.0–7.0, FeO 5.0–8.0, MnO 0.2–0.3, MgO 8.0–11.0, CaO 10.0–12.0, Na_2O 2.0–3.5, K_2O 1.0–2.0, and P_2O_5 0.5–1.0 (wt%). The material is open-pit mined from a single basaltic unit through “small-scale” mining with minimum blasting in order to avoid material contamination by soil, etc. Material is crushed (less than 100-mm-sized pebbles), washed, and then filled through the shaft to a kiln heated by natural gas. Temperatures of 1180°C to 1240°C are maintained in order to completely melt the material into a homogeneous melt reservoir. Melting takes approximately 1 hr, since preheating takes place in the shaft above the kiln. The reservoir of basaltic melt is kept close to or slightly above liquidus temperature in order not to destroy crystallization nuclei present in the melt. The crystal nuclei play an important role during the quenching and cooling of the melts.

The process of casting itself is similar to metal casting, although differences exist due to the lower density and higher viscosity of basaltic melt. Molds are made from either metal (Fe) for the tiles or sand forms for more complicated casts. To avoid a completely glassy product, which alters the cast properties, products are recrystallized. This represents “cooling” in the tunnel kiln with a temperature gradient of 900°C to 50°C where the products are kept for 24 hr in order to partly crystallize. Massive products are cooled longer. The products that are part crystallized and part glassy appear to have the best features. The cast-basalt products have excellent properties with respect to strength (pressure measured according to DIN51067 is 300 MPa). At room temperature, the cast basalts are inert to acid solutions (except HF) and to hydroxides. The resistance to leaching decreases with increasing temperature. Cast basalt has a high tolerance to temperature change; it is frost resistant and it is not porous. The density of cast basalt is 2900–3000 kg m^{-3}.

The need for shielding and building material makes the cast basalts an ideal material for planetary outposts. High durability and extremely low abrasive wear also makes the cast-basalt tiles an ideal material for communication paths.

The composition of the lunar regolith depends on the proportions of mare and highland components. Compared to terrestrial materials, both lunar components are SiO_2, Na_2O, and K_2O poor. Mare components contribute high amounts of TiO_2, FeO, and MgO, whereas highland components contribute high Al_2O_3 and CaO. The chemical and mineral compositions as well as the grain size of regolith fines appear suitable for melting. Due to higher than terrestrial FeO content of lunar fines, the melting temperatures will be comparable to those of terrestrial composition.

Because of the easy casting of the detailed parts (relatively low viscosity of basaltic melts), locks and catches could be designed and formed in order to make molded bricks into a self-locking system without the need for another joint material or additional parts for both vertical and horizontal constructions.

Mineral Wool Production: There is one disadvantage of cast-basalt material: it has a relatively high thermal conductivity. In order to ensure high insulation properties, fiberglass mineral wool should be produced contemporaneously with the cast basalts. This should not pose any technological problem with emplacement of the rotating disk next to the casting equipment.

Oxygen Production: The production of cast-basalt molded bricks and construction elements from ilmenite-enriched or Fe-rich lunar basalt could be accompanied by the production of O. The method should use an effect of Fe reduction at higher than liquidus temperatures. It has been shown earlier and it is easily demonstrated that the O fugacity could be achieved through the addition of a reducing medium such as coke and also by the increase of temperature. In the silicate system (e.g., basaltic system) the increase of the temperature above the liquidus by about 300°C causes depolymerization of melts and, as a consequence, contemporaneous decomposition of FeO into metallic phase (2FeO) and O (O_2). The release of O is accompanied by the gases escaping from such melt will contain amounts of Na and K oxides. This reaction could be achieved without additional parts and complicated technological equipment, e.g., equipment for the electrolysis. Such a process would require further laboratory research and experiments with superheated melts.

The availability of materials for the production of molded bricks should be included among the site selection criteria.

Since the basalt used by the Eutite company could easily be modified to simulate the chemical composition of lunar fines, it is suggested that experiments with casting basalts of such composition should be carried out and the properties of cast products, e.g., molded bricks, floor tiles, and pipes, should be studied.

CONSIDERATIONS ON THE TECHNOLOGIES FOR LUNAR RESOURCE UTILIZATION.

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Various types of lunar-derived materials will be required for lunar base construction and other lunar activities. They include O, nonprocessed lunar regolith, cast basalt, glass, ceramics, cement, and metals. Activities on the Moon will be gradually expanded following the lunar developmental scenario as suggested in many previous studies. A possible scenario could consist of the following phases.

Survey of the Moon. Unmanned missions such as scientific explorations using lunar roving vehicles and lunar orbiters will be conducted. Simple experiments could be also performed on the Moon.

Lunar outpost. A small lunar surface station will be constructed using structural materials transported from Earth. The station will provide a living environment, an observatory, and a laboratory for humans to stay for short periods.

Initial lunar base. The lunar surface station will be expanded. The base structure will be partially constructed using lunar-derived materials. Advanced studies on lunar material processing and life support will be conducted.

Expanded lunar base. Most of the base structure will be constructed from lunar materials. Large-scale material processing plants will be developed.

Autonomous lunar base. Dependence of lunar activities on terrestrial materials will become minimum. The lunar base will become a logistics support station for further space exploration.

The scenario for lunar resource utilization will be greatly affected by this scenario of lunar development. The outlines of each material are summarized below:

Oxygen. The unmanned experimental production of lunar O could be performed during the survey phase, and reliable processes selected from those experiments. This technology will be matured in the following phases, and lunar O will gradually become an important material for supporting various lunar activities. After the expanded lunar base phase, lunar O will also be used as an oxidizer for spacecraft.

Nonprocessed regolith. The most primitive structures, which might be used as warehouses, will be constructed by utilizing natural caves or by tunneling crater walls. In this case, lunar regolith could be the structural material just by digging and banking it. More advanced utilization of the regolith will include sandbags, which can be piled up to make simple structures such as warehouses and shielding walls.

Cast basalt and glass. Cast basalt and glass can be produced by a relatively simple process of cooling molten basalt. High-quality materials can be obtained by controlling factors such as chemical composition and processing temperature profile.

Ceramics. Ceramics will be made by sintering formed lunar soil. A sintering furnace may also be needed for making ceramics. Casting and sintering technologies can be combined in the advanced stages of material processing to produce composite products such as cast bricks formed with ceramic. The tempering process will also be performed in the sintering furnace to make cast material more ductile and useful.

Cement. Cementitious materials such as concrete basically consist of cement, water and aggregates (sand and gravel) and are produced by curing mixed material in molds. Although H may need to be transported from Earth to provide water, all other concrete materials can be produced from lunar resources. Cementitious materials are expected to be applied to many types of lunar structures such as heat insulators, radiation shields, foundations, and roads.

Metals. Metals will be extracted from lunar resources by means of reduction and/or electrolysis processes. Properties of the product metal will vary depending on the degree of refinement and the alloyed elements. As both cementitious materials and metals will require relatively complex production systems, the production of these materials on the Moon would appear to be realized in the later phase of lunar base operations.

A range of technologies will need to be developed, as outlined below.

Mining and materials transportation. Any type of resource utilization requires fundamental technologies such as excavation, mining, surface transportation, and energy, which is a combination of power generation and power transmission. Size and structural components of these systems will change depending on the lunar developmental phases.

Preliminary processing. Preliminary material processing on the Moon includes beneficiation, heating and cooling control, reduction, electrolysis, melting and solidifying, and sintering technologies.

Beneficiation. Separation and concentration of components of lunar soil will be required in some material processes to improve the efficiency of the following steps.

Heating and cooling control technology. Temperatures of up to 1000 K will be used for desorbing gases such as He and H. Temperatures of 1500 K can be used for sintering processes, and 2000 K will be used for melting lunar materials. Much higher temperature will vaporize or ionize the materials. Lunar resource utilization will certainly require this technology.

Chemical reduction. Various reduction processes have been proposed up to this point. Reductants could be H, C, CO, CH_4, F, Al, Li, Na, and so on. Since each process, which uses each one of these reductants, has its own merits, demerits, and target products, selection of the most promising process seems difficult at this point. Further studies will be required.

Electrolysis. Many processes require the electrolysis of liquid water at ordinary temperature, although in some O production processes, electrolysis of vapor water at high temperature is required. Regolith melts with or without fluxes could be also electrolyzed.

Cast and glass products will be made by means of the melting and solidifying process, and these products will be utilized as bricks, rods, pipes, cables, and so on. This process may consist of mold production, spin or cast forming, finishing, and tempering processes.

Sintering process could also produce similar products as cast materials. Powder production, powder mixing, forming, sintering, and tempering processes will be essential.

Secondary processing. Secondary processing includes more sophisticated technologies such as refining and purifying, concreting, and assembling. Pure metals and complicated composites could be produced from this processing.

THE SALTS OF MARS — A RICH AND UBIQUITOUS NATURAL RESOURCE.

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The Viking and Pathfinder Mars landers have shown that martian soil is highly enriched in Cl, S, P, and perhaps Br, which, in all likelihood, occur as salts (chlorides, sulfates, phosphates, and perhaps bromides). Carbonates also may be present. Many martian salt minerals are believed to be hydrated. These water-soluble constituents of the soil will offer the first colonists a rich source of many industrial commodities needed to sustain and grow the colony. Being hydrous, martian salts hold a tremendous potential to supply water in regions of Mars where otherwise preferable ice may be absent or difficult to access. A caliche-like form of concrete or adobe may be manufactured by the drying of briny mud. Sulfates and phosphates may be used as additives for the manufacture of soil prepared and balanced for agriculture. Sulfates and chlorides offer a raw material for the manufacture of sulfuric and hydrochloric acids. Electrolytic processes applied to magnesium sulfate solution may yield metallic Mg. In short, martian salts will offer colonists a broad industrial base of chemical substances potentially useful in development of indigenous construction, chemical, and agricultural industries. Best of all, such salty dust deposits are among the most widespread and chemically uniform (i.e., dependable) raw materials on Mars. A simple method of preprocessing martian soil to extract and isolate the major salt consituents and to obtain water will be presented, as will a more thorough presentation of possible industrial uses of these materials in a Mars base.

MATERIALS REFINING FOR STRUCTURAL ELEMENTS FROM LUNAR RESOURCES.

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Use of *in situ* resources for construction on the Moon will require manufacturing structural materials out of lunar resources. Many materials that are currently used for aerospace and construction require materials that have low availability on the Moon [1]. For example, graphite fiber, SiC fiber, and artificial fiber composites (such as Kevlar, Spectra, etc.) are used as advanced lightweight structural materials on Earth, but the low availability of C on the Moon makes these poor choices. Likewise the polymers used as the matrix for these composites, epoxy or polyester, also suffer from the low availability of C. Bulk paving and construction materials such as cement or concrete suffer from the low availability of water on the Moon, while asphalt, a common paving material on Earth, suffers from the low availability of C.

Structural materials that could be manufactured from lunar materials include steel, Ti, Al, and glass. Composite materials could be made of a glass/glass composite, while paving/construction could be done using sintered-regolith brick or a glass-matrix regolith brick.

Figure 1 shows a flow chart for a generic manufacturing process for making construction materials from *in situ* materials. For a practical process, the following criteria need to be used to select a process:

1. To minimize input from Earth, the process must include 100% recycling of nonlunar reactants (slag must not bind reactant or catalyst), and the need for replacement parts should be minimized (crucibles should require many batches without replacement and sacrificial electrodes should be avoided).
2. To minimize energy requirements, the process should avoid high-temperature process steps where possible, and subject to other constraints, the simplest possible process, and a process that can make as many useful materials as possible, should be chosen.

Candidate process sequences for manufacturing these materials out of lunar regolith are proposed. For example, the simplest possible process for Fe production from lunar regolith may be to separate out meteoritic Fe, metallic Ni-Fe that is present in concentrations of a few tenths of a percent in lunar regolith, deposited in the form of micrometeorites. This may be separated from soil using magnets, although the process may require grinding the soil first. An alternate process would be to refine Fe from lunar regolith. This will be a more complicated and energy-intensive process, but may well be the same process used for refining Al or Si, and will also produce O as a byproduct. (The converse is not true: Fe is not a byproduct of O production, since the lowest cost O production sequences typically do not reduce the lunar regolith all the way to refined Fe.)

Likewise, a F processing sequence discussed elsewhere [2] for manufacture of Si and other components for solar arrays could be used to refine Al, Ti, and glass-forming elements. Aluminum can also be produced by electrolysis techniques [3], a process that also might

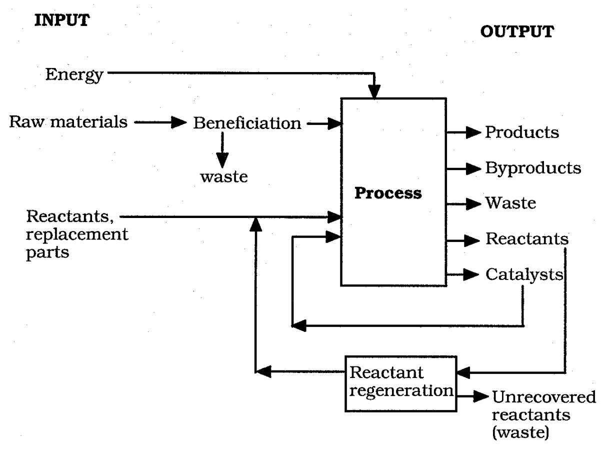

Fig. 1. Flow chart for generic manufacturing process on the Moon.

might produce Si usable for solar cell manufacture [4]. Process sequences for glass-glass composite can be developed to produce a composite using anorthite fibers in an aluminosilicate glass [2,5].

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LUNAR AND MARTIAN RESOURCE UTILIZATION — CEMENT AND CONCRETE.

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Concrete is used in massive amounts on Earth for the construction of buildings, foundations, roadways, pipes, and specialty uses. Its use on the Moon and Mars has to take into consideration the availability of the natural materials as well as the environment in which it is cast and cured. It has not been considered ideal for planetary surface construction because it requires water, which has been assumed to be in short supply, and because special processes would have to be used in the very low atmospheric pressure environment of the Moon and Mars. However, the authors have conducted a cement/concrete research program using simulated lunar and martian materials over a period of several years. Funding has come from governmental agencies in the United States, Japan, Indonesia, and Taiwan.

NASA has considered various approaches to building outposts on other planets. Concepts that establish habitation for several crew members, power supplies, and processing plants to produce propellant from indigenous sources have been considered. The availability of construction materials from indigenous sources can enable the construction of shelters for habitats and unpressurized storage areas, as well as radiation, meteoroid, and thermal shielding without the importation of large masses of materials from the Earth. Concrete is a versatile material that can be derived entirely from the natural resources of the planet's surfaces.

The surface of the Moon is covered by broken-up rocks that have been altered by micrometeorite impact to produce regolith. The regolith is fine-grained and poorly sorted and consists of rock fragments, mineral fragments, and glass from volcanic and impact sources. It is possible to easily separate coarser material, which would make the sand and gravel constituents of concrete. Lunar mare basalts have low CaO concentrations and are unsuitable for making conventional Portland cement; however, lunar anorthosites are high in CaO and could be a starting material for Portland cement production. Calcium carbonate is not known to exist on the Moon. Alternatively, simulated lunar anorthosite rocks (17% CaO) and lunar basalt (12% CaO) have been successfully used by the principal author in 1998 to formulate cementitious materials that hydrate exceedingly well in a steam environment.

Early discussions of lunar concrete considered that the Moon was poor in water, and it was suggested that H might have to be brought from Earth. Whereas the total water content of cured concrete is low, the amount of H that would be needed would be less than 0.5% of the total concrete weight. Now, with the possible discovery of water in the polar cold traps at the lunar north and south poles, lunar water can also be considered available. If no material for concrete production must be brought from Earth, the indigenous materials will provide great leverage and should be considered in the design of surface facilities.

Martian surface materials apparently are derived from basaltic rocks and are therefore low in CaO. However, there is speculation that water played a part in the surface history of Mars, and evidence is being sought for the existence of evaporites (e.g., gypsum, carbonates), which could be enriched in Ca. If small concentrations of Ca-bearing minerals can be identified, it may be possible to concentrate the CaO by chemical or physical means. Mars contains water in its atmosphere and its polar caps, and we require only further surface exploration to determine whether there is abundant water in the form of permafrost, hydrated minerals, or even in the form of water in deep, isolated reservoirs.

We have recently developed a Dry Mix/Steam-Injection (DMSI) method of concrete production, which can be used to manufacture precast concrete. This method can be developed for application in the surface environments of the Moon and Mars, through technologies similar to those being discussed for inflatable structures. Laboratory tests carried out at the National Chiao-Tung University, Taiwan, have successfully demonstrated production of 10,000 psi concrete after 18 hr of steaming a dry mixture of Portland cement and normal weight aggregate. Based on the measured water-cement ratios of 0.24 to 0.33, the calculated weight percentage of water in a DMSI concrete is approximately 5%, less than one-half that of a comparable wet-mix concrete.

A small international group has been formed to study lunar cement formulation and lunar/martian concrete production using simulated lunar anorthosite rocks, lunar soils, and martian soils. The results of these investigations show that mortar cubes made with the formulated lunar cement using the DMSI procedure developed strengths ranging from 5000 psi (Hokkaido anorthosite) to 7000 psi (California anorthosite). On the other hand, test cubes made with the conventional wet-mix procedure using ordinary Portland cement and lunar/martian soil simulants provided by Johnson Space Center for aggregate application produced slightly more than 5000 psi for lunar concrete and only 880 psi for martian concrete. Obviously, more research will be needed to study the possible use of martian soils in casting concrete.

Several issues associated with concrete production have been identified: the application of solar energy to evaporate nonessential oxides and to sinter raw materials; quenching and milling procedures in low-*g*, high-vacuum environments; DMSI precasting procedures; conceptual design for precast structures for planetary outposts; and remote-control and automation systems for casting concrete.

VOLCANIC GLASSES — CONSTRUCTION MATERIALS.

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Natural glass is the product of rapidly cooled molten rock. Two natural sources of the melt are volcanic eruption and meteoritic impact. Pure glass is an amorphous aggregate. Volcanic glass is a material that could be utilized in the construction of extraterrestrial outposts. Pumice and perlite are volcanic glasses currently used in the building industry. Samples of natural volcanic glass found in the lunar regolith were returned to Earth as part of the Apollo and Luna programs. An alpha proton X-ray spectrometer onboard the Pathfinder recently examined martian rocks located in the vicinity of the lander craft. Preliminary results of chemical composition by weight of SiO_2 50–55%, Al_2O_3 11–13%, K_2O 1–2%, Na_2O 2–5%, CaO 4–6%, MgO 3–7%, FeO 12–14%, SO_3 2–5%, and MnO <1% were given for two rocks. Parenthetically, the values for K and Mn were perhaps too high, and the analysis was based on X-ray data only. The appreciable amount of silica already found on Mars and empirical evidence to support the hypothesis that the planet once had water sufficient to rapidly cool magma imply the possibility of discovering natural glass of volcanic origin in subsequent missions.

Pumice contains innumerable cavities produced by the expansion of water vapor in the erupting magma. For this reason, the porous material is an excellent thermal insulator. It is also lightweight and easy to handle. Finely ground pumice becomes an additive to cement and an abrasive for cleaning, polishing, and scouring compounds. The cavities are usually oblong and tubular in shape set by the direction of lava flow during solidification. Between vesicles, the glass is fibrous and threadlike. Typically, the molten igneous rock consolidates to a froth in an interval of time too short for crystals to form. In older volcanic rock, however, the vesicles can be filled with minerals introduced by percolating water. What is interesting about this glass is its connection to another glass, obsidian. Laboratory experiments can demonstrate how shards of obsidian under pressure and fusion change into pumice as measurable quantities of dissolved gases are released. Rhyolite and trachyte pumices formed during extreme vesiculation are white in color, and have a specific gravity of 2.3–2.4. Andesite pumice is yellow or brown, and basaltic pumice is black.

Similar to granite in chemical composition, perlite possesses distinctive concentric cracks probably resulting from contraction of the cooling glass under hydration. Their arrangement causes spherules to separate from the surrounding material. The spherules may form a matrix or coalesce to form polygon-shaped pellets. The glass may have large crystals of quartz, alkali feldspar, and plagioclase. Some small glass pellets show double refraction, suggesting a strained condition in the material. Double refraction also appears at the surface contiguous with phenocrysts caused by differential contraction. Perlite carries 3–4% water, and therefore it can be “popped” in a furnace like popcorn in an oven. When heated to a softening temperature of about 1100°C, the water turns to steam, tiny encapsulated bubbles are generated, and the sample swells. Specimens can reach 20× their original volumes. Heat treated perlite substitutes for sand in lightweight wall plaster and concrete aggregate. Its porous constitution is ideal for heat insulation and its pearly luster appearance enhances ceramic finishes. Initiated along cracks and crystal boundaries, devitrification transforms the material into a fine crystalline aggregate. Perlite has a Mohr hardness of 5.5, a density of around 2.37 before expansion, and a refraction index of 1.495. The density increases with index of refraction.

Lunar samples brought back to Earth were identified from volcanic glass groups that had significant amounts of glass. Many were taken from sites of meteoritic impact and the rest were believed to be of volcanic genesis. The change of kinetic energy per unit time throughout impact can generate enough heat to liquefy meteoritic and target rock materials and alter their internal energies. The net effect is then equal to the work done by the pressure wave in deformation. A pressure level of perhaps 60 GPa is necessary to convert silica into glass. An efficient heat sink is required to rapidly cool the molten mass. Impact glasses taken from the lunar regolith possess a surprising degree of homogeneity, but have variable crystallinity. Inclusions within spherules can contain silicates and metals such as Fe and Ni incorporated through reduction of iron sulfide. Researchers have observed a strong correlation between quench rate and the density of glass formed. Compared with volcanic glass, those of impact origin are more amorphous and metastable. Clear spherule impact glass may have the chemical composition of SiO_2 42%, Al_2O_3 25%, FeO 8%, MgO + CaO 24%, $Na_2O + K_2O < 1\%$, and traces of TiO_2 and Cr_2O_3. Concerning the color of these melts, some investigators believe that if the melt temperature were sufficiently elevated to support reduction such as $Fe^{2+} + 2e^- \rightarrow Fe^0$, the glass would be colorless, and the metal would be uniformly distributed at tens of angstroms in diameter.

Volatiles from volcanic felsic glass of terrestrial origin are released when heated to melting temperature. Bubbles formed during gas liberation are restricted by melt viscosity within a narrow range and by the presence of surfactants. Ions open silicate networks and regulate diffusion along percolation paths without severing Si-O covalent bonds. Water vapor comes off in largest amount followed by the oxides of C, FH, then by H_2S, O_2S, and lastly ClH. Degassing depends on heating rate, soak duration, and the original state of crystallinity. This suggests a mathematical question of determining the optimal control of heating that ultimately gives the maximum bulk volume per unit mass.

The thickness of glass formed depends on the amount of silica in the original melt and, to a lesser degree, the cooling rate. For example, a basaltic magma found on the ocean floor undergoes fast cooling and possesses low viscosity in the watery environment. Diffusion rate is high and leads to the formation of crystals, but within thin sheets. The meager production of glass is an outcome of the rather low content of SiO_2, 35–45% by weight. This type of glass is also metastable because devitrification progresses over a short geologic period lasting no more than thousands of years. In contrast, rhyolitic lava is viscous and therefore the crystallization field that results is underdeveloped. Slow cooling on dry land still produces a hefty yield of glass. Rich rhyolitic lava can have the chemical composition by weight of SiO_2 72–78%, Al_2O_3 12–14%, K_2O 3–5%, Na_2O 3–5%, CaO + MgO 1–2%, FeO + Fe_2O_3 1%, and H_2O <1%. This type of glass is stable and has a life span estimated at millions of years.

Devitrification involves the transformation from glassy to a crystalline state in which the vitreous character is lost and a stony appearance is assumed. It is affected by the water content in the glass, the temperature, and the hydration rate into the surface. Glasses with little or no water resist devitrification since the activation energy of viscosity is high. When heated, crystals would develop at the lower end of the energy scale. Published data show that once cooled, bound water in crystals already grown would be released and further the formation of spherulites, offsetting the effect of increased viscosity at the lower temperature. The relative scarcity of natural glass found on Earth, in contrast to crystalline rock, is probably due to an abundance of water present during the solidification process. Water can appreciably reduce the viscosity of magma and thereby promote diffusion dissolved oxides to form crystals.

CATALOG OF MARTIAN MATERIALS.

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The long-term exploration of Mars will require the utilization of surface and near-surface materials for construction, radiation shielding, and life support. Eventually, such materials could be used as raw materials in manufacturing. While there is a resemblance between the surface of Mars, as revealed in Viking and Pathfinder images, and terrestrial desert environments, there are distinct differences that will affect the utilization of *in situ* resources. In general, the surface geological features are extremely old compared to Earth, dating back to the early evolution of the solar system. Therefore, materials created by proceses such as impact cratering are important on Mars. Impact cratering probably created extensive sheets of impact melt bearing breccias on the surface and resulted in the formation of a thick regolith of broken rock fragments in the ancient terrains of Mars. Another key feature is the lack of rainfall over most of Mars' history. This resulted in the lack of extensive erosion. On Earth, extensive erosion of volcanic centers, for example, has exposed deep hydrothermal deposits that are mined for Cu, Mo, and W, but such deposits are not likely to be exposed at the surface on Mars. Similarly, deposits of quartz sand, used for glass making, are created by the erosion of granitic terrains on Earth, and are not likely to be found on Mars. The soil on Mars is also very different from wind-blown material on Earth. Virtually no organic material is present, and the material is enriched in volatile elements, such as S and Cl, and possibly also toxic heavy metals, derived from volcanic gases and hydrothermal waters that poured onto the surface. The volatile elements have remained in the soil due to the absence of processes that recycle volatile elements back into the planet's crust. Hydrogen peroxide originally formed in the atmosphere is also mixed into the soil and regolith, and was probably responsible for the "oxidant" found in the soil by the Viking biology experiments. The surface may also contain material delivered to the surface, including solar-wind ^{3}He, and chondritic material from meteorites and cosmic dust. One of the biggest problems is the probable lack of water any where near the surface, except in the the form of ice near the poles. The following list summarizes some of the familiar and unfamiliar materials that may be encountered on the martian surface.

Familiar Materials:

- Basaltic rock from lava flows
- Silica-rich rock (Icelandite or Andesite)
- Volcanic ash and glass from cinder cones
- Soil (generally fine grained and globally homogenous)
    - enriched in S, Cl, K, and Br
    - may contain hazardous enrichments of As, Cd, and Pb
    - ubiquitous dunes
    - formation of duricrust or hardpan
- Lake sediment formed in impact crater lakes or Valles Marineris
- Water ice and CO_2 ice at the poles
- Groundwater and/or permafrost near poles
- Silica-rich rock (Icelandite or andesite)
- Clays from Yellowstone-like local hydrothermal alteration (illite, montmorillonite, and palagonite)?
- Carbonate material in localized areas (evidenced by ALH 84001)

Unfamiliar Materials:

- Impact melt sheets and impact melt breccias (similar to suevite from the Ries Crater in Germany, which is used in making waterproof cement)
- Impact-produced glasses and shocked minerals
- Helium-3 and other solar wind byproducts that have passed through the thin atmosphere and been absorbed by the martian soil?
- Impact-generated regolith in the ancient terrains
- Lava tubes and small craters for habitat and other construction

NEW TECHNOLOGIES FOR RELIABLE, LOW-COST *IN SITU* RESOURCE UTILIZATION.

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New technologies can dramatically alter overall mission feasibility, architecture, window-of-opportunity, and science return. In the specific context of planetary exploration/development, several new technologies have been recently developed. It is significant that every one of these new technologies won a NASA NTR award in 1997–1998.

In the area of low-cost space access and planetary transportation, hybrids are discussed. Whether we carry all of the fuel and oxidizer from Earth, or we make some or all of it *in situ*, mass advantages are shown through calculations. The hybrisol concept, where a solid fuel is cast over a state-of-the-art solid propellant, is introduced as a further advance in these ideas,. Thus, the motor operates as a controllable, high I_{sp} rocket initially, and transitions to a high-thrust rocket after ascent, at which time the empty oxidizer tank is jettisoned. Again, calculations show significant advantages.

In the area of efficient energy use for various mechanical actuations and robotic movements, *muscle wires* are introduced. Not only do we present detailed systems-level schemes, but we also present results from a hardware mechanism that has seen more than 18,000 cycles of operation.

Recognizing that *power* is the real issue in planetary exploration/development, the concept of LORPEX is introduced as a means of converting low-level energy accumulation into sudden bursts of power that can give factors of millions (in power magnification) in the process; this robot employs a low-power ISRU unit to accumulate ISRU-generated fuel and oxidizer to be consumed at a rapid rate, chemically in an engine. Drilling, hopping, jumping, and ascent, or even return to Earth, are possible. Again, the hardware has been built and initial systems checkout demonstrated.

Long-duration exploration and long-distance travel are made possible through aerobots, as is well known for planets with an atmosphere. However, power has again been a limiting factor. With our new concept of PV-enhanced aerobots, the aerobot surface is covered with ultra-lightweight photovoltaic cells that generate power. The power is used for buoyancy enhancement, communication, and science instruments.

In the area of fuel/oxidizer generation, a new concept is introduced that avoids the fragile solid oxide electrolyzers (SOXE) and Sabatier reactors (that need H). The new concept of MIMOCE is naturally suited for the local atmosphere, operates at a significantly lower temperature (<400° C), and has no troublesome seals or electrodes with bonding problems. In cooperation with a senior engineer at JPL, the concept is being thoroughly investigated for early incorporation into a mission.

It is concluded that *new technologies* can make revolutionary advances in increasing the feasibility and lowering the cost and risk of planetary missions. It is hoped that the technologies pioneered at the University of Arizona SERC during the last few months will receive serious consideration by mission planners, especially since these technologies have been proved through hardware demonstrations.

SYNTHESIS OF ETHYLENE AND OTHER USEFUL PRODUCTS BY REDUCTION OF CARBON DIOXIDE.

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Advanced life-support systems are essential for the success of future human planetary exploration. Striving for self-sufficiency and autonomous operation, future life-support systems will integrate physical and chemical processes with biological processes, resulting in hybrid systems. A program is under way to demonstrate the synthesis of ethylene and other useful products, e.g., polyethylene and ethanol, from metabolic wastes, i.e., CO_2 and water, as an adjunct to the life support systems required in manned spacecraft, such as Space Station Freedom, and planetary bases, such as the Moon and Mars. These products will be synthesized using inorganic processes based on chemical engineering principles, making use of the major components of metabolic waste, C, H, and O.

The program focuses on two synthetic paths to produce ethylene in conversions greater than 95%: (1) direct catalytic reduction of CO_2 with H and (2) catalytic reforming of methane. The benefits to be derived from the program are (1) conversion of metabolic wastes to useful products for use on manned spacecraft and planetary bases; (2) weight savings that result from reduced onboard supply requirements; (3) manufacture of useful products based on efficient engineering principles, mass, volume and energy; and (4) reduced resupply from Earth.

The chemistry and chemical engineering that will be demonstrated on the program will be directly applicable to the development of closed life-support systems for manned spacecraft, lunar and martian bases, and, ultimately, lunar and martian colonies, e.g., the conversion of the martian atmosphere to methane, ethylene, ethanol, and a variety of polymers for construction and other uses.

The chemistry and chemical engineering processes that will be demonstrated on the program will be presented and discussed, e.g., the direct two-step synthesis of ethylene using water electrolysis and modified Fischer-Tropsch processes. This may be followed by other interesting syntheses of, e.g., polyethylene, a plastic with many varied uses, and ethanol, a potential foodstuff and precursor to polyesters, another very useful plastic.

HOW MUCH INDIGENOUS MATERIAL FOR CONSTRUCTION IS AVAILABLE ON THE MOON?

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With the use of a remote sensing technique of assessment of surface material properties, the average content of the fine fraction and a relative content of glasses and glassy particles in the local lunar soil for a number of regions has been calculated. From the data it may be suggested that about 50% of the volume of covering material in a number of regions consists of powder-like particles (effective size of particles is about 9 µm). Sintered fine-fraction bricks and blocks could be used in construction. High-Ca lunar fine-fraction bricks could be used as cementitious material needed for the manufacture of lunar concrete.

A remote-sensing maturity parameter can serve as a quantitative index of a relative content of glasses and glassy particles in the covering lunar material. The most mature soil (about 80% of agglutinates) has been discovered on about 57% of the nearside of the Moon. Lunar glass composites could be used successfully as construction materials.

Concentration of fine-grained metallic Fe increases steadily with increasing maturity. The concentration amounts to about 0.8 wt% for the most mature soils. This easily-produced metallic Fe could be concentrated by magnetic concentrators and separated by melting for use as a construction material. Adopting a value of the relative H content in a rather mature soil, it is possible to determine the relationship between the dimensions of the lunar surface working site to the H mass to be produced. Combined with the assessment of surface material chemical composition, an average O mining possibility can be determined. When lunar O facilities are established, lunar water could be produced by combining lunar O with lunar H (excluding polar regions where water may be extracted from ice areas).

IN SITU GENERATION OF A "TO SCALE" EXTRATERRESTRIAL HABITAT SHELL AND RELATED PHYSICAL INFRASTRUCTURE UTILIZING MINIMALLY PROCESSED LOCAL RESOURCES.

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ISRU Structures in Southern California: Advanced crewed lunar and Mars bases will require structurally safe and environmentally self-sustained habitats that are well protected against the vacuum or very low atmospheric pressures, very large diurnal temperature variations, harmful solar and galactic radiation, micrometeorites, and severe dust storms (on Mars). They also need to be habitable and made as safe and comfortable as possible for the crew.

The architecture of such a remote base habitat entails the harmonious integration and operation of two essential and major systems: the physical structure of the enclosure and the environmental control and life-support system that will make the dwelling habitable.

In Situ Resource Utilization based Stabilized Soil Technology (SST) structures that are being built here at the edge of the Mojave

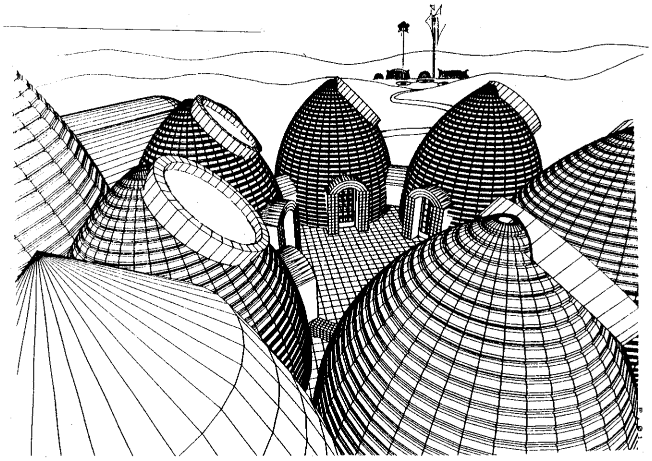

Fig. 1. Architect's vision of an ISRU technology extraterrestrial base habitat complex.

High Desert in Hesperia, California, promise to offer a versatile solution to these habitats and related physical infrastructure, providing highly innovative and promising solutions to critical aspects of protection, safety, and habitability issues that are paramount to the optimal long life-cycle operation of these advanced bases.

From a variety of experimental structures already built, tested, and certified in Hesperia, it seems that it is quite possible to build the physical structure of the primary habitat structure itself out of local soil using special techniques that are being researched, tested, and evolved. SST habitats capable of providing thermal, micrometeoritic, and radiation protection for crew and supporting life systems with acceptable atmospheric leakage rates can be built *in situ* and evolved in accordance with needs as the base evolves.

Extensive Tests Already Performed: Several stabilized soil structures have been built and are ready for inspection and evaluation near the proposed base construction site at Cal-Earth in Hesperia. Extensive building activity and structural testing of stabilized soil structures is well under way.

After two years of extensive testing under severe zone 4 seismic conditions by the City of Hesperia Building and Safety Department in consultation with ICBO (International Conference of Building Officials), The Hesperia Desert Moon Village including the Hesperia Nature Museum is being constructed using this technology. Note that several earthquakes have jolted the area since activities began a few years ago, and every structure has survived flawlessly, to date.

Project Focus: Using current research from the TRANSHAB/BIOPLEX facilities at NASA, we intend to build a SST structure that will simulate the requirements of an advanced lunar or Mars base habitat. The SST material will be tested for stability and durability, and the structure buildup activity will be monitored scientifically from start to finish in order to study the human effort required to build and commission it for human occupancy. EVA and robotics-assisted techniques are expected to evolve during this exercise that will provide insight into how to further improve productivity of the assembly crew engaged in building and operating a remote outpost as well as their limitations.

Furthermore, this technology will be extended to build a related "to scale" physical infrastructure that will include a stretch of permanent road for vehicular access between structures, a service tunnel, a specimen landing/launch pad for a range of service spacecraft, a variety of unpressurized structures for storage and maintenance as well as a communications and observation tower suite.

Space Technology for Science and Humanity: Much of this activity is also directly applicable for building remote bases here on Earth, that are to be established in harsh conditions like the Antarctica using maximum *in situ* resources. Furthermore, SST structures built using space technology could benefit a multitude of the Earth's population by providing cost-effective self-help shelter, thus reaping the benefits of space technology directly to meet the needs of humanity on Earth.

UTILITY OF LAVA TUBES ON OTHER WORLDS.

B. E. Walden, T. L. Billings, C. L. York, S. L. Gillett, and M. V. Herbert, Oregon Moonbase, Oregon L5 Society, P.O. Box 86, Oregon City OR 97045, USA (BWalden@aol.com).

Location: On Mars, as on Earth, lava tubes are found in the extensive lava fields associated with shield volcanism [1]. Lunar lava-tube traces are located near mare-highland boundaries [1], giving access to a variety of minerals and other resources, including steep slopes [2], prominent heights for local area communications and observation, large surface areas in shade [3], and abundant basalt plains suitable for landing sites, mass-drivers, surface transportation, regolith harvesting, and other uses.

Detection: Methods for detecting lava tubes include visual observations of collapse trenches and skylights [4], ground-penetrating radar [5], gravimetry, magnetometry, seismography [6], atmospheric effects [7,8], laser, lidar, infrared, and human or robotic exploration [9].

Access: Natural entrances to lava tubes are at the ends of sinuous rille collapse trenches and roof collapse skylights. Artificial access should be possible by drilling or blasting at any desired location through the roof of the lava tube [10].

Composition: Lava tubes are found only in extremely fluid pahoehoe basalt, where they are a major mechanism of lava deposition [11]. Lava tubes are therefore an integral part of the basalt bedrock. The bedrock floors and walls might be used to provide solid foundations or anchor heavy equipment, particularly on the Moon where bedrock surface exposures appear to be rare [12]. On lower-gravity worlds, lava-tube caves can be larger than on Earth. On Mars we may find widths of a hundred meters; on the Moon spans of more than 300 m are possible [13], and there is some evidence spans may be much larger (up to 1.3 km, with lengths of several kilometers) [4]. This amount of sheltered volume can be a significant resource.

Volatiles: Cold air can pool in lava tubes. Water draining into this cold trap freezes. Some terrestrial caves can nearly fill with ice [7]. On Mars, some lava tubes may contain reservoirs of ancient water ice, possibly preserving records of the planet's dramatic climate changes as well as serving as a ready resource. Cometary volatiles could have made their way into lunar lava tube shelter and still be preserved. Volcanic volatiles may also be present [4].

Dust: Lava-tube caverns probably have extensive areas free of the abrasive and problematic dust endemic to the surfaces of the Moon and Mars.

Shelter: Lava-tube caverns have roofs tens of meters thick (roughly 40 m on the Moon, perhaps 20 m on Mars). This makes the cave environment relatively safe from solar radiation, cosmic rays, micrometeorites, and even small macrometeorites (up to 20-m crater sustainable on the Moon) [14]. Transportation between operational and habitation sites within the lava tube is protected by the basalt shield. Stable cave temperatures (Moon est. –20° C) are less stressful on equipment than the wide diurnal swings on the surface [14]. The cave interior could act as one pole of an oscillating heat engine, with heat transfer occurring inward during the day and outward at night. On Mars the caves could provide shelter from the winds and dust storms.

Morphology: The shape of lava tubes can be useful. Lava ponding might provide a stable, level foundation with little preparation. Parallel benches or parallel lava-tube walls could support crossbeams. The void below might become a service corridor. The strong arched roof can support suspended transportation elements and even facilities. Herbert estimates a roof only 3.5 m thick could support 45,835 kg/m^2 on Earth [10]. Assuming similar basalt strengths, this translates to 137,000 kg/m^2 on Mars and 275,000 kg/m^2 on the Moon. Thicker roofs on the Moon or Mars could be expected to carry correspondingly larger loads. Piles of "breakdown" boulders make surface traverses difficult and dangerous, but they also represent a resource. Their blocky, rectilinear shapes might make them useful for simple rock constructions [15]. They are also of portable weight, making them useful for ballast and counterweights. Transportation over these "breakdown" areas might be provided by a suspended cable car system. Gentle slopes of the lava-tube system can be useful in a variety of ways for utilities and industrial processes [14].

Construction: Actually sealing and pressurizing these large caves is a major and expensive undertaking, and probably will not be attempted until later development. Initial construction inside a lava tube could be achieved through simple inflatable structures [16]. Ongoing construction could be lighter, built faster, and maintained more easily than surface structures [14]. Productive base operations could commence sooner than with equivalent surface bases. On the Moon strong anhydrous glass could be used for structural elements such as beams, walls, and cables. Woven glass threads can be used to create a strong fabric for tents and inflatable structures [17]. Steel can be made from *in situ* resources on the Moon (and probably Mars) and has better structural characteristics than Al [18].

Psychology: The psychological value of being able to work and relax under the secure shelter of tens of meters of basalt shielding should not be underestimated. Cave-ins are unlikely in lava-tube caverns that have survived for thousands, millions, or billions of years. Of course, human activity that might provoke collapse, such as blasting or drilling, should be conducted with care. Views on the lunar surface are restricted due to the need for radiation shielding. Within the lava-tube caverns, large windows can look out on great vistas, increasing the "psychological space" of small pressurized habitats [19]. Larger, more spacious habitats can be built without regard for heavy shielding. People will be able to watch the bustling activity of the base.

Economics: Lava tubes can be economically advantageous immediately and realize continuing economic advantages [16].

The amount of excavation necessary to prepare a lava-tube entrance should be comparable to that required to shield a surface lunar outpost, and may be used for that purpose. In return, access is provided to a large shielded volume [14]. The sheltered construction environment within a lava-tube cavern significantly decreases risk from radiation and solar storms. This should reduce insurance costs and other costs of risk. Since construction within the lava tube does not require shielding, each structure can realize a significant cost savings. The stable interior temperature of the lava-tube environment means environmental control can be simpler. It also means less energy need be expended to counter wide diurnal temperature swings. Equipment will require less maintenance due to decreased wear and tear of wide temperature swings. Lack of dust should reduce maintenance due to that contaminant, as well as reducing the need for dust mitigation in various base and habitat elements. Lightweight, flexible "thinsuits" might be used in the protected environment, increasing efficiency of workers and reducing fatigue [14].

Summary: It would be structurally, economically, and even aesthetically advantageous to utilize lava-tube resources that are already in place and available on the Moon and Mars.

Acknowledgments: Portions of this work were supported under NASA contract NASW-4460.

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PLASMA-BASED STEEL ROD OR REBAR PRODUCTION FROM *IN SITU* MATERIALS.

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The probability of lunar ice has redefined the importance of earlier research reporting Fe as a byproduct of O production from lunar regolith [1,2]. That emphasis is now on Fe and other materials for *in situ* resources for construction. In pursuit of O from lunar ilmenite, we have tried (1) a resonating cavity microwave plasma reactor, (2) a nontransferred arc plasma torch feeding a cylindrical reactor, and (3) an inductively coupled plasma reactor feeding a quench chamber with relative success [3,4]. Instead of using these or other O-focused strategies, and instead of using commercial submerged electric arc smelting of ilmenite to produce Fe, a compact, portable, light, plasma-based cyclone reactor could be adapted as another choice. Cyclone reactors have been under development for several decades, and P. R. Taylor and coworkers have extended their evolution and used them effectively on iron taconites as well as other materials [5]. The advantages of the plasma reactor over other current steel making processes include continuous operation, higher throughputs in small reactors, enhanced heat and mass transfer rates, higher temperatures, easy separation of liquids and gases, capture and recycle of plasma gases, and no feed agglomeration. The procedure for producing steel was to feed taconite and CO/CO$_2$ mixtures into the cyclone reactor (Fig. 1). The results were excellent. The procedure and results for lunar ilmenite would be similar. Electrostatically concentrated ilmenite and magnetically concentrated Fe and associated agglutinates would be fed into the reactor along with reductant. We smelted Moon simulants and successfully produced Fe with a plasma torch, although cyclone reactor experiments are yet to be run. Hydrogen reduction has been reported (Equation 1), even though the Gibbs free energy is slightly positive, and the equilibrium constant is low. Given ice, H would be available, and is like CO (Equation 2). Methane is even more effective (Equation 3), as is ammonia (Equation 4). The variety of species shown in the free energy minimization results for reacting methane and ilmenite (Fig. 2) emphasizes the superior reducing power of C sources from, say, carbonaceous chondrites. In the cyclone reactor Fe is reduced while molten material flows down the walls in a falling film. Molten Fe and slag are collected in the chamber below, where decarburization or other ladle metallurgy can occur. The resulting steel can be tapped and continuously cast into bar for concrete reinforcement, roof bolts, and restraints for underground habitat construction, metal mesh to be plasma spray-coated with lunar soils, and other forms. A light graphite cyclone reactor system would produce an estimated 2000–10,000× its weight in Fe before needing liner replacement, not including power supply. Thus, *in situ* Fe would cost a small fraction of gold, rather than the estimated five or more times gold if transported from Earth. Plasma reactors can be modified to produce Al, Ti, glass, ceramics, and advanced materials, and an already automated reactor system can be further automated for remote operation [6].

1) FeO*TiO2 + H2(g) = Fe + TiO2 + H2O(g)

T C	deltaH kcal	deltaS cal	deltaG kcal	K
800	10.045	3.798	5.969	6.084E-002
1000	10.009	3.779	5.198	1.281E-001
1200	9.332	3.285	4.493	2.155E-001

2) FeO*TiO2 + CO(g) = Fe + TiO2 + CO2(g)

800	1.989	-3.486	5.730	6.808E-002
1000	2.402	-3.121	6.376	8.044E-002
1200	2.142	-3.310	7.019	9.091E-002

3) 4FeO*TiO2 + CH4(g) = 4Fe + 4TiO2 + CO2(g) + 2H2O(g)

800	86.225	68.486	12.728	2.556E-003
1000	86.764	68.997	-1.080	1.532E+000
1200	84.465	67.322	-14.711	1.523E+002

4) 3FeO*TiO2 + 2NH3(g) = 3Fe + 3TiO2 + 3H2O + N2(g)

800	68.993	44.950	20.755	5.928E-005
1000	93.998	66.264	9.634	2.219E-002
1200	124.844	88.694	-5.815	7.290E+000

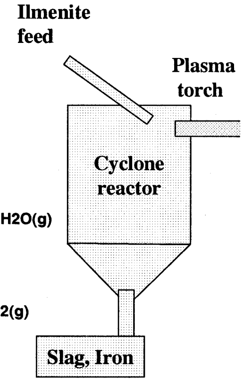

Fig. 1.

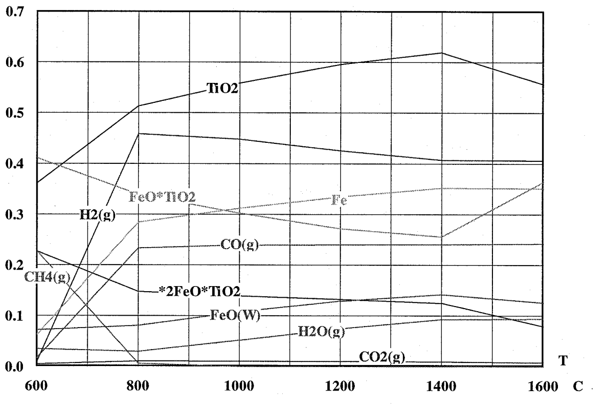

Fig. 2.

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ICE AS A CONSTRUCTION MATERIAL.

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This presentation shows how water and ice can enable exceptionally simple ways to construct structures in deep space. Practicality is underscored by applying advanced tank methods being developed for Mars missions.

Water or ice is now known to be present or abundant on most objects in the solar system, starting with the planet Mercury. Thermal processes alone can be used to melt ice. The cold of space can refreeze water back into ice. The anomalous low vapor pressure of water, about 7 mm Hg, permits bladder containers. Tanks or bladders made with modern polymer fiber and film can exhibit very small (<0.1%) equivalent tankage and ullage fractions and thus hold thousands of tons of water per ton bladder. Injecting water into a bladder whose shape when inflated is the desired final shape, such as a space vehicle, provides a convenient way to construct large structures. In space, structures of 10,000-T mass become feasible because the bladder mass is low enough to be launched. The bladder can weigh 1000× less than its contents, or 10 T. The bladder would be packed like a parachute. Shaped memory materials and/or gas inflation could reestablish the desired structure shape after unpacking. The water comes from space resources.

An example examines construction of torus space vehicle with 100-m nominal dimension. People would live inside the torus. A torus, like a tire on an automobile, would spin and provide synthetic gravity at its inner surface. A torus of order 100 m across would provide a gravity with gradients low enough to mitigate against vertigo. The example vehicle would use ice as the structural material. Water ice becomes as hard as brick, with a tensile strength between 50 and 180 psi at temperatures between –5º and –30º C and salinity below 0.1%. Selection of the proper thermo-optical surface for the bladder could keep the ice in this temperature range. Analysis shows that a torus with 1-m-thick walls will not fly apart when spun to provide between 1/5 and 1 *g*. The bladder tank for this vehicle could weigh <10 T.

Injection of water at pressures just above its critical point permits vapor bubbles to be collapsed with slight overpressure. The bladder accommodates expansion of water ice upon freezing. The tank for this torus would be formed using the same technologies being developed for Mars missions.

Special Presentations

IN SITU RESOURCES FOR LUNAR BASE APPLICATIONS

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Introduction

Lunar resources have been cited either as an economic driver to justify a return to the Moon or as being useful in the creation and maintenance of a lunar civilization. Except for He_3 as a fusion fuel, the former is unlikely.

Lunar Composition

- 45% chemically bound oxygen
- Also: silicon, iron, calcium, aluminum, magnesium, titanium

$$89\% \left\{ \begin{array}{l} SiO_2\text{-}45\%,\ TiO_2\text{-}2.5\%,\ Al_2O_3\text{-}9\% \\ FeO\text{-}22\%,\ MnO\text{-}0.3\%,\ CaO\text{-}10\% \end{array} \right.$$

- And: helium, hydrogen, nitrogen, carbon

Robotics vs. Manned

- The mix of automated and human-based construction and maintenance for a first base will be heavily dominated by the latter. With time, more will be borne by robotics.
- Primary structures of an initial lunar base will likely be prefabricated.
- Robots + regolith = short life and low reliability

Lunar Base Structural Needs

- Shelter for humans and machines
- For humans (and other living things): pressurized, radiation-free volumes
- For machines: depending on the item, various needs can be anticipated (e.g., dust-free volumes, radiation-free volumes, pressurized volumes)
- Some shielding against micrometeorites
- Internal pressures drive structural design
- Power generation and distribution systems
- "Life" systems: water, sewage, air
- Roads and foundations
- Landings/launching pads
- Manufacturing facilities

Resources and Their Uses

- Lunar oxygen: propellant, life support
- Iron, aluminum, titanium: structural elements
- Magnesium: less strong structural elements
- Regolith: sintered blocks

Potential Applications

- Structural beams, rods, plates, cables
- Cast shapes for anchors, fasteners, bricks, flywheels, furniture
- Solar cells, wires for power generation and distribution
- Pipes and storage vessels for fuel, water, and other fluids
- Roads, foundations, shielding
- Spray coatings or linings for buildings
- Powdered metals for rocket fuels, insulation
- Fabrication in large quantities can be a difficult engineering problem in terms of materials handling and heat dissipation

Related Issues: Reliability

- Design life and reliability are very difficult to estimate for the lunar site
- It is imperative to develop techniques that allow such estimates to be made, especially for components created from *in situ* material

Concluding Thoughts

- Key components of a lunar outpost can be built from *in situ* resources (2nd generation)
- Robotic construction needs advances (3rd generation)

FRAMEWORK FOR BUILDING SYSTEMS

H. Benaryoya

Types of Applications

Habitat/Constructed Volume Types

- Pressurized (living and working)
- Agriculture
- Airlocks: ingress/egress
- Temporary storm shelters for emergencies and radiation
- Open (unpressurized) volumes

Storage Facilities/Shelters

- Cryogenic (fuels and science)
- Hazardous materials
- General supplies
- Surface equipment storage
- Servicing and maintenance
- Temporary protective structures

Supporting Infrastructure

- Foundations/roadbeds/launchpads
- Communication towers and antennas
- Waste management/life support
- Power generation, conditioning and distribution
- Mobile systems
- Industrial processing facilities
- Conduits/pipes

Application Requirements

Habitats

- Pressure containment
- Atmosphere composition/control
- Thermal control (active/passive)
- Acoustic control
- Radiation protection
- Meteoroid protection
- Integrated/natural lighting
- Local waste management/recycling
- Airlocks with scrub areas
- Emergency systems
- Psychological/social factors

Storage Facilities/Shelters

- Refrigeration/insulation/cryogenic systems
- Pressurization/atmospheric control
- Thermal control (active/passive)
- Radiation protection
- Meteoroid protection
- Hazardous material containment
- Maintenance equipment/tools

Supporting Infrastructure

- All of the above
- Regenerative life support (physical/chemical and biological)
- Industrial waste management

Types of Structures

Habitats

- Landed self-contained structures
- Rigid modules (prefabricated/*in situ*)
- Inflatable modules/membranes (prefabricated/*in situ*)
- Tunneling/coring
- Exploited caverns

Storage Facilities/Shelters

- Open tensile (tents/awning)
- “Tinker toy”
- Modules (rigid/inflatable)
- Trenches/underground
- Ceramic/masonry (arches/tubes)
- Mobile
- Shells

Supporting Infrastructure

- Slabs (melts/compaction/additives)
- Trusses/frames
- All of the above

Material Considerations

Habitats

- Shelf life/life cycle
- Resistance to space environment (uv/thermal/radiation/abrasion/vacuum)
- Resistance to fatigue (acoustic and machine vibration/pressurization/thermal)
- Resistance to acute stresses (launch loads/pressurization/impact)
- Resistance to penetration (meteoroids/mechanical impacts)
- Biological/chemical inertness
- Reparability (process/materials)

Operational Suitability/Economy

- Availability (lunar/planetary sources)
- Ease of production and use (labor/equipment/power/automation and robotics)
- Versatility (materials and related processes/equipment)
- Radiation/thermal shielding characteristics
- Meteoroid/debris shielding characteristics
- Acoustic properties
- Launch weight/compactability (Earth sources)
- Transmission of visible light
- Pressurization leak resistance (permeability/bonding)
- Thermal and electrical properties (conductivity/specific heat)

Safety

- Process operations (chemical/heat)
- Flammability/smoke/explosive potential
- Outgassing
- Toxicity

Structures Technology Drivers

Mission/Application Influences

- Mission objectives and size
- Specific site-related conditions (resources/terrain features)
- Site preparation requirements (excavation/infrastructure)
- Available equipment/tools (construction/maintenance)
- Surface transportation/infrastructure
- Crew size/specialization
- Available power
- Priority given to use of lunar material & material processing
- Evolutionary growth/reconfiguration requirements
- Resupply versus reuse strategies

General planning/design considerations

- Automation and robotics
- EVA time for assembly
- Ease and safety of assembly (handling/connections)
- Optimization of teleoperated/automated systems
- Influences of reduced gravity (anchorage/excavation/traction)
- Quality control and validation
- Reliability/risk analysis
- Optimization of *in situ* materials utilization
- Maintenance procedures/requirements
- Cost/availability of materials
- Flexibility for reconfiguration/expansion
- Utility interfaces (lines/structures)
- Emergency procedures/equipment
- Logistics (delivery of equipment/materials)
- Evolutionary system upgrades/changeouts
- Tribology

Requirement Definition/Evaluation

Requirement/Option Studies

- Identify site implications (lunar soil/geologic models)
- Identify mission-driven requirements (function and purpose/staging of structures)
- Identify conceptual options (site preparation/construction)
- Identify evaluation criteria (costs/equipment/labor)
- Identify architectural program (human environmental needs)

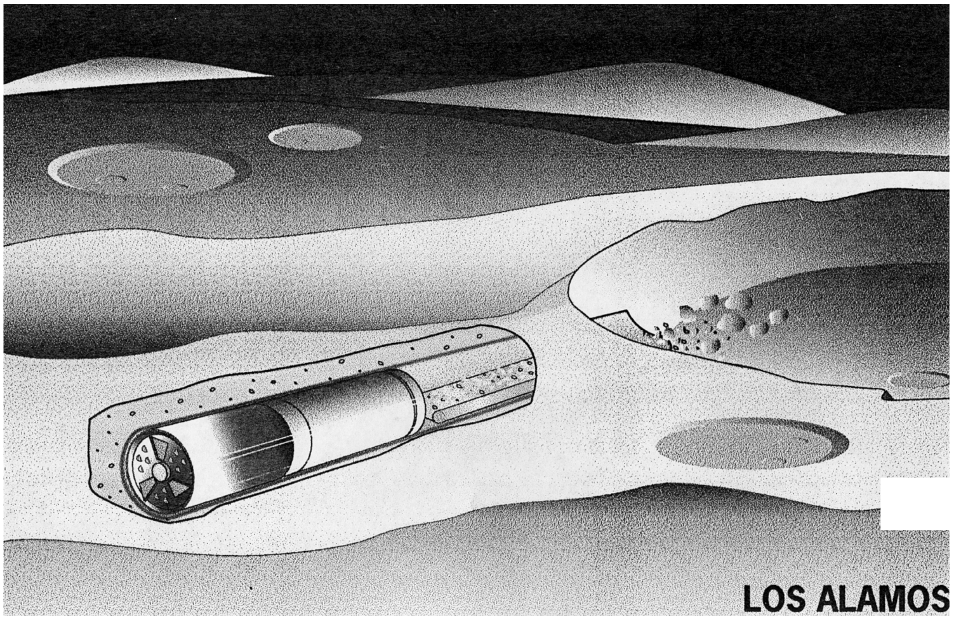
Evaluation Studies

- Technology development requirements
- Cost/benefit models (early/long-term)
- System design optimization/analysis

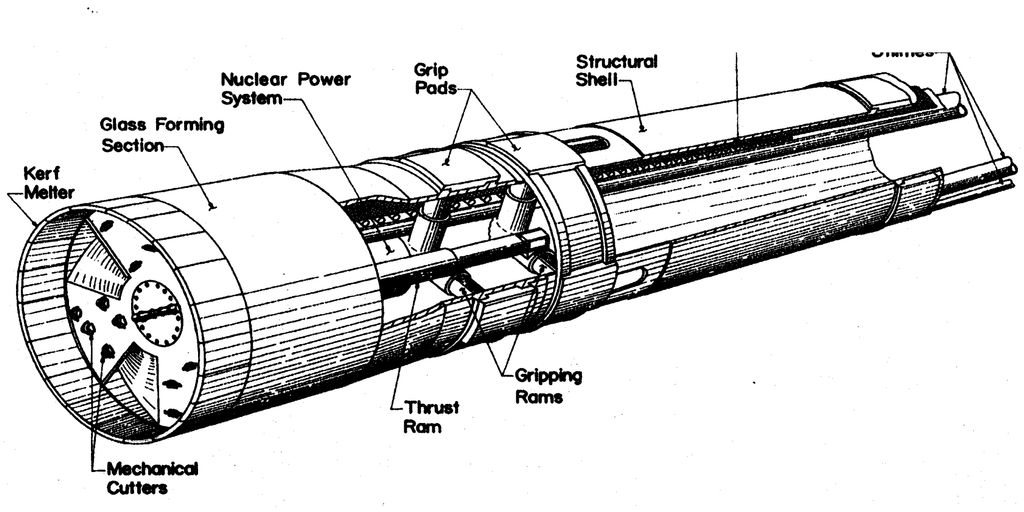
CONSTRUCTION OF PLANETARY HABITATION TUNNELS USING A ROCK-MELT-KERFING TUNNEL-BORING MACHINE POWERED BY A BIMODAL HEAT PIPE REACTOR

J. D. Blacic, M. G. Houts, *Los Alamos National Laboratory*
T. M. Blacic, *University of California at Davis*

Planetary Tunnel Concept



Tunnel Borer Concept (Rock melt kerfing for tunnel support)



Lunar Kerf-Melting TBM

	Tunnel Diameter		
	2m	3m	5m
Thermal Power, kW	245	365	604
Habitat Volume Produced per day, m^3	25	56	157

Assumptions:

Advance rate — 8 m/d
Thickness of glass structural lining — 5 cm
Regolith bulk density — 2000 kg/m^3
Glass density —3300 kg/m^3
Regolith melting temperature — 1150°C
Specific heat — 1 kJ/kg K
Latent heat of fusion — 420 kJ/kg

200 kWt/5 kWe HPS Point Design

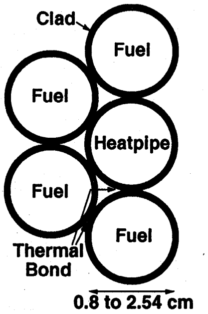
❖ UN Fueled reactor (passive shutdown)	250 kg
♦ Nb-1Zr or Mo heatpipes, Na or Li working fluid	
❖ Shield	50 kg
♦ Reduce radiation dose to sensitive components	
❖ Thermoelectric power conversion	85 kg
❖ Instrumentation and control	50 kg
❖ Power Conditioning	20 kg
❖ Cabling	30 kg
Total	*485 kg*

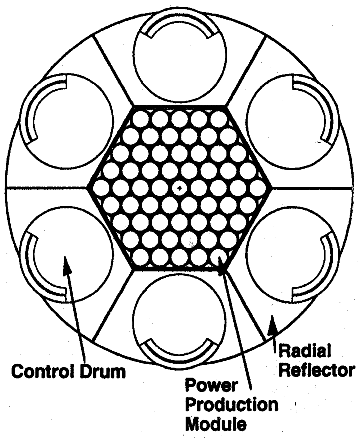
Additional Features

- TBM can be steered by asymmetric heating using manipulation of reactor control drums.
- Excess heat (after electrical conversion) removed by heating conveyed rubble or by providing coprocess heat
- Residual thermal cooling cracks in glass lining sealed by plasma spraying an indigenous metal (e.g., Fe, Al, etc.)
- After habitat building, TBM parked with kerf melters exposed to space — provides electrical power to habitat for ~10 years.

HPS: One Potential Power Source

- Couples well to rock-melt-kerfing TBM
- Several point designs have been investigated.
  - System mass (5 kWe/10 year life) less than 600 kg
  - System mass (50 kWe/10 year life) less than 2000 kg
  - Potential for development cost <\$100 M, unit cost <\$20 M
    - Modules contain 2 to 6 fuel pins and one heatpipe.
    - Heat conducts from fuel to primary heatpipe.
    - Primary heatpipe transfers heat to secondary heatpipe and/or power converters.
    - Temperature to power converters > 1275 K.





HABITAT CONSTRUCTION REQUIREMENTS

Marvin E. Criswell and Jenine E. Abarbanel
Center for Engineering Infrastructure & Sciences in Space and Department of Civil Engineering
Colorado State University, Fort Collins, Colorado

Introduction

<u>Demand</u>	≤	<u>Supply</u>
Loads, forces	Satisfy with acceptable	Resistance
Requirements	reliability and economy	Solutions

Conditions on the Moon and Mars (similar but different)

- ❖ Less than 1% of Earth's atmosphere
- ❖ 17% and 38% of Earth's gravity
- ❖ Dusty, rocky regolith surfaces
- ❖ Wide temperature ranges

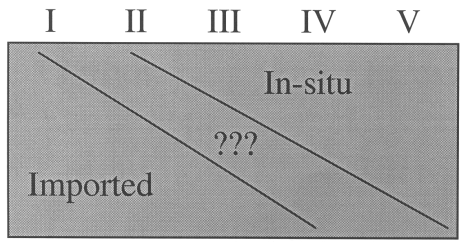
Overall Goal: Mission Economy

Less Costs	↔	Less transportation cost	↔	Less mass to import
Net imported mass savings	=	Reduction	–	Increase
		Less imported end product Replace x kg of imported product with y kg of *in situ* (usually y>x)		More imported systems - mining, transporting - processing, refining - manufacturing - fabrication - humans, robotics - life support - power

Question: What is feasible and economical? When?
First step: What is possible?

Habitat needs	depend on	Base Maturity
Feasible uses	depend greatly on	Base Maturity

	(Sadeh, Criswell)	(Eckart)	(IAA Lunar Base Group)
I	Exploratory	Prepatory/Exploratory	Temporary Outpost
II	Pioneering	Research Outpost	Permanent Outpost
III	Outpost	Operational Base	Full Lunar Base
IV	Settlement	Extended Base	Factory
V	Colony	Self-sufficient colony	Settlement



← To judge the need and feasibility of *in situ* material use, must identify base maturity assumed

Changes in Habitat Needs with Base Maturity

- Some requirements are basic for human life — always there (changes are in size, magnitude, volume)
  - Shelter
  - Internal atmosphere
  - Food, water
  - Temperature control
  - Other needs for humans to survive and thrive
- Others depend on base/habitat maturity (stage)
  - Expanded mission and role
  - More use of plants for food, other biological systems
  - Facility becomes more "permanent"
  - Crew stays become longer

Opportunities and Practical Uses of In Situ Materials

- Opportunities — increase greatly with base maturity
  - More resources (human, energy, equipment)
  - More synergism with base "commercial" products
  - More incentives to "close loops" for self-sufficiency
  - More knowledge about local resources
  - More time to acquire and use technology and equipment
- What uses are feasible, economic?
  - Very dependent on maturity of
    - Base, habitat
    - Enabling technologies
    - Base site and mission

Comment: A use may not be economic at the given stage, but may have a payoff for the long term.

Categories of In Situ Material Use

- In-place habitat structure
  - Structural shell, shielding, fixture, facilities
- Habitat interior life support contents
  - Artificial atmosphere, water, environmental systems
- Closely associated base infrastructure
  - Pathways, roadways, landing/launchpads, human-occupied manufacturing and commerce areas
- Energy and other habitat support systems
  - Electric power, heat management, plant growth, and other food systems
- Construction equipment

Requirements — Basic Habitat Structures

- Structurally contain 10–14.7 psi (70-100 kPa) internal pressure
  - Human occupied habitats are pressure vessels!
  - Basic structure must be strong in tension
- Provide shielding — radiation, micrometeorites, thermal stability
  - Passive system of mass shielding
  - Less downward gravity force from shielding than upward from pressure
- Provide high reliability, damage control, durability, low leakage
  - Design, materials, fabrication all involved
- Support habitat/base functions; adequate size, shape
  - Functional planning and architecture
  - Compatible with outfitting, operations
- Stay open and retain basic form if depressurized (planned, unplanned)
  - Hard/Rigidized/Frame
- Facilitate access to "outside," other base facilities
  - Air locks (personnel, supplies); interface to rovers; dust control; minimum air loss

Uses of In Situ Materials — Basic Habitat Structure

- Pressure vessel: Imported rigid or membrane tensile structure
    - Later → *in situ* for secondary interior structure; abrasion, insulating, other layers of shell
      Still later → glass, metal, post-tensioned concrete, cermaics, etc. for primary structure
- Shielding: Regolith (loose, bagged, otherwise contained)
    - Blocks of concrete, masonry, ice arch or igloo
    - Boxes of sintered basalt, etc. filled with regolith
- Interior walls, floor, furnishings
    - Early structural use within habitat?
    - Continue to import high value products, such as hinges, screws
- Foundations, anchors
    - Minimize and simplify through design
    - Existing and upgraded regolith for fill and foundations
    - Screw anchors into suitable regolith/geology
    - Tension line plus anchor mass — low *g*, high friction

Requirements: Habitat Interior, Life Support

- Artificial atmosphere:
    - Pressure
    - Mix of gases:
        - Oxygen for human needs
        - CO_2 for plants
        - Low enough O_2 for fire safety

Comments: O_2 is 21% of Earth's atmosphere

- Large volume × low density = large mass, a lot to import
- Leakage = loss of mass = $$$
- Water: Human consumption, other operations, sanitation
- Food
- Other life support and waste resource recycling systems
- Special needs to support base mission/operations

Use of In Situ Resources — Inside Habitat, Nonstructural

- Atmospheric Gases

Availability	Human Needs			Plant Needs
		Buffer Gasses		
	Oxygen	Argon	Nitrogen	Carbon Dioxide
Moon	Oxides/Water	?	?	?
Mars (thin atmosphere)	0.13% O_2	1.2%	3%	95%

Note: Oxygen is less than 1/3 of artificial atmosphere mass. Source of other needed gases on the Moon TBD.

- Water
    - From oxides
    - From water deposits (where? how much? how easy to get?)
    - Byproduct/coproduct with fuel generation and other products

Closely Associated Infrastructure

Needs	*In situ* material use
❖ Transportation infrastructure Paths and roadways	❖ Use coarser fraction of regolith for gravel roads
♦ Concerns: Trafficability; dust maintenance want hard, smooth surface	♦ place over imported or locally produced textiles
❖ Launch/landing areas	❖ Early use for concrete, sintered basalt ceramic, etc.
♦ Concerns: Blast and dust control. Need hard surface to minimize dust pickup; berms to direct the blast.	❖ Paving blocks
❖ Tanks, boxes, containers	❖ Simple, not glamorous
❖ Other human-occupied areas (see habitats)	❖ Need; too "simple" to import. Early use of marginally structural materials? High pressure tanks later.

Energy and Other Habitat Support Systems

Needs	*In Situ* Material Use
❖ Energy generation	
♦ Solar cells	♦ *In situ* derived cells?
♦ Supporting structure	♦ Metals, glass, ceramics?
♦ Wiring, piping	♦ Metals in basic shapes?
❖ Energy management	
♦ Electric energy storage (including for night time use)	♦ ?? EEs — help
♦ Insulation	♦ Regolith granular materials? Ceramic foam? Fiber glass?
♦ Heat energy storage or dissipation	♦ Granular regolith "heat sink" plus heat pump, heat pipes?
❖ Plant growth systems	♦ Regolith-derived soils

Construction Equipment and Operations

❖ Imported Construction Equipment	
♦ Problem — want small mass to import, but need mass for friction, stability	Imported equipment made with carbon and other composites. Design so some members, containers can be filled with regolith
❖ Tie downs, mining, excavation equipment, etc.	
❖ Equipment for more mature base	Combine imported components with frames, booms, buckets — made of local metals?

Summary

- ❖ Habitat material-related requirements depend on base maturity
- ❖ Opportunities & feasibility of *in situ* material use depends greatly on base maturity (also its size and mission).
  - ♦ Thus, identify proposed *in situ* material use with base maturity and mission
- ❖ Savings in imported mass through the use of *in situ* materials must consider "investment in mass" needed to gather, process, fabricate, etc.
  - ♦ Thus, big technical challenges in miniaturizing processes
- ❖ Habitats are pressure vessels containing gases having significant mass. Also provided — shielding, thermal stability.
- ❖ Many requirements/needs in areas of secondary structures, surfaces, containers — other "routine, nonglamorous" areas
- ❖ Appropriate mix of high value imported and locally available/produced will constantly change.

SEMICONDUCTORS: *IN SITU* PROCESSING OF PHOTOVOLTAIC DEVICES

Peter A. Curreri
Space Science Laboratory, NASA Marshall Space Flight Center

Lunar PV Cells

- Silicon options
    - Bulk crystal
    - Thin films (Landis 90)
        - Polycrystalline thin films
        - Amorphous thin films
- Design for Vacuum
    - Back contact cells (Sinton & Swanson 90)
    - Laser cut junction isolation (Micheels & Valdivia 90)
    - Ion implantation (Bentini et al. 82)
- Vacuum Processing
    - Thin films (Landis 89)
    - Metals extraction (Fang 88)
    - Resources extraction (Curreri 93)

Key Challenges

- Growth production facilities using *in situ* materials and minimal import (Earth "smarts" vs. mass)
- Use solar power for extraction and fabrication
- Design power systems, production facilities, extraction facilities for:
    - Maximum production from *in situ* materials
    - Maximum use of solar power
    - Minimum import from Earth

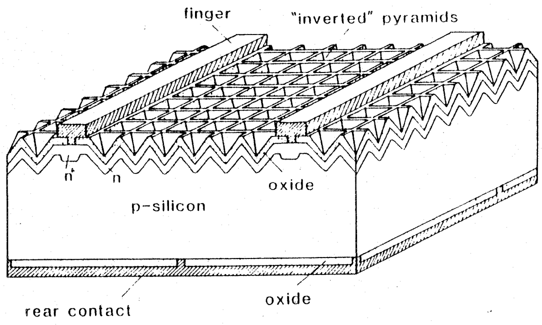


Fig. 1. Schematic diagram of the passivated emitter and rear cell (PERC cell).

Fabrication of Large Photovoltaic Arrays in Space from Lunar Materials

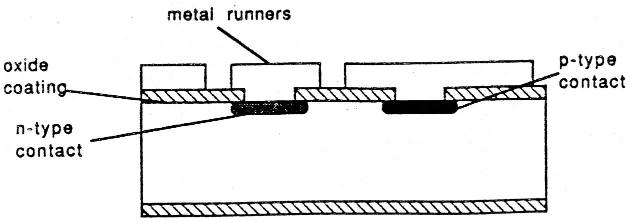


Fig. 2. A cross-sectional diagram of a point-contract solar cell.

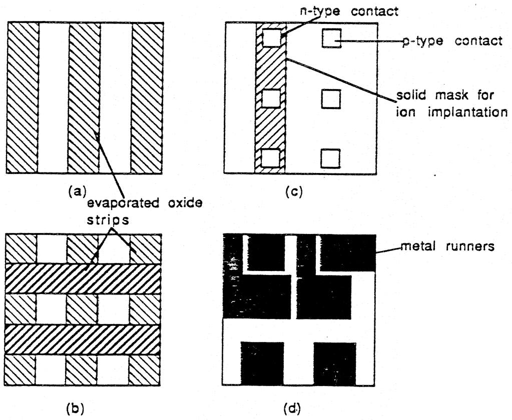


Fig. 3. Fabricating point-contact solar cells in space. (a) Evaporated oxide strips on silicon. (b) Crossing oxide strips forming point contacts to silicon. (c) Solid masking used to ion implant n- and p-type contacts. (d) Metal runners for electrical contact to silicon.

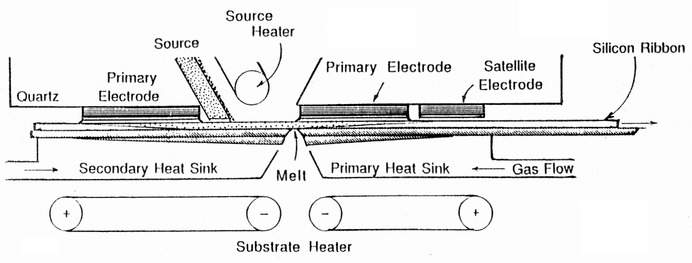


Fig. 4. Schematic of the growth apparatus.

OPPORTUNITIES FOR ISRU APPLICATIONS IN THE MARS REFERENCE MISSION

Michael B. Duke
Lunar and Planetary Institute, Houston, Texas

Objectives of Presentation

- Consider whether ISRU other than propellants/life support consumables can be useful to the Reference Mission
- Outline the type of analysis that has to be performed to evaluate the benefits of ISRU use
- Suggest some areas for investigation

Question

- Can use of indigenous planetary materials reduce the cost or risk of the reference mission?

Ways to Reduce Cost

- Offset the need to transport mass from Earth to Mars
- Increase the duty cycle or capacity or system lifetime of operating systems
- Reduce crewtime requirements for operations, maintenance, etc.

Ways to Reduce Risk

- Increase robustness of infrastructure
- Mitigate environmental hazards
- Reduce risk of accident or malfunction

Strategies

- Preplacement of assets with robotic systems
- Crew enhancements to surface systems

Characteristics of Robotic Preplacement Strategies

- Reduce total system mass by producing over a long period of time
- The mass of the robotic production system must be a fraction of the mass of the materiel that would have to be transported to Mars to provide the same function
- Actions that are simple and repetitive will be most effective

Example — Create Pressurizable Volume

- Benefits and Reduced Risks
    - Offsets requirement to transport mass to Mars for living and working areas, including plant-growth facilities
    - Allows more efficient volumetric transportation modes for internal systems brought from Earth
    - Allows economical expansion from initial base
    - Provides for ground-level or below-ground facilities to reduce radiation risk
- Costs and Increased Risks
    - Complex production system
    - Additional assembly tasks for crew
    - Technical risks associated with airlock designs
    - Unfamiliar technology

Concrete Structures

- Assume that all materials for concrete and rebar are available, including water
- Approximately 10 metric tons of the reference mission's Mars surface habitat is associated with structures — structure is 7.5 m diameter × 7.5 m high, with two floors
- Assume that all floors and walls are constructed of reinforced concrete, 25 cm thick. Total amount of concrete required: $52 m^3$ – 104 T
- If produced in 1 yr, this requires production of 280 kg of concrete/day - ~30 kg/hr for a 10 hr day
- If that amount of reinforced concrete can be produced, mixed, formed, cured, etc. with 1–2 T of robotic equipment, concrete may be able to compete with Earth supply

Other Possibilities

- Concrete or sintered blocks for roadways and pads
  - Reduce dust dispersion
  - Increase traverse speed/reduce power required
  - Move large objects
- Sintered regolith for radiation shielding
  - Reduce radiation hazard
  - Simplify hab module design
- Concrete for unpressurized structures
  - Protection of pressurized, unpressurized rovers from radiation, thermal cycling, dust reduces maintenance requirements

Example — Road-Grading

- Road grading can be done robotically
  - Can be performed with a 200 kg robotic system (which is able to add rock or soil ballast for additional weight)
  - Rover assumed to be able to prepare 1 m of roadway in 10 min
  - Production of 1.5 km of roadway requires 15,000 min
- Road assumed to allow traversal at 15 km/hr instead of 3 km/hr
- Transportation required between two habitat modules located 1.5 km apart, twice a day for two people
  - Road saves 40 min of traverse time daily for 500 day mission, or 20,000 minutes (60,000 minutes for three mission strategy)
  - Saves crew time
  - Could use same rover, modified for crew transport

Conclusions

- Use of ISRU in the construction of Reference Mission infrastructure is more complex than bringing things from Earth.
- Because many activities can be done robotically over long periods of time, the daily production/accomplishment rate can be quite low, consistent with capabilities of low-mass systems.
- More detailed studies could provide savings for the Reference Mission and build capability for expansion beyond an initial outpost.

MATERIALS TRANSPORTATION

H. A. Franklin
Bechtel Technology Inc., San Francisco

Move Materials, Cargo

- Forklifts
- Loaders
- Telescopic handlers
- Skid steers
- Cranes
- Conveyor belts

Move Dirt and Rocks

- Bucket excavators
- Bulldozers
- Scraper earthmovers
- Trenchers
- Backhoes
- Skid steers
- Conveyors and pipelines

Typical Skid Steer Data

- Operate through doorways and in confined spaces
- Versatile, adaptable tool modules
- Payload capacity: 900 to 1800 lbs
- Vehicle weight (1*g*): 3000 to 6000 lbs
- Power required: 30 to 60 HP (22 to 45 KW)
- Equivalent area PV cells: up to 5500 sq. feet

Typical Large Earthmovers

- Dedicated to hauling large volumes on rough mining roads
- Payloads: 120 to 340 tons
- Vehicle weight (1*g*): 230 to 435 tons
- Power required: 1200 to 2500 HP (900 to 1900 KW)
- Equiv. area PV cells: up to 227,000 sq.ft.

Road Services

- Reduce damage to terrain
- Reduce stress, damage to vehicles
- Reduce dust to facilities
- Reduce navigation demands
- ISRU applications
  - Concrete, basalt, etc. pavers
  - Glass, concrete poles for drag grading

Heatpipe Power System (HPS) and Heatpipe Bimodal System (HBS)

Michael G. Houts, David I. Poston, and Marc V. Berte
Los Alamos National Laboratory and Massachusetts Institute of Technology

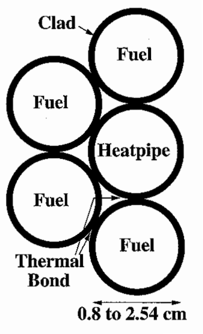
Assumptions behind the HBS and HPS

- Space fission systems can enhance or enable potential missions of interest:
  - Advanced exploration of moon and Mars.
  - Advanced deep space missions.
  - Defense missions.
  - Commercial missions.
- Space fission systems will only be used if they are safe, have adequate performance, and can be developed within reasonable cost and schedule. Cost and schedule will be drivers.

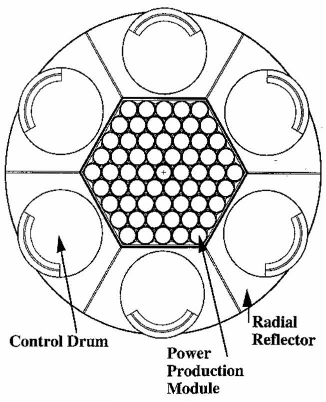
Goal is to develop an approach that will allow space fission systems to be utilized.

HPS: One approach to power-only systems.

- All desired system attributes for ensuring utilization.
- Several point designs have been investigated.
  - System mass (5 kWe/10 year life) less than 600 kg (unicouple TE).
  - System mass (50 kWe/10 year life) less than 2000 kg (unicouple TE).
  - Potential for development cost < $100 M, unit cost < $20 M.



- Modules contain 2 to 6 fuel pins and one heatpipe.
- Heat conducts from fuel to primary heatpipe.
- Primary heatpipe transfers heat to secondary heatpipe and /or converters.
- Temperature to power converters >1275 K.



HPS: Why Low Cost?

- Passive safety. Safety verified by zero-power criticals.
- Simple system, few system integration issues.
- Full power electrically-heated test of flight unit.
- Flight qualification with electrically-heated tests and zero-power criticals. No ground nuclear power test unless requested by sponsor.
- Fuel and core materials operate within database, even for multi-decade missions. No nuclear-related development required.
- No pumped coolant loop or associated components.
- Assured shutdown without in-core shutdown rod.
- Most issues resolved by electrically-heated module tests.
- Can be built with existing U.S. technology. Russian technology can enhance performance; international cooperation may be cost effective.
- Multiple fuel and power-conversion options.

HPS: Why Low Mass?

- ❖ Higher core fuel fraction than other concepts:
    - ♦ Reduces reactor volume/mass
    - ♦ Reduces shield volume/mass
- ❖ Simple:
    - ♦ No hermetically sealed vessel / flowing loops
    - ♦ No EM pumps
    - ♦ No lithium thaw system
    - ♦ No gas separators
    - ♦ No in-core shutdown rods
    - ♦ No auxiliary coolant loop
    - ♦ Simplified system integration

HPS 5 kWe "Off-the-Shelf" Design

❖ UN Fueled Reactor (passive shutdown)	250 kg
♦ Nb-1Zr / Na heatpipes	
❖ Shield	100 kg
♦ 2 m dose plane at 10 m, 1013 nvt/5 × 10^5 rad in 10 yr	
❖ Thermoelectric Power Conversion	85 kg
❖ Instrumentation and Control	50 kg
❖ Power Conditioning	20 kg
❖ Boom/cabling	70 kg
Total	575 kg

HPS Power Options

	HPS7N HPS7O/SA HBS10O	HPS7O	HPS12O/SA	HPS12O
TE	6 kWe	12 kSe	36 kWe	60 kWe
AMTEC	16 kWe	32 kWe	96 kWe	160 kWe
CBC	25 kWe	50 kWe	150 kWe	250 kWe

Rated thermal power assuming worst-case single heatpipe failure.
Mass of core, reflector, control drums, and primary heat transport: HPS7N = 240 kg; HPS7O = 325 kg; HPS10O = 370 kg; HPS12O=480 kg.
Mass of power conversion, shield and other components not included.

HPS/HBS Safety

- ❖ Virtually non-radioactive at launch (no plutonium)
- ❖ Passive removal of decal heat
- ❖ High radial reflector worth eases design for launch accident subcriticality
- ❖ Passive launch accident subcriticality (current baseline) can be ensured by using liners or structures that contain absorbers (rhenium or other)
- ❖ If desired, launch accident subcriticality can also be ensured by any one of the following methods
    - ♦ Launch shutdown rod
    - ♦ Removal of some fuel from the core during launch
    - ♦ Removable boron wires placed in interstitials

HPS Module Test Accomplishments

- Utilized existing test apparatus and heaters to reduce cost and schedule
- Demonstrated that high power (4 kWt) can be conducted into a 2.54-cm-diameter heatpipe operating at >1300 K and transported to the condenser against gravity
- Demonstrated adequate heatpipe performance at >1300 K with peaks (corresponding to fuel pin bonds) in evaporator radial heat flux
- Demonstrated that module thermal and mechanical bonds have adequate resistance to thermal stresses, thermal cycling, and other loads
- Demonstrated advanced refractory metal bonding and machining techniques
- Module fabrication/initial tests const <$75 K

Summary of Module Tests Performed to Date

Parameter	Value
Peak operating power (transported to condenser-end)	4.0 kWt
Peak heatpipe operating temperature (during module test)	>1400 K
Peak heatpipe operating temperature (during module fabrication)	>1500 K
Number of module startups (frozen to >1300 K and/or >2.5 kWt)	9

HPS / HBS Development Status

- Neutronic and thermal performance verified for numerous point designs
- Mass and lifetime estimates made for numerous point designs
- HPS module fabrication complete, module tests successful
- Conceptual design of HBS module. HBS module, heatpipe, and heaters under fabrication. Full-power test planned for 1998.

Next Step

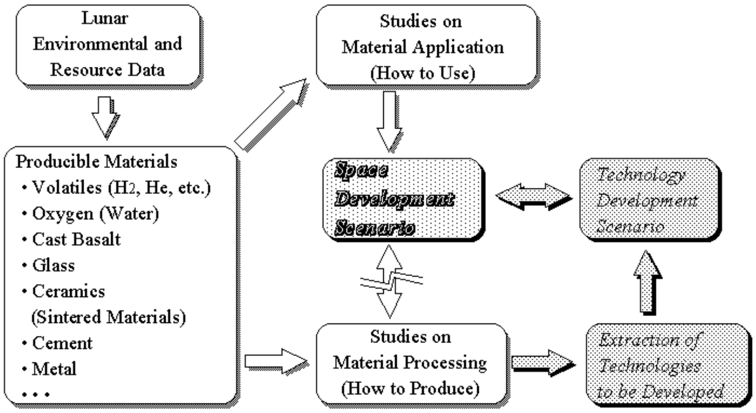
- Fabricate HPS or HBS core and demonstrate system thermal hydraulics using resistance heaters to simulate nuclear fuel. Evaluate normal and off-normal operation, plus startup.
  - Superalloy system < $0.5M
  - Refractory metal system $1.0M
  - Option to add power conversion subsystem at modest cost
  - First full thermal-hydraulic demonstration of US space fission system since 1960s
- Use core to demonstrate nuclear properties
  - Add fuel, reflector, and control system
  - Perform zero-power criticals at LANL, SNL, or elsewhere

Goal: Get something flying!

CONSIDERATIONS ON THE TECHNOLOGIES FOR LUNAR RESOURCE UTILIZATION

Hiroshi Kanamori
Shimizu Corporation, Space Systems Division

Resource Utilization Studies



Evolutional Scenario of Lunar Base

		Developmental Phase				
		I Survey	II Outpost	III Initial	IV Expand	V Autonomous
Crew Size		0	4	5	8	15 <
Mission Period		< 14 days	45 days	90 days	180 days	Permanent
Electrical Power	(day)	< 1 kW	20 kW	40 kW	120 kW	200 kW <
	(night)		9 kW	15 kW	45 kW	90 kW <
Number of Habitats			1	1	1	2 <
Number of Laboratories			0	0	2	4 <

Candidates for Lunar Products

Products	Components	Process examples	Lunar Base Phases				
			I	II	III	IV	V
Oxygen	O_2	Reduction, Electrolysis, etc.	······	···——	——	——	——→
Non-Processed Regolith	Regolith, Bags	Digging, Banking, Bagging, Piling	······	···——	——	——	——→
Cast Basalt and Glass	Silicates	Gradual or Rapid Cooling of Molten Basalt	······	···——	——	——	——→
Ceramics	Al_2O_3, MgO SiO_2, etc.	Sintering Regolith		······	——	——	——→
Cement	CaO, Al_2O_3, SiO_2, etc.	Sintering and Crushing Anorthite			······	——	——→
Metals	Fe, Ti, Si, Al, Mg, etc.	Reduction and/or Electrolysis			······	——	——→

Technologies to be Studied for Lunar Resource Utilization

		Gas Desorption	Oxygen		Non-processed Regolith	Cast Basalt & Glass		Ceramics		Cement	Metals		Composites
			Initial	Advanced		Initial	Advanced	Initial	Advanced		Initial	Advanced	
Infrastructure	**Excavation, Mining**	●	●	●	●	●	●	●	●	●	●	●	●
	Surface Transportation												
	Energy												
Preliminary Processing	**Beneficiation**	●		●			●		●	●	●	●	●
	Heating and Cooling Control	●	●	●		●	●	●	●	●	●	●	●
	Reduction		●	●						●	●	●	●
	Electrolysis		●	●							●	●	●
	Melting and Solidifying					●	●				●	●	●
	Sintering							●	●	●		●	●
Secondary Processing	**Refining and Purifying**						●		●			●	●
	Concrete (Mixing, etc.)									●			●
	Assembling (Welding, etc.)					●	●	●	●	●	●	●	●

Infrastructure Technologies

- Excavation, Mining
  > Drill, Core (include Sampling)
  > Scrape, Scoop, Shovel
  > Cave, Blast

- Surface Transportation
  > Conveyor, Cart, Truck

- Energy
  > Generation
  > Transmission
  > Storage

Preliminary Processing

- Beneficiation
  > Sizing (Screen, etc.)
  > Electrostatic Separation
  > Magnetic Separation

- Heating and Cooling Control
  > ~ 1000 K (Gas Desorption)
  > ~ 1500 K (Sintering)
  > ~ 2000 K (Melting, Smelting)
  > ~ 3000 K (Pyrolysis)
  > ~ 10000 K (Plasma)

Preliminary Processing (2)

• Reduction	> H_2, C, CH_4, F, HF, Al, Li, Na, etc.

• Electrolysis	> ~ 373 K (Liquid Water) > ~ 1000 K (Vapor Water) > ~ 1000 K (Molten Salts w/ Flux) > ~ 1700 K (Molten Silicates)

Preliminary Processsing (3)

• Melting and Solidifying	> Casting > Other Forming (Spinning, etc.) > Finishing (Fine Form) > Tempering

• Sintering	> Powder Production and Mixing > Forming > Sintering > Tempering

Secondary Processing

• Refining, Purifying	> Gas Purification > High Grade Glass and Ceramics > Pure Metal

• Concreting	> Mixing, Forming > Curing

• Assembling	> Jointing > Welding

Materials Refining for Structural Elements from Lunar Resources

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Ohio Aerospace Institute, NASA Lewis Reseearch Center

Use of *in situ* resources for construction on the Moon will require manufacturing structural materials out of lunar resources. Likely materials that could be manufactured from lunar materials include steel, titanium, aluminum, and glass (for glass-fiber composite). Process sequences for manufacturing these materials out of lunar regolith are discussed.

Lunar Structural Materials

Low availability on the Moon:

- Graphite fiber; SiC fiber; artificial fiber composites (Kevlar, Spectra, etc.)
  - Used as advanced lightweight structural materials on Earth, but low availability of carbon on the Moon makes these poor choices.
- Polymer-matrix composites (epoxy; polyester)
  - Low availability of carbon on the Moon makes these poor choices
- Cement, concrete
  - Common paving and building material on Earth, but low availability of water on the Moon makes these poor choices.
- Asphalt
  - Common paving material on Earth, but low availability of carbon on the Moon makes this a poor choice

Available on the Moon:

- Metals
  - Steel
    - Common terrestrial structural material; many variant compositions
  - Aluminum
    - Common terrestrial structural material
  - Titanium
    - Uncommon terrestrial material; used where extremely light weight is required; high temperature makes it difficult to work with
- Composites
  - Glass/glass composite
- Paving/construction materials
  - Sintered-regolith brick
  - Glass-matrix regolith brick

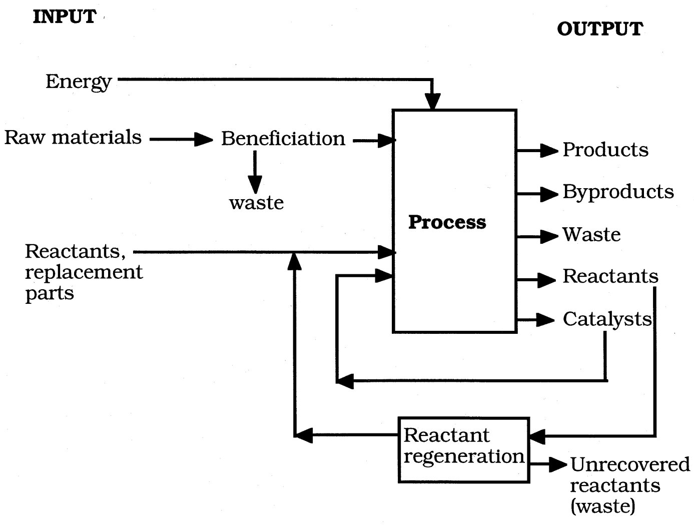

Fig. 1. Generic flow chart for material processing.

Process Selection Criteria

- Make as many useful materials as possible
- Minimize input from Earth
  - 100% recycling of non-lunar reactants (slag must not bind reactant or catalyst)
  - Minimum replacement parts need (crucibles require many batches without replacement avoid sacrificial electrodes)
- Minimize energy requirements
- Avoid high temperature process steps where possible
- Subject to other constraints, chose simplest possible process

Steel Production from Meteoritic Iron

- A few tenths of a percent of the regolith may consist of metallic nickle-iron deposited in the from of micrometeorites
- Separate from soil using magnets may require grinding soil first
- Product will be iron/nickel alloy typical of meteorites
- Minimum energy requirements
- Probably the easiest structural material to refine

Alternate process: refine iron from lunar regolith

- More complicated and energy-intensive process
- Same process as refining aluminum
- May be byproduct of silicon manufacture

Glassmaking for Composites

- A glass/glass composite requires two components; fibers and matrix
- Bulk glass is excellent in compression; poor in tension
- Glass fiber is excellent in tension
- Glass/glass composites have good strength in both tension and compression

Proposed composite: Anorthite fibers in aluminosilicate matrix

Part 1: Fibers

- Anorthite fiber — Anorthite (calcium aluminosilicate) is purified from the lunar plagioclase, then melted to make glass. The melting point of anorthited, approximately 1550°C, is relatively high, making it difficult to work with. Mackenzie and Claridge suggest addition of calcium oxide, to form a composition of roughly 46% CaO, 42% SiO_2, 11% Al_2O_3, and 1% trace, to reduce the melting point to 1350°C. Purity of starting materials is not critical unless transparency is needed.
  - Simple two-step process
    - beneficiate to pure anorthite
    - melt and draw into fibers
  - Moderate energy requirements (1350°–1550°C)
  - Requires some prospecting to locate best ore
  - Requires refined calcium oxide to lower melt temperature
- Alternative: Fused silica fiber — the low thermal expansion coefficient of pure silica is a disadvantage, since it is desirable for the matrix material to have a lower thermal expansion coefficient than the fiber.
  - Well-developed technology
  - High temperature process (1710°C)
    - Corrosive
    - Needs high temperature crucibles
    - Energy intensive
  - Requires refined silicon oxide
  - Other components can be added to lower melt temperature

Part 2: Matrix

The matrix must consist of a material with a significantly lower melting temperature than the fibers.

Aluminosilicate glass

- Typical composition:

SiO_2	57%
Al_2O_3	20%
MgO_3	12%
CaO	5%
B_2O_3	4%
Na_2O	1%
trace oxides	1%

    - Major constituents are common on the Moon.
    - Minor constituents are less common, but available.
    - Melt temperature (ca 1130°C) is 200–400° below melt of anorthosite, so this can be used as a matrix.
    - Melt temperature will below melt temperature of regolith, so this could be used as a matrix for sintered regolith bricks.
    - Melt temperature and thermal expansion coefficient can be modified by changing composition.
- More complicated process; requires refined input materials.
- Modest energy requirements (1140°C) plus energy required for refining
- Requires refining Na and B; elements of low abundance on the Moon
    - Prospecting may be desirable, to find pyroclastic deposits enriched in these materials.
    - Deleting Na and B from formula will increase melt temperature slightly; this change may be worth making if Na or B is difficult to refine.
    - If there is lage-scale refining of lunar material for other purposes (i.e., producing silicon for solar cells), Na and B will be produced as an un-used byproduct. In this case it may be desirable to add more NaO and B_2O_3, to decrease melt temperature.

Aluminum Production

Aluminum is likely to be a byproduct of silicon production. Aluminum production processes include electrolysis processes and fluorine reduction.

Terrestrial aluminum production require sacrificial electrodes and uses nonrecycled cryolite; not applicable to the Moon. Modified electrolysis techniques are possible.

For silicon production on the Moon, see (1) Landis G., "Materials Refining for Solar Array Production on the Moon," presented at the Workshop on Space Resource Utilization, Lunar and Planetary Institute, Houston TX, Dec. 11–12, 1998, and (2) "Solar Array Production on the Moon," SPS-97: Space and Electric Power for Humanity, Aug. 24–28, 1997, Montreal, Canada, pp. 311–318.

Aluminum produced during silicon production (same process also refines glass precursors)

- Fluorine brought to the Moon in the form of potassium-fluoride/sodium fluoride/calcium fluoride salt mixture
- Potassium fluoride electrolyzed from eutectic salt to form free fluorine and metallic potassium; temperature: 676°C
- Fluorine reacted with heated lunar regolith to form SiF4, oxygen, and metal fluorides; temperature: 500°C
- Gaseous SiF_4 and TiF_4 separated from oxygen by condensation; 178°K
- SiF_4 reacted in plasma to form silicon and recover fluorine reactant; 300°C
- Potassium metal added to metal fluorides to produce metallic aluminum and iron; temperature: 500°C
- Oxygen added to mixture of potassium metal with calcium fluoride to recover potassium fluoride and calcium oxide; temperature: 520°C

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