

***SPACE RESOURCES  
ROUNDTABLE II***

**November 8–10, 2000**

**Colorado School of Mines  
Golden, Colorado**

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## SPACE RESOURCES ROUNDTABLE II

November 8–10, 2000  
Golden, Colorado

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## Preface

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This volume contains abstracts that have been accepted for presentation at the Space Resources Roundtable II, November 8–10, 2000. The Steering Committee consisted of Joe Burris (*WorldTradeNetwork.net*), David Criswell (*University of Houston*), Michael B. Duke (*Lunar and Planetary Institute*), Mike O’Neal (*NASA Kennedy Space Center*), Sanders Rosenberg (*InSpace Propulsion, Inc.*), Kevin Reed (*Marconi, Inc.*), Jerry Sanders (*NASA Johnson Space Center*), Frank Schowengerdt (*Colorado School of Mines*), and Bill Sharp (*Colorado School of Mines*).

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**Developing Technologies for Space Resource Utilization – Concept for a Planetary Engineering Research Institute.** J. D. Blacic<sup>1</sup>, D. Dreesen<sup>2</sup> and T. Mockler<sup>2</sup>, <sup>1</sup>Los Alamos National Laboratory, MS D443, Los Alamos, NM 87545, jblacic@lanl.gov, <sup>2</sup>Los Alamos National Laboratory

### Introduction

There are two principal factors that control the economics and ultimate utilization of space resources - 1) space transportation, and 2) space resource utilization technologies. Development of space transportation technology is driven by major government (military and civilian) programs and, to a lesser degree, private industry-funded research. Communication within the propulsion and spacecraft engineering community is aided by an effective independent professional organization, the American Institute of Aeronautics and Astronautics (AIAA). The many aerospace engineering programs in major university engineering schools sustain professional-level education in these fields. NASA does an excellent job of public education in space science and engineering at all levels. Planetary science, a precursor and supporting discipline for space resource utilization, has benefited from the establishment of the Lunar and Planetary Institute (LPI) which has served, since the early post-Apollo days, as a focus for both professional and educational development in the geosciences of the Moon and other planets. The closest thing the non-aerospace engineering disciplines have had to this kind of professional nexus is the sponsorship by the American Society of Civil Engineers of a series of space engineering conferences that have had a predominantly space resource orientation. However, many of us with long-standing interests in space resource development have felt that an LPI-like, independent institute was needed to focus and facilitate both research and education on the specific engineering disciplines needed to develop space resource utilization technologies on an on-going basis.

### Proposal

We propose that the time is right for establishment of an independent research and education institute focused on extraterrestrial engineering science and patterned on the very successful Lunar and Planetary Institute. A Planetary Engineering Research Institute (PERI) would focus non-spacecraft engineering research needed for the next phase of planetary exploration and resource utilization. For the first time, large-scale civil (deep drilling/sampling of the Martian subsurface) and chemical engineering missions (Mars in situ propellant production) are poised to enter the mainstream of NASA programmatic support. Similarly, any significant, sustained return to the Moon or exploitation of near-earth asteroid resources will require advances in civil, chemical, power and other engineering sciences to extend terrestrial knowledge and practices to the new environments of space and planets in the decades ahead. One can envision the emergence of a new integrating discipline of planetary engineering science, analogous to planetary science. The current and anticipated needs for planetary engineering research and education will be focused in the discipline areas of civil/mechanical, chemical/process, materials, and nuclear & renewable power engineering – with a cross-cutting need for remotely-managed, semi-autonomous process control technology and robotics engineering. A PERI can meet these needs as a service to NASA, DOE, universities and private industry.

It is proposed that NASA, Department of Energy, National Academy of Engineering and industry support be solicited to fund the formation of the Planetary Engineering Research Institute. On the pattern of LPI, the

institute would have a small (5-6) permanent research staff, a limited-term staff of visiting engineer/scientists, research fellows and students, and a small support staff. Future growth could include conference facilities to extend and supplement the facilities at LPI for topical workshops and conferences. For this extended phase of development, host state support could be solicited because of the desirable visitor revenue that would accompany conferences. Because of the nature of engineering research, it is anticipated that significant laboratory space will be needed to support bench-scale working prototypes of engineering systems and subsystems. In-house capabilities would be supplemented with more extensive facilities at regional universities and government laboratories. We envision that PERI activities will be concentrated in the following engineering sub-disciplines:

1. Civil/Mechanical/Materials – e.g., planetary drilling and excavation, resource mining, surface trafficability, habitat construction & shielding, in situ structural materials production, thermal management systems.
2. Chemical & Process – e.g., in situ resource beneficiation, in situ chemical processing, life support systems.
3. Energy – nuclear power systems, in situ/renewable energy systems (solar, geothermal, hydro).
4. Robotics – because of the nature of space resource utilization, a high degree of automation will be needed in all systems, and so robotics engineering cross-cuts all the others.

We estimate that an annual operating budget of ~\$5M will be needed for the first phase of PERI, as described above, and would be allocated roughly as follows: Technical personnel - \$2M, laboratory and other research facility support - \$2M, and support and education personnel - \$1M. Initial start-up funding of ~\$1M would seem appropriate.

We believe there are compelling reasons for establishment of PERI and we seek

support from participants in the Space Resource Roundtable and others to advance the concept.

**Results of a Conceptual Systems Analysis of Systems for 200 m Deep Sampling of the Martian Subsurface.** J. Blacic<sup>1</sup>, D. Dreesen<sup>2</sup> and T. Mockler<sup>2</sup>, <sup>1</sup>Los Alamos National Laboratory, MS D443, Los Alamos, NM 87545, jblacic@lanl.gov, <sup>2</sup>Los Alamos National Laboratory

### Introduction

Recent robotic orbital and lander missions at Mars are part of a renewed campaign of exploration that seeks to build on the early successes of the Viking program. Current plans feature a vigorous series of orbital, surface and subsurface robotic missions with a probable return of a small number of atmosphere, rock and soil samples to Earth, and culminate in human exploration before the end of the second decade of the new millennium. The latest discoveries of this program are lending increasing support to models of a water-rich Martian history in which most of the remaining water is now thought to reside in the subsurface. Furthermore, the top-level goal of seeking evidence of extant or fossil life on Mars has evolved a strategy of "follow the water", since experience shows that life on Earth seems to require the presence of liquid water. In addition, water, if found, would be the most valuable in situ resource that could be developed to support manned exploration of Mars. These developments have led to a compelling argument for deep subsurface in situ measurements and sampling on Mars, a challenge never faced by planetary science on any body other than the Earth.

### Analysis Results

We have performed a conceptual systems analysis study to identify critical issues and assess the best technologies for accessing and sampling the Martian subsurface to a depth of 200 m. A near-equatorial landing site is assumed at which the average surface temperature is 200 K and the atmospheric pressure is 600 Pa. The shallow rock to be penetrated is assumed to be an interbedded sequence of basaltic volcanic rocks, fine-to coarse-grained sediments and conglomerates, impact glasses and breccias, and ice in the form of pore ce-

ment, pure ice lenses or massive ground ice. A landed mass of 750 kg is assumed, of which 250 kg is allowable for the drilling/sampling system. Power of 1000 Watts per Sol is assumed available for drilling operations. We assume that target depth must be reached and all sampling completed 200 days after landing.

An extensive search of sources identified a LONG LIST of 36 distinct systems that might be capable of achieving the mission objectives and for which there was some description and/or data under terrestrial conditions. This list was reduced to a SHORT LIST of 15 systems on the basis of first order decisions of whether or not each system could meet fundamental mission constraints. This remaining list of systems was subjected to more detailed engineering analysis and modeling to identify those best able to meet mission requirements and constraints. Nearly all existing terrestrial systems were eliminated by this screening, but a list of critical subsystems was determined from which custom prototype systems could be constructed for testing. The main problem in identifying specific systems was the general lack of quantitative operational data to use in calculations and to form objective criteria for comparison and selection. This was particularly true for data taken under temperature and pressure conditions simulating the Martian environment; in fact, no such data was found. As a result, only general conclusions could be reached, the primary of which was that *only high-efficiency, mechanical, overburden-type drilling approaches are feasible for this mission*, with hole diameters of ~35 mm and core samples of ~15 mm diameter; core samples may have to be sub-sampled to meet contamination constraints.

To illustrate what a credible system might look like for this mission, three EXAMPLE SYSTEMS were constructed from the analysis combining the best subsystems for rock comminution, drill hole conveyance of subassemblies, drill cuttings transport and disposal, well bore stabilization, power transmission from surface to hole bottom, and thermal management. One of these example systems featuring coiled tubing deployment of the bottom hole assembly and down hole fabrication of hole support is shown conceptually in Figure 1. Continuous coring was found to be feasible, and so all samples were assumed to be of this form. The example systems were described conceptually and total system estimates for mass and power were determined. We conclude that the assumed mass and power mission constraints are feasible.

The analysis concludes with recommendations for subsystem research and prototype demonstrations that must be performed before any detailed mission design can be undertaken.

Our priority recommendations are:

- 1) Investigate critical subsystems that require early and extensive laboratory-scale testing. These include comminution, cuttings transport, drilling process automation and robotics, and sample handling.
- 2) Perform mechanical drilling demonstrations in a 600 Pa, 200 degree K, CO<sub>2</sub>-filled chamber.
  - Investigate rotary, percussive, and combined.
  - Investigate various percussive frequencies, rotary speeds and thrust levels.
  - Investigate subsystem performance using a large variety of rocks and formations
  - Collect extensive data to model bit performance and optimize cutting performance over a wide variety of conditions.
- 3) Investigate bit cleaning and cuttings transport in a 600 Pa, 200 degree K, CO<sub>2</sub>-filled chamber.
- 4) Investigate bit cooling and core heat-up in a 600 Pa, 200 degree K, CO<sub>2</sub>-filled chamber.
- 5) Perform coefficient of friction measurements in a 600 Pa, 200 degree K, CO<sub>2</sub>-filled chamber for sample drill system materials and special, extra-dehydrated rock samples (Martian rock simulants).
- 6) Perform demonstrations of example systems in the laboratory and in the field.
  - Develop a test bed for developing sensors, telemetry and control systems.
  - Demonstrate remote-controlled and automatic-controlled drilling in Mars-like drilling environments with various drilling systems.
  - Use appropriate time-delayed communication for remote control.
  - Test various control methodologies under as realistic simulation of the special requirements and environments for Martian drilling as is feasible.
  - Develop a test bed for evaluating and determining the best technical approach for bore wall stabilization.
- 7) Investigate total system thermal management.
- 8) Investigate methods for prevention of contamination of core and samples.
- 9) Determine the learning curve for developing test plans and procedures for testing second generation, optimized systems based on results from laboratory investigations and field demonstrations.

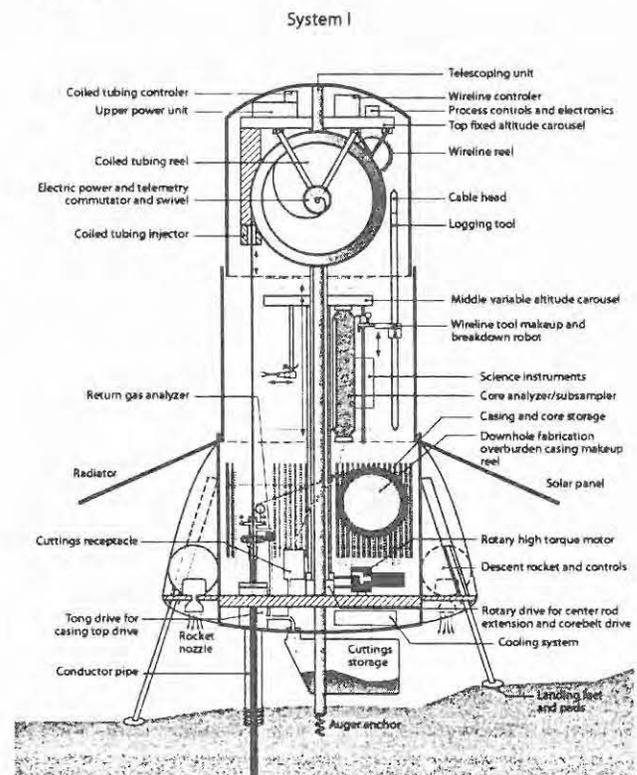


Figure 1. Conceptual arrangement of subsystems for an example system that meets the systems requirements and constraints for 200 m deep sampling on Mars.

**THE ROLE OF NEAR-EARTH ASTEROIDS IN LONG-TERM PLATINUM SUPPLY.** B. R. Blair, PhD Student, Division of Economics and Business, Colorado School of Mines, Golden CO 80402 (bblair@mines.edu).

High-grade platinum-group metal concentrations have been identified in an abundant class of near-Earth asteroids known as LL Chondrites. The potential existence of a high-value asteroid-derived mineral product is examined from an economic perspective to assess the possible impacts on long-term precious metal supply. It is hypothesized that extraterrestrial sources of platinum group metals will become available in the global marketplace in a 20-year time frame, based on current trends of growth in technology and increasing levels of human activities in near-Earth space. Current and projected trends in platinum supply and demand are cited from the relevant literature to provide an economic context and provide an example for evaluating the economic potential of future asteroid-derived precious and strategic metals.



**CORE DRILLING FOR EXTRA-TERRESTRIAL MINING.** D. S. Boucher<sup>1</sup>, and E. Dupuis<sup>2</sup>, <sup>1</sup>Northern Centre for Advanced Technology Inc., 1400 Barrydowne Road, Sudbury, Ontario, Canada, P3A 3V8 (dboucher@norcat.org), <sup>2</sup>Canadian Space Agency, 6767 route de l'aéroport, St-Hubert, Québec, Canada, J3Y 8Y9.

**Introduction:** Space Resource Utilization involves the active identification and mining of planetary bodies for commodities ranging from platinum group metals [1] to water [1],[2], such as might be realized from a dormant comet or carbonaceous chondrite like 1998 KY26, estimated to contain over 1 million gallons of water [3]. Some proposed ET mining processes [2],[4] require access to sub-surface "mining zones" ranging from 10 to 200 metres and beyond [6]. The technology used must support the identification, mining and extraction processes and must operate in milli-gravity, airless and extreme environments [1],[2].

This paper proposes the use of the diamond core drilling apparatus as a multi-purpose enabling technology for any extra-terrestrial sub-surface resource utilization. It specifically examines the mechanics of Diamond Drill Coring and addresses the issues required to adapt the technology to space based operations.

**Core Drilling Mechanics:** Diamond Drill Coring is a mining process within which a hollow tube and cylindrical bit penetrate the ground leaving an internal core to be retrieved for analysis.

This technology has been shown to be an energy efficient method of hole propagation when compared to other mining technologies, such as ITH, top hammer, Tri-cone, or button bits that require high amounts of energy to overcome rebound, and drill string elasticity.

Diamond drill coring is highly adaptable to variations in drilling media, allowing hole propagation to proceed in ground ranging from voids to hard rock. Stabilization of the hole is achieved via the drill rods, which prevent stress flow of the hole walls.

Investigations performed on alternatives to diamond coring [5] indicate these generally perform poorly when compared to diamond core drilling as an application specific technology.

**Components:** The sub-system components of a diamond core drill are: drill bit, drill rods, core tube, drive system and anchoring system.

The bit is a hollow cylinder constructed of a matrix with embedded diamond chips. The bit grinds its way through rock stripping the matrix away carrying used diamond chips with it and exposing new chips to the rock interface.

Drill rods transfer energy to the bit from surface mounted drive mechanisms, carry balings from the rock interface, carry cooling water to the bit, and provide a conduit for retrieval of the core. The rods are hollow, thin walled sections extending from the drive unit to the bit. Presently, drill rods are added to and removed from the drill string manually.

The core tube is an in-situ receiver for the core produced during the drilling operation. It is temporarily

attached to the bit and will ride down with it, enveloping the core. Small dogs attached at the bit end grip the core when the core tube is retracted. Core is then recovered using a winch system inside the drill string that automatically mates to the core tube.

The drive system is typically a surface hydraulic unit. A dedicated rotary drive applies torque to the drill rods and thrust cylinders apply the axial forces to push the drill bit against the rock. Both sets of forces are carefully controlled to ensure accurate and efficient hole propagation.

Terrestrial drills mass in excess of 5 tonnes, but still require the use of an anchoring procedure to ensure the unit remains stable. This is normally accomplished via the manual placement of a resin activated anchor or bolt, after which the operator must then carefully align the drill and begin drilling, using the anchor to absorb reaction forces.

Table 1. Typical Specifications of a Core Drill: [7]

Parameter	Value (nom.)	Units
System Mass (est.)	5000	kg
Power (est.)	45	kWatt
Energy per hole (est.)	1800	kW-hr
Hole Depth (up or down)	600	metre
Hole Diameter	48	mm
Core diameter	27	mm
Rotation Torque(stall)	1,750	Nm
Rotation Velocity (max.)	1,300	RPM
Axial Thrust at bit	35,500	Newton
Axial Rate of Penetration	250	mm/min.

**Process:** Energy in the form of rotary action and axial force are imparted to the drill bit via the drives and drill string. The energy is released at the rock interface in the form of shearing and heating, which can be intense enough to cause micro-welding between the bit and the rock. Under some conditions this can cause a form of spalling.

Balings are the cuttings produced during a drilling operation. The majority are carried away, but a small portion remain at the rock interface to aid in the grinding. Present day machines use water to carry away the balings and cool the bit. The balings must not be allowed to compact above the bit or vast amounts of energy would be required to overcome binding.

Core retrieval is triggered by a full core tube or "wedging". Once the tube is full, drilling can no longer proceed as torque requirements rise due to core tube friction. Wedging is caused by severely fractured ground forming wedges of core in the core tube, re-

sulting in severe radial forces. Torque and axial forces rise dramatically and the bit polishes off, preventing further drilling.

**Adaptation to Space:** *Core Drilling as a System:* The diamond core drilling unit as a system is a multi-purpose exploration and exploitation tool having inherent capabilities to stabilize the drill hole, support "In The Hole" technologies like heaters and sensors, and can be used as a conduit for resource extraction technologies.

*Power and Drive System:* The adaptation of this technology to space would require the development of an all electric unit capable of drilling to depth with greatly reduced power requirements. Fortunately, this can be achieved by effectively extending the "Mining Cycle" time and reducing rates of penetration with attendant forces and instantaneous energy consumption (Table 2).

*Balings/Dry Drilling:* Present day machines use water to carry away balings and also to cool the bit. Adaptation of the technology to space would require the development of a dry drilling system. This would require a drill bit design capable of staying "sharp" during dry drilling. Lower RPM and thrust will alleviate the water cooling requirement, but balings removal is still an issue. Some work has been started to examine mechanical augers as a potential solution.

*Mass:* The largest contributions to the mass of a drill are the power pack, the drive mechanisms and the drill steel. Smaller diameter cores, new high strength materials and novel electric drives are being designed to reduce the mass of a Space Drill.

*System Autonomy:* Terrestrial units are developing as semi-autonomous and tele-operated devices. Units for space based applications are being designed for fully autonomous operation. Much work has been performed to remove critical decisions from the operator in a transparent algorithm set. These algorithms are being modified into an operating mode that will more readily lend itself to ultimate autonomy.

Presently, advanced algorithms are in use for autonomous control of Thrust, Rate of Penetration, Wedging recovery, Rod Make/Break cycles, Rod tripping, and Rod Handling.

*Anchoring:* Automated anchoring of a drill unit is a requirement for any autonomous rig. A self deploying anchor is now commercially available for terrestrial drills. This unit is capable of absorbing reaction forces generated during the terrestrial drilling cycle (Table 1). A primary stage anchor will be developed and integrated to allow deployment of the final stage under milli-gravity conditions.

*Core and Rod Handling:* An autonomous unit must be capable of dealing with rod changes and core retrieval. Algorithms already in use can recover core from a maximum of 10 metres depth. Work must be performed to develop algorithms and mechanics to allow core retrievals for the full 100 metres depth.

Rod handling algorithms have been in use for some time that effectively handle rod changes. The limit is rod storage configuration and transfer mechanisms. The advantage of the Space Drill is that there would be no need to remove rods from the string, once they are installed.

Table 2. Space Core Drill Specifications

Parameter	Value (nom.)	Units
System Mass	150	kg
Power Consumption	1000	Watts
Energy Available per hole	8700	kW-hr.
Hole Depth	100	metre
Hole Diameter	20	mm
Core diameter	10	mm
Rotation Torque(stall)	500	Nm
Rotation Velocity (max.)	200	RPM
Axial Thrust at bit	8,000	Newton
Penetration (Intermittent)	10	mm/min.

These values are based upon a hypothetical mission to Mars with a two year drilling cycle to recover 100 metres of core sample using a 1000 Watt solar power supply.

**Conclusion:** Diamond Core Drilling can be and is being adapted for use in space resource utilization. Effective adaptation of this technology requires development work in the following areas: 1) light weight all electric drive system, 2) primary anchoring system for milli-gravity deployment, 3) dry drilling technology, 4) rod and core handling systems, 5) system autonomy.

Canada, and Sudbury in particular, has long been recognized as the world leader in the development and application of mining and exploration technologies. Canadian mining equipment manufacturers have already started to address the issues of adapting terrestrial mining equipment to space based operation, and is using their extensive base of expertise in harsh environments along with Canada's known expertise in space based robotics, to achieve this goal.

**References:** [1] John S. Lewis (1996) *Mining The Sky* [2] Mark J. Sontner (1997) *The Technical and Economic Feasibility of Mining the Near Earth Asteroids*. [3] S J. Ostro et al (1999) *Radar and Optical Observations of Asteroid 1998 KY26*, Science Vol. 285 p557-559 [4] D.L. Kuck (1992) *In-Situ Recovery of Water from Dormant Comet Cores and Carbonaceous Chondrites*, Space '92 [5] D.S. Boucher (1997) *Alternative Exploration Drilling Technologies, Laser and Water Based Drills for DMC Drilling Supplies Ltd.*[6] J. Blacic et al, (2000) *Proceedings: Concepts and Approaches for Mars Exploration* pp 31-32 [7] Longyear Australia Pty Ltd., *Longyear LM 75 Operations and Service Manual*.

**RECOMMENDATIONS BY THE "LSP & MANUFACTURING" GROUP TO THE NSF-NASA WORKSHOP ON AUTONOMOUS CONSTRUCTION AND MANUFACTURING FOR SPACE ELECTRICAL POWER SYSTEMS.** D. R. Criswell<sup>1</sup> and A. Ignatiev<sup>2</sup>, <sup>1</sup>Inst. Space Systems Operations, c/o 16419 Havenpark, Houston TX 77059-6010, USA (dcriswell@uh.edu), <sup>2</sup>University of Houston, Houston TX 77204, USA.

The National Science Foundation and NASA sponsored a workshop to explore the implementation of space solar power systems in space and on the Moon. Specific attention was focused on employing construction and manufacturing techniques that might lend themselves to autonomous growth based on local resources. The workshop was held in Arlington, Virginia (4 - 7 April 2000) and organized by Prof. George Bekey of the University of Southern California and Mr. Ivan Bekey of Bekey Designs, Inc. The complete final report should be available in September, 2000 from USC. The workshop findings, recommendations, and documentation were organized around four working groups. Group IV focused on the manufacture of a

Lunar Solar Power (LSP) System. The primary topics were:

- Overview of the lunar solar power system
- Demonstration base of the lunar solar power system
- Lunar solar power and sustainable economic growth
- Manufacturing of solar photovoltaics directly on the lunar surface  
(provided by Prof. Alex Ignatiev, Un. Houston)
- Findings and
- Recommendations

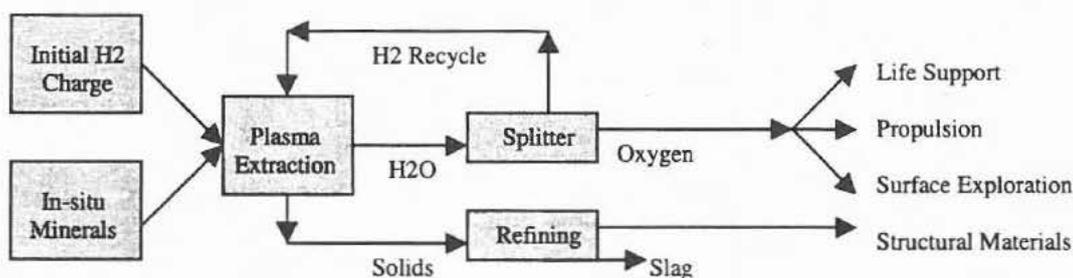
This paper summarizes the first four topics, reviews the major findings and recommendations of Group IV, and lists its participants.



## Plasma Processing of Lunar and Planetary Materials

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Space exploration and colonization must include oxygen for propulsion and life support, as well as, structural materials for construction. To the extent possible, these should be derived from locally available planetary resources. We propose an extractive metallurgy and oxygen recovery process well-suited for resource utilization in space. Locally available minerals are placed in a radio frequency-generated hydrogen plasma. This is accomplished using a fluidized bed contacting device. Electromagnetic energy is coupled to the hydrogen gas forming a non-equilibrium plasma. The plasma produces the ideal reducing agent – atomic hydrogen – in direct and intimate contact with the solid particles. When using oxide minerals as a feed, atomic hydrogen extracts oxygen from the matrix through the formation of water. The water is subsequently split into oxygen and hydrogen (the hydrogen is then recycled back to the plasma reactor). The processed solids could then be refined to produce structural materials. A conceptual process flow diagram, which requires an initial charge of hydrogen, is given in Figure 1.



**Figure 1. A cross-cutting oxygen extraction process.** The oxygen could be used directly for life support or for propulsion (e.g. combustion of methane or in ion acceleration (plasma) propulsion schemes). It could also be used as an oxygen source for fuel cell powered robots engaged in surface exploration. The processed solids would be reduced from the oxides towards the base metals and could (with further refining) be used as structural materials.

Central to this process is the plasma fluidized bed (PFB) reactor. In such a device, gas flows upward through a bed of particles such that the upward hydrodynamic drag force on the particles counter-acts the gravitational forces. At this point the bed becomes "fluidized." We have shown that a plasma can be maintained in such devices under the proper flow regimes. We screened extractive chemistry in plasma fluidized beds using a hydrogen-argon plasma. The plasma was generated using a microwave applicator (2.45 GHz) coupled directly to a quartz tube (the tube passed through the waveguide). The bed was fitted with a port just above the bed which allowed gas samples to be withdrawn for mass spectral analysis. We have successfully produced water from several surrogates of interest. As a lunar surrogate, we used  $\text{FeTiO}_3$  (ilmenite). With this surrogate, water production from the hydrogen-argon plasma fluidized bed was fairly constant over time and significant changes in crystal structure were observed. These effects are shown in the mass spectra signal for water and in the x-ray diffraction pattern (Figure 2).

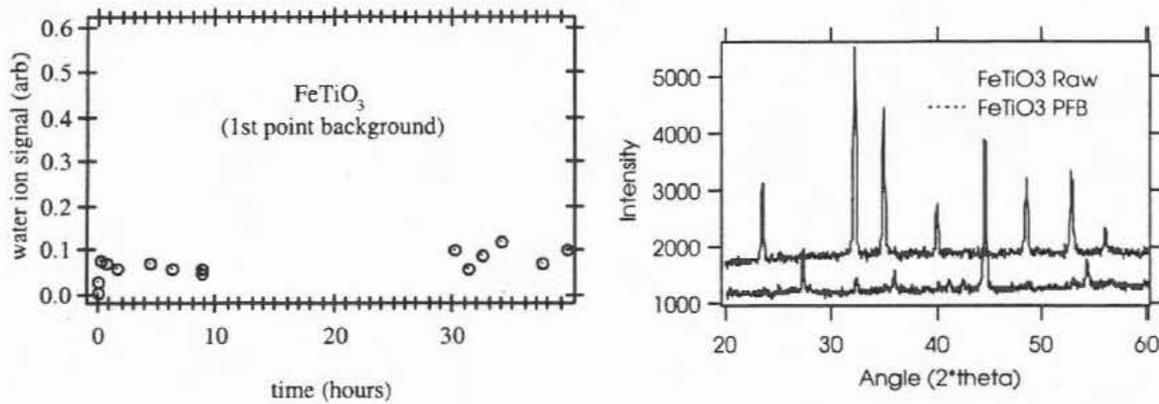


Figure 2. Mass Spectral signal for water. XRD pattern for raw and processed FeTiO<sub>3</sub>.

As a Martian surrogate, we examined a more complicated magnesium silicate mineral (olivine). Again, we were able to produce water at a fairly constant rate over extended periods. We also observed changes to the crystal structure, as probed by XRD.

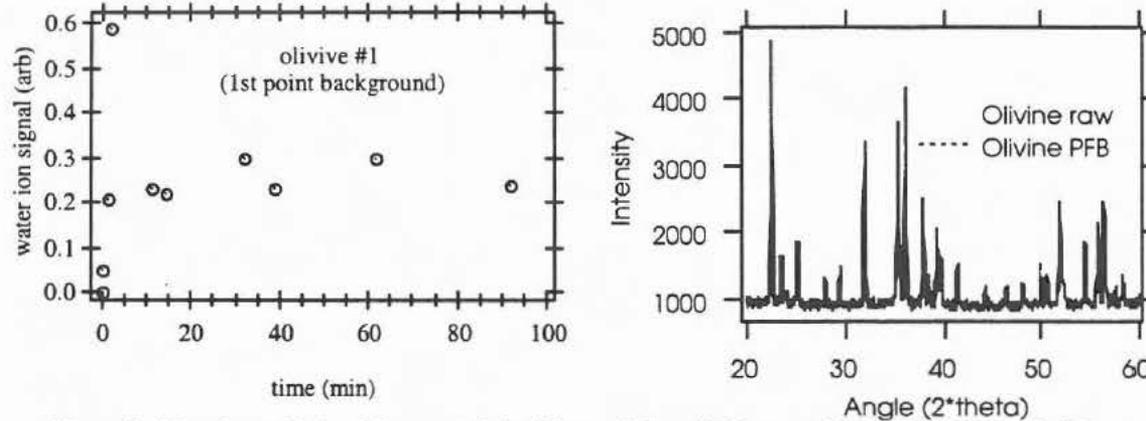


Figure 3. Mass Spectral signal for water derived from olivine. XRD pattern for raw and processed olivine.

Our other experiments in the plasma fluidized bed process indicate a general capability to form water from an even wider variety of oxide minerals. Also, unlike many conventional noncatalytic gas-solid reactions, this extraction technique does not appear to show a strong dependence on particle size. However, only a preliminary screening of these chemistries has been conducted and no concerted effort has yet been made to optimize the global kinetics. In order to do so, additional topics must be addressed in order to produce a compact design for space-based applications. These include reactor design for higher plasma densities, optimization of the kinetics, exploration of particle dynamics in reduced-gravity fluidized beds, and integrated process design (including the required separators).

By reducing insulation requirements and by having a compact design for a plasma reactor, this relatively low temperature plasma process may offer advantages over high temperature (thermally activated) water extraction processes which use molecular hydrogen as a reactant.

**PERCUSSIVE FORCE MAGNITUDE IN PERMAFROST.** A. W. Eustes III<sup>1</sup>, E. Bridgford<sup>1</sup>, A. Tischler<sup>1</sup>, and B. H. Wilcox<sup>2</sup>, <sup>1</sup>Colorado School of Mines, Petroleum Engineering Department, Golden, Colorado 80401, aeustes@mines.edu, <sup>2</sup>Jet Propulsion Laboratory.

**Introduction:** An in-depth look at percussive drilling shows that the transmission efficiency is very important; however, data for percussive drilling in hard rock or permafrost is rarely available or the existing data are very old.

Transmission efficiency can be used as a measurement of the transmission of the energy in the piston to the drill steel or bit and from the bit to the rock. Having a plane and centralized impact of the piston on the drill steel can optimize the transmission efficiency from the piston to the drill steel. A transmission efficiency of near 100% between piston and drill steel is possible. The transmission efficiency between bit and rock is dependent upon the interaction within the entire system. The main factors influencing this transmission efficiency are the contact area between cutting structure and surrounding rock (energy loss due to friction heat), damping characteristics of the surrounding rock (energy dampening), and cuttings transport. Some of these parameters are not controllable.

To solve the existing void regarding available drilling data, an experiment for gathering energy data in permafrost for percussive drilling was designed. Fifteen artificial permafrost samples were prepared. The samples differed in the grain size distribution to observe a possible influence of the grain size distribution on the drilling performance. The samples were then manually penetrated (with a sledgehammer) with two different spikes. A more detailed description of the performed experiment is available in Bridgford et al.<sup>1</sup>

Because of a lack of available data regarding the necessary energy and force for percussive penetration of permafrost in connection with a continuous penetrator, CSM designed an experiment to determine the necessary force and energy data. With this experiment, the force necessary for penetration was determined. By knowing the penetration force and impact time, the necessary energy was computed.

The experiment was to measure the impact force on a penetrator hammered into synthetic permafrost. Two penetrators were designed and instrumented with a strain gauge. The synthetic permafrost consisted of a mixture of 20/40 mesh and 200 mesh oilfield type fracturing quality sand flooded with de-aired water and frozen over a week in a refrigerated laboratory at -24° C. The permafrost container consisted of a piece of steel casing welded onto a small steel plate. An opening on the top of the container enables the penetrator to enter the container.

To ensure a low temperature environment, the experiments were performed inside the National Ice Core Laboratory (NICL) at the Denver Federal Center. The temperature in the laboratory is computer controlled and maintained continuously at -24° C. The data acquisition computer was maintained in an insulated 'hot' box. The impacts on the penetrator were applied by a 10-lbm-sledge hammer welded by a graduate student. Upon initiation of a recording run, the student impacted the top of the penetrator as hard as possible. After the strain gauge data was recorded,

the penetration was measured. Then the next set of data was gathered.

**Tool Description:** To determine if any there were any effects of differences in cutting structure and to see the effects of indexing, two different penetrators were selected. The first penetrator was manufactured from a round stainless steel rod with a diameter of 3.75 cm and a length of 45.5 cm. The penetrator had a cone at the cutting end with an opening angle of about 45°. The side length of the cone was 4.5 cm. The shaft length was 41 cm. The penetrator cutting structure is smooth and does not show any particular bit shape (see Figure 1).

The second penetrator was similar in size to the first penetrator. The difference was in the cutting structure. It had a star shaped cone. The star shape blades started in the center of the cone axis. Each blade had a width of 1.25 cm. The four blades ran up to a height of 33 cm measured from the bottom of the penetrator (12.5 cm as measured from the top).

**Permafrost Sample Specification:** The permafrost was created using pure silica sand of two different mesh sizes. They were 20/40-mesh and 200-mesh sand. Three different grain size mixtures were chosen to compare the penetration resistance to a continuous penetrator in coarse-grained, medium-grained, and fine-grained soil. Samples of a 20/40-mesh, an 80% 20/40-mesh and 20% 200-mesh, and a 200-mesh mixture were developed. The research indicated that the penetration resistance should increase with increasing grain size. The penetration resistance was expected to be the highest in the coarse grained 20/40 mixtures.

After performing the sieve analysis to confirm the mesh size, the permafrost was created. The water used to freeze the soil was de-aired to minimize the compressibility of the permafrost. Because permafrost generates its highest compressive strength at 21% porosity, the sand was compressed before being saturated with water. To ensure the highest possible compaction, the sand was mixed with 10% by volume of the de-aired water. The wet sand was packed in the sample holder canisters and compacted with a standard compaction 10-lbm sledgehammer.

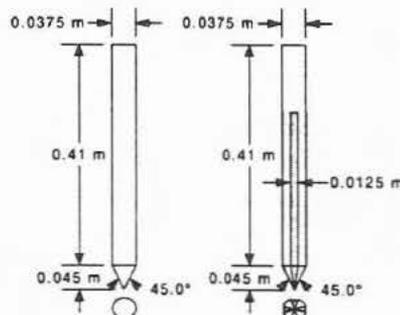


Figure 1: Penetrator Designs

**Experiment Setup:** The impact tests were performed in the refrigerated storeroom at the NICL. After placing an assembly from the storage room into the test cold room, a drilling lid was placed on the canister. The instrumented penetrator was connected to the data acquisition computer. The penetrator was driven into the permafrost sample for about two inches in order that the tip and a short length of the shaft were buried in the sample.

The height of the penetrator above the permafrost level was recorded. After an impact, the depth of penetration was measured and recorded. The reference point for all length measurements was the surface of the drilling lid. After completing all measurements for an impact, another impact was recorded. The goal was to drive the penetrator as far into the synthetic permafrost as possible. The test on a sample was discontinued if the penetrator significantly deviated from the vertical. The sample frequency was 60,000 Hz. Around 30,000 samples (0.5 seconds) per impact were recorded.

**Experiment Results and Analysis:** The following visual observations were made. During the test on a sample, the penetrators (grooved and smooth) were bouncing back. This back-bouncing is believed to occur because of a lack of sidewall friction. The buried part of the penetrator must be deep enough to ensure a high shaft friction. By preventing the penetrator from bouncing back, the maximum amount of energy is transferred from the penetrator to the formation.

After bouncing occurred, the penetration was often negative. This means the buried depth of the penetrator was less than before the impact. This effect can be explained by cuttings falling back into the borehole. This blocks the penetrator from returning to the starting depth. The result is a negative penetration.

The borehole created by the round penetrator was larger than the diameter of the penetrator itself (penetrator diameter: 3.75 mm, borehole diameter: 4 mm). This is an increase of about 6.7%.

Visual inspections after a series of impact tests showed similar effects. The borehole created by the smooth penetrator and the grooved penetrator always showed the same effects. The first observed layer was a grayish-black layer. This layer appeared to be corroded penetrator material. Observations of the penetrator cutting structure showed that the surface finish was rougher than its initial appearance. The next radial layer was crushed and dry silica sand. The penetrator crushed the silica sand (compressive strength approximately 5,000 psi) and compressed the removed cuttings into this crushed zone (lower porosity). This crushed zone was determined to stretch over a distance of about 3 mm around the borehole. The next layer was untouched artificial permafrost. It could not be determined if the crushed zone around the borehole was also thawed at any time.

The tip of the smooth penetrator did not show any signs of dulling, even after the final test. However, freeze back on the penetrator was obvious after almost every test run.

The grooved penetrator bounced as much as the smooth penetrator. As soon as the sidewall friction was large

enough, however, the penetration was higher with the smooth penetrator (sometimes by 200%).

Directional control was easier with the grooved penetrator. The smooth penetrator deviated from vertical more often than the grooved penetrator. However, this may not be an effect of the grooves. The impact direction of the sledge hammer plays a major role.

On both penetrators, the following effect was observed (more often at the smooth penetrator). After several impacts in a row, the penetration would be zero. After the next impact, the penetration was high (2-5 mm) and was then decreased with subsequent impact. A potential explanation for this effect is that initially, the permafrost is ground into powder by the penetrator tip. The powder is no longer brittle but rather shows a ductile behavior. This powder is not fractured by the penetrator but compressed at its tip. After being compressed by the penetrator with continued impacts, the powder resumes a brittle behavior. The powder can be fractured and a positive penetration is possible.

Additionally, micro-fractures are created during the compression of the ductile powder. When these micro fractures are large enough, some of the powder can be displaced into these created fractures.

The first and highest change in the strain gauge recorded voltage is assumed to be the peak of the impact wave. There may have been a problem with a 'picket fence' effect in the data stream. That is the recorded points on the curve do not include the actual peak point. This might explain why the calculated calibration force from the standard compaction hammer was 9% larger than the actual recorded values.

**Conclusions:** The tests showed that at least a force between 20,000 lbf (88,964 N) and 50,000 lbf (222,411 N) is needed to reach an average penetration of about 2 mm per impact. The lowest recorded force that gave a penetration was 18,886 lbf (84,005 N). The highest recorded force was 63,826 lbf (306,138 N). To achieve a penetration, there is a minimum threshold force.

The energy necessary to achieve the corresponding impact forces was difficult to calculate because the penetration system was not closed. None-the-less, it is assumed that the entire energy transferred from the sledge hammer to the drill steel is used for penetration and that no energy is lost due to dampening of the system or heat generation due to friction. In addition, the transmission efficiency between drill steel and the rock is 100%. These calculated energy values assume no loss and can only be considered a rough estimate. The calculated values show a maximum energy value of 1,100 J (corresponding to a power output of 6,111 kW) and a minimum value of about 83.72 J (corresponding to a power output of 465.13 kW). The power requirements are based on an assumed impact time of the sledge hammer on the penetrator of 180  $\mu$ s.

**References:** [1] Bridgford, E., Tischler, A.; and Eustes, A.; (2000) *Force Penetration Values for Permafrost in Relation to the Mars Subsurface Explorer*, ETCE/OMAE 2000 Conference.

**SUMMARY OF THE ISSUES REGARDING THE MARTIAN SUBSURFACE EXPLORER.** A. W. Eustes III<sup>1</sup>, L. S. Gertsch<sup>2</sup>, N. Lu<sup>1</sup>, E. Bridgford<sup>1</sup>, A. Tischler<sup>1</sup>, M. S. Stoner<sup>3</sup>, and B. H. Wilcox<sup>4</sup>, <sup>1</sup>Colorado School of Mines, Petroleum Engineering Department, Golden, CO 80401, aeustes@mines.edu, <sup>2</sup>Michigan Technological University, Mining Engineering Department, Houghton, MI 49931, lgertsch@mtu.edu, <sup>3</sup>Stoner Engineering, <sup>4</sup>Jet Propulsion Laboratory, 4800 Oak Grove Drive, Pasadena, CA 91109, brian.h.wilcox@jpl.nasa.gov.

**Introduction:** This is a summary of research work accomplished to date for the Jet Propulsion Laboratory by the Colorado School of Mines and the Michigan Technological University for the Martian Subsurface Explorer (SSX). The task involved a thorough review of the state of the art in drilling in the petroleum and mining industries in the following areas:

- 1) Drilling mechanics and energy requirements
- 2) Sidewall friction in boreholes
- 3) Rock property characteristics of basalt, permafrost, and ice
- 4) Cuttings transport and recompaction of cuttings
- 5) Directional control at odd angle interfaces

**Drilling Mechanics and Energy Requirements<sup>1</sup>:** The energy requirements for rock fracturing are as follows. The drill must overcome the surface energy developed by fracturing. The strain energy must be overcome. Strain wave propagation in both loading and unloading require energy. Finally, other energy use includes rock crushing, fluid pressurization, and plastic deformation. To compare the different available drilling methods, a normalization technique called the specific drilling energy is used. The specific drilling energy is defined as the amount of energy required to remove a unit volume of rock.

This research included an in-depth look at three drilling modes. These were the ultrasonic drill, rotary drilling, and percussive drilling. The advantages of ultrasonic drilling are fast rate-of-penetration in hard rocks, no dulling, and small borehole size. The disadvantages are high-energy requirements, low rate-of-penetration in soft rocks, and the need for an acoustical connection (fluid). The key advantage of rotary drilling is its adaptability to any type of formation. In addition, underbalanced drilling has a significant increase in rate-of-penetration. There are also a wide range of bit styles and sizes. Finally, rotary drilling is the most popular and widely used drilling method available. The disadvantages of rotary drilling include dulling and subsequent replacement of the bit. Rotary bits also require enough force applied to overcome the threshold pressure needed to start drilling. The advantages of the percussive continuous penetrator are no required drilling fluids, no drillstring, and a high rate-of-penetration in unconsolidated formations. The disadvantages are low rate-of-penetration in hard rocks, high dulling rate, potentially enlarged borehole diameter, and difficulty in transporting cuttings from under the tool.

The continuous penetrator drill has been selected for the design of the SSX.

**Sidewall Friction<sup>2</sup>:** The performance of a continuous percussive penetrator is similar to pile driving. The penetration resistance can be divided into two main effects: cone resistance and shaft friction. The cone resistance is the primary penetration resistance. The shaft friction is not as

significant. These two effects combine to form the penetration resistance. This value depends strongly upon two parameters: the internal and external friction angle. These angles can be determined by experimental work and by application of the Mohr-Coulomb failure criterion.

Another contribution to the penetration resistance is the cone angle. This is important because it determines the soil particle displacement. From experimental data, it was found that 30° to 40° cone angles produce the least cone resistance.

Penetration in permafrost is more difficult because of the higher penetration resistance. This is because of the compaction and the low temperature of the soil. Lower temperatures mean higher resistance from a strength increase from soil water freezing and cementing. Additional problems occur if clay present in the permafrost swells or the borehole has freeze-back pressure.

A potential source of friction reduction would be to apply vertical vibration to the continuous penetrator. The optimum driving frequency in resonant sonic drilling has been found to be the second harmonic natural frequency of the penetrator. An additional decrease in penetration resistance can be achieved by rotation of the penetrator.

**Physical Properties of Basalt, Ice, and Permafrost<sup>3</sup>:** There are three primary materials expected to be encountered in the Martian subsurface: basalt, ice, and permafrost. Since these materials are subject to a wide variety of geologic forces, they each display a certain degree of variability in their mechanical properties. Of the three materials that the SSX may encounter, basalt is the most stable and predictable. However, basalt also has the highest compressive strength and would require the most energy to drill. Permafrost and ice have highly variable properties that could change significantly in the presence of the SSX. This variability may create problems other than the physical destruction of the permafrost surface such as borehole stability and freeze back pressures. However, ice and permafrost have relatively moderate compressive strengths and require less energy to drill through than basalt.

Each of these materials varies by an order of magnitude in their ultimate strengths. Ice is the weakest, with strengths on the order of 100's to possibly low 1,000's of psi. Permafrost will vary between 1,000 to possibly 10,000-psi compressive strength. Basalt has the highest compressive strength and is therefore that most difficult to drill. Compressive strengths may vary from the low 10,000 to 100,000-psi range.

No studies have been found which investigate permafrost and ice drillability under a percussive system. In fact, most studies deal with very low stress and strain rates, which result in foundations or similar structures. CSM experimented with synthetic permafrost and penetration. The results are shown in Bridgford et al.<sup>4</sup>

## SUMMARY OF THE ISSUES REGARDING THE MARTIAN SUBSURFACE EXPLORER.

Eustes, Gertsch, Lu, Bridgford, Tischler, Stoner, and Wilcox.

It is not clear how a percussive system will function in the drilling of permafrost. At this point it is difficult to predict the behavior of the SSX because of the highly variable nature of permafrost and the fact that heat generated by the SSX may significantly influence drilling properties of the medium. In addition, the properties of permafrost are expected to change with depth. These changes will influence compressive strength, mode of failure, well control, and borehole stability.

**Cuttings Recompaction and Related Issues<sup>5</sup>:** The problem of cuttings recompactment behind the SSX body as it advances consists of two separate mechanisms: particle size reduction (crushing and grinding) and particle packing to reduce pore volume. Crushing requires fracture of solid material. Particle packing requires fluidization of the particle mass by addition of liquid, or by vibration.

Elastic particles are crushed by impact, compression, shear, and/or attrition; particles of plastic materials merely change shape when energy is input and so cannot be crushed in the size-reduction sense. Size classification effects accompanying all real crushing and grinding and are expected to be significant in any solution of the cuttings transport problem for the SSX. Some fundamental aspects of crushing and grinding:

- More energy is needed to crush small particles than larger ones.
- Particle breakage results in a bimodal size distribution of resultant particles.
- As grinding time increases, all particles tend to become the same, fine size.
- For the same total applied energy, multiple small impacts create finer particles than fewer large impacts.
- Viscoelastic materials (such as permafrost) are more sensitive to loading rate.
- There is a minimum particle size below which the material behaves plastically (depending on material, the diameter ranges from tenths to tens of microns).

The stiffness and strength of granular materials rise significantly when even a minor amount of cementation exists at the grain-grain contact points. The ice within the sediments of permafrost certainly acts as a cement and since the compressive strength of ice increases with decreasing temperature, this may explain the observed inverse relationship of permafrost strength with below-freezing temperature.

Recompactment of rock cuttings and transported sedimentary grains is important also to enabling the particles to bypass the SSX body. In addition, additional space for cuttings disposal may be available through fracture of the surrounding media, if it is stiff enough and elastic enough to fracture.

The cuttings created under the nose of the SSX must be transported from the front to the back of the SSX for advance to occur. This can happen either through cuttings disposal at the nose, direct motion past the SSX, temporary storage along the wall of the borehole while the SSX passes by, or a dynamic combination of the three processes.

**Directional Control of the Subsurface Explorer<sup>6</sup>:** Many factors affect directional control. These include geology, borehole conditions, bit design, and bottom hole as-

semblies. Geological effects include the overall structure of the rock formations such as inclination and dip of the beds and fracturing. Rock properties that affect directional drilling include strength, hardness, stress/strain behavior, and abrasiveness. Borehole conditions that affect directional drilling include hole diameter (gauge), stability, and trajectory. Boreholes larger than the diameter of the SSX will cause a loose fit for the directional control structures of the SSX. Borehole collapse will cause loss of directional control. The previous trajectory of the borehole will influence the current trajectory.

The bit design is critical to the success of the SSX. The bit cutting structure and material properties will need to be optimized for encounters with a variety of soft, medium, and hard rocks. In addition, the bit design will need to be designed for directional control. The bit tilt angle and side cutting ability of a bit will determine the directional characteristics of the bit. A bit that easily tilts has a greater tendency to deviate. Thus, this is the better bit for directional drilling; but, such a bit will not drill a very straight borehole. Likewise, a bit with a greater side cutting ability will have the same tendencies.

The section behind the bit will have a major effect on the directional drilling characteristics, too. The size and location of stabilization will dictate the degree of bit tilt, bit force magnitude and direction, and side cutting forces. These can include an articulated body or variable stabilizers.

The directional plan will be a factor in the design of the SSX. The SSX can be either a maneuverable or a straight hole design. A maneuvering design has the advantage of avoiding potential problem areas and the ability to stay in areas that are optimal for the bit cutting structure. This means a faster rate-of-penetration. However, it is recognized that there may be unavoidable conditions that need to be handled. A straight hole SSX can be designed to penetrate all that is encountered; but, such capability comes at the expense of directional capability and rate-of-penetration.

**Conclusion:** Many of the issues regarding the SSX raised here are being addressed through research efforts at the Colorado School of Mines, Michigan Technological University, and the Jet Propulsion Laboratory.

**References:** [1] Tischler, A., Eustes, A., and Gertsch, L., [1999] *Drill Energy Report in Support of the Martian Subsurface Explorer*. [2] Tischler, A., Eustes, A., and Lu, N., [1999] *Sidewall Friction Report in Support of the Martian Subsurface Explorer*. [3] Bridgford, E. and Eustes, A., (1999) *Physical Properties of Basalt, Ice, and Permafrost Report in Support of the Martian Subsurface Explorer*. [4] Bridgford, E., Tischler, A.; and Eustes, A.; (2000) *Force Penetration Values for Permafrost in Relation to the Mars Subsurface Explorer*, ETCE/OMAE 2000 Conference. [5] Gertsch, L., (1999) *Terrestrial Technology for Mining and Civil Engineering for the Mars Subsurface Explorer*. [6] Eustes, A. and Stoner, M., (1999) *Directional Control of the Subsurface Explorer Report in Support of the Martian Subsurface Explorer*.

## A COSTING STRATEGY FOR MANUFACTURING IN ORBIT USING EXTRATERRESTRIAL RESOURCES

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At the First Space Resource Utilization Roundtable we presented abstracts [1,2] discussing the technology of Acoustic Shaping, and its relevance to the development of a Space-based economy. This paper extends the work to study the impact of lunar-based materials on the construction of orbital infrastructure needed for long-term missions. It suggests ways of dealing at a rudimentary level with the uncertainties in cost estimation encountered in considering such endeavors.

In [1] we argued that a key to the development of civilization in space is a space-based marketplace. Such a marketplace, where both suppliers and consumers are located away from Earth, would remove the need to compete in earth-based markets, along with the constraint of launch costs from Earth. The established criteria for Space-based business enterprise are [3-7]:

1. The existence of an Earth-based market where high prices can be commanded for an extended period (e.g. drug and crystal manufacture), or mass-market delivery at a low per-customer cost (e.g., communication or solar power delivery utilities).
2. A 3-to-5 year Return on Investment is seen as essential for space-based business concepts [8].

In [2], we described the technology of "acoustic shaping" where particles of arbitrary shape and materials could be induced to fill surfaces of specified shape, using resonant acoustic fields in a container. This was proposed for inexpensive moldless manufacturing of the bulky panels, shields and enclosures needed for space-based infrastructure. The economics of any start-up company in the business of space-based construction [1], encounters the usual problem that there is little infrastructure away from earth. This results in a huge initial cost, incurred for several years before any return on investment. The solution to this problem, was argued to be a national-level investment in some rudimentary items of infrastructure, specifically two items:

1. An electromagnetic launcher on the Moon
2. Pressurized orbital workspace modified from expended Main Tanks of STS missions.

In this paper we consider how the presence of such items affects cost of building other infrastructure. We assume that lunar-based generation of solar cells and power-beaming utility stations are viable, with markets located on Earth, in orbit, and on the Moon. Customers for lunar-based power would include prospectors extracting metals, oxygen / hydrogen; these would generate substantial amounts of loose regolith and other by-products. Such materials form the raw materials for construction of panels suitable for orbiting vehicles, using acoustic shaping in microgravity. The raw materials needed for space-based construction could come either from Earth or from the lunar surface.

A vehicle of the "Mars Cyclor" type proposed by Aldrin [9] is considered as an example of permanent space-based infrastructure where inexpensive building materials are needed on a large scale. The Cyclor travels continuously in an Earth-Mars orbit, offering more interior space than a usual space mission craft, as well as long-term storage and radiation shielding sufficient to protect and provide for many traveler-years. In the literature, concepts for structures in space are limited to assembly of earth-built modules [10] or using extra-terrestrial resources with conventional construction techniques [11-13]. The latter is for habitats.

### Infrastructure Test Case for Cost Estimation

The Mars Cyclor [9] was chosen as a specific example to focus cost comparisons. Typical dimensions for such a vehicle might be a length of 50m, diameter of 20m, and shell/panel thickness equivalent to 0.05m of hollow aluminum spheres. Three cases were compared:

1. Modular construction on earth and assembly in space using human and robotic labor. Pre-built panels probably require large launchers.
2. Earth-based materials in particulate form shipped to construct panels using Acoustic Shaping in orbit. The launch costs come down because the compact material allow several shipping options.
3. Construction using extra-terrestrial resources and Acoustic Shaping Technology.

The cost in the first case was \$ 2.6 billion, which reduced marginally to \$ 2.53 billion in the second case (Fig.1). The third case uses lunar materials, shaped using Acoustic Shaping technology. The shapes required are obtained by modifying the sound field, and assembled by robotic arms. Here the estimation process runs into a roadblock because the very existence of commercial operations to extract lunar materials presupposes a market which makes such operations economically viable. The solution is argued below.

### Delivered Cost Approach

The lowest projected launch cost today (Year 2000) is roughly \$1000 per lb to Low Earth Orbit. This is the lowest price at which investors are likely to support any venture which delivers hollow aluminum spheres to the L-2 point from the Moon. Higher prices will open the competition to Earth-based launchers. Ref. [13] projects a far lower cost of such materials, lending confidence to our estimate. The precise cost of extracting and shipping the material is irrelevant to our estimate. Using this reasoning, the cost dropped sharply to \$ 1.16 billion. An accelerated production schedule using multiple acoustic-shaping chambers, showed a negligible increase to \$ 1.2 billion (Fig.1). Figure 2 considers the Net Present Value of a company started

up using the Cyclor shell construction project. Here the a partnership gives NASA a 50% stake in the corporation in exchange for funding the R&D through the various Technology Readiness Levels before flight, and for providing space at a NASA Center to develop the manufacturing facility, and boost the facility to the L-2 Lagrangian point.

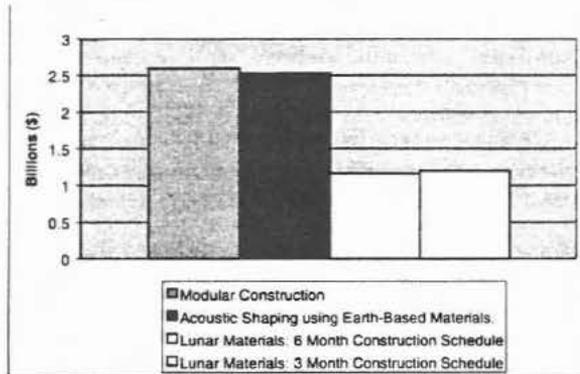


Figure 1: Cost Comparison

The presence of this facility provides the initial customers for the material collected on the lunar surface, and helps bring that entrepreneur into business. The NASA outlay is justified by the fact that the money goes into establishing a growing infrastructure, and cuts the per-unit cost of building craft such as the Cyclor for NASA missions. This goes with our argument in Ref. [1] that a national-level investment in infrastructure is essential to developing a space-based economy.

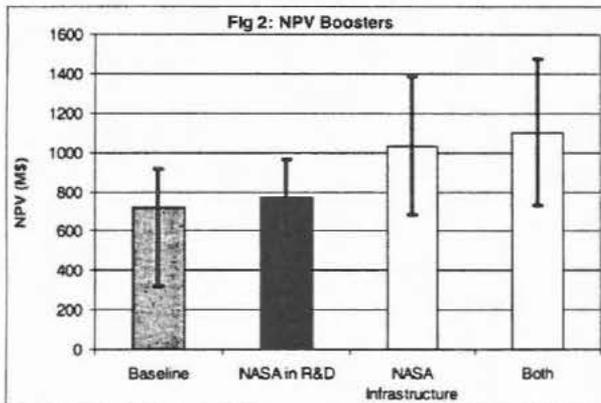


Figure 2: Net Present Value of an Acoustic Shaping company modified from [1], constructing a Mars Cyclor vehicle shell at L-2.

Assuming the same outlay and incomes in all the years of the development of the system (a simplifying assumption), initial calculations project a cost saving of \$ 400 million in the 13th year of operation, compared to Earth-based competitors. Compared to the NPV projections for a startup company given in Ref. [1], the initial uncertainty period is now eliminated. Such a facility will operate with minimal recurring costs, because the product is something required over an

extended period, with minimal design changes other than the custom-tailoring of shape which is done on Earth, and the operation is robotic. Barring disasters such as meteoroid impact, the company shows promise of being profitable. The other side is that in the process of the Cyclor project, it also helps the lunar-based material extractor and shipper make revenue as well. Further refinements of this model of cost estimation and space-based construction will be presented at the Roundtable.

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**MINE PLANNING FOR ASTEROID OREBODIES.** L. S. Gertsch<sup>1</sup> and R. E. Gertsch<sup>2</sup>, Michigan Technological University, Mining Engineering, 1400 Townsend Drive, Houghton, MI 49931-1295, <sup>1</sup>lgertsch@mtu.edu, <sup>2</sup>rgertsch@mtu.edu.

**Introduction:** Given that an asteroid (or comet) has been determined to contain sufficient material of value to be potentially economic to exploit, a mining method must be selected and implemented. This paper discusses the engineering necessary to bring a mine on-line, and the opportunities and challenges inherent in asteroid mineral prospects. The very important step of orebody characterization is discussed elsewhere.

The mining methods discussed here are based on enclosing the asteroid within a bag in some fashion, whether completely [1] or partially [2], [3]. In general, asteroid mining methods based on bags will consist of the following steps. Not all will be required in every case, nor necessarily in this particular sequence. Some steps will be performed simultaneously. Their purpose is to extract the valuable material from the body of the asteroid in the most efficient, cost-effective manner possible. In approximate order of initiation, if not of conclusion, the steps are:

1. Tether anchoring to the asteroid.
2. Asteroid motion control.
3. Body/fragment restraint system placement.
4. Operations platform construction.
5. Bag construction.
6. Auxiliary and support equipment placement.
7. Mining operations.
8. Processing operations.
9. Product transport to markets.

**Anchoring and Tethering:** Before mining or processing can begin, the asteroid must be under control and the machinery and people must be fixed firmly to it. This will require a suite of robust anchoring systems to which tethers can be attached, for example:

1. Single sling around asteroid.
2. Multiple slings around asteroid.
3. Penetration anchor.
4. Expansion anchor in drilled hole.
5. Friction anchor in drilled hole.
6. Glued (grouted) anchor in drilled hole.

Slings rely on the cohesion of the asteroid as a whole, a quality that recent findings are putting into question [4]. Point anchors rely on the tensile strength of the asteroid material. Geologic materials are always weak in tensile strength, with the lone potential exception of pure metallic bodies unweakened by rock inclusions. The drill-and-place systems are mechanically similar to each other, but differ in placement method. The most likely scenarios will include several types of anchor systems at various stages in the mine develop-

ment. Slings may be applicable during the stages of processing when the asteroid loses its cohesiveness.

**Asteroid Motion Control:** If motion control is necessary, it should begin soon after placement of tethers strong enough to withstand the necessary forces. It is not clear that de-spin will always be necessary or desirable, because the rotational energy of the asteroid may be usable to assist transport of rock. This would have to be coordinated with the planned sequence of fragmentation.

**Restraint System:** A network of cable and/or structures will be necessary to bind the body together and control it while it is under attack by the mining process. It must prevent catastrophic failures, such as splitting, slabbing, or unwanted rubbleization, resulting from motion control or mining. Even when an asteroid experiences engineered fragmentation, a wide range of uncontrolled failure types is possible. Asteroid restraint can be accomplished in several ways, which can be combined as the situation requires:

1. Anchor and tether wrap.
2. Cable cage.
3. Rigid cage.
4. Bag.

The level of difficulty involved in these restraint methods increases from the tether wrap to the rigid cage concept.

**Operations Platforms:** Full-scale operating platforms will be set up after the major tethers and restraint systems, since platform construction needs a staging area. The design specifics of secure working platforms from which to attack the asteroid will depend on the mining method. The requirements of both the mining and the processing systems will have to be fully addressed at this stage. A well-designed tether-restraint-platform system will enhance the safety and efficiency of moving equipment and personnel.

**Bagging:** After the asteroid motion is under control and the body is restrained, bags would be placed either around the entire body or covering any portion of its surface, to contain material fragments, to provide a processing vessel, and to provide an operating platform for mining machinery. Bags will have to be lightweight, robust, and flexible in the cold vacuum of interplanetary space. The mechanical and chemical demands of the mining and processing to be accomplished within their confines also will dictate their material properties.

**Auxiliary and Support Equipment:** Equipment selection and delivery scheduling are controlled by the

mining method selected and by the location of the orebody with respect to supply sources and to markets.

**Mining Operations:** Mining includes fragmentation, excavation, and transport of the resulting broken rock to the processing system. The experience accumulated by humans on Earth over the last several thousand years has allowed us to develop numerous minimum-energy approaches to these required steps. This presentation describes how some of these can be adapted to asteroid orebodies. The most efficient and cost-effective ways of achieving this depend significantly on the physical characteristics of the bodies themselves (see table below, from [5]). Not of least concern will be the degree of pre-existing fracturing.

asteroid type	mining	processing
ice mixtures	blast, heat, distill	phase separation
friable rock	blast, rip	phase separation, mech, chem, mag
hard rock	blast, disc cutters	mech, chem, mag
metallic Ni-Fe (massive)	concurrent with processing	smelting, carbonyl methods
hard rock-metallic Ni-Fe	blast, heat, rip	mech, chem, mag; smelting

*Ice Mixtures and Friable Rock.* Ice composite and water-containing friable (easily crumbled) rock asteroids are expected to be weaker than stony and metallic materials. This mining scheme would place these types of asteroid entirely within an impervious, structurally robust bag. Solar energy focused on the body would first melt the water-ice (or free the water of hydration of some included minerals), then turn the water into steam. The pressure generated would transport the mineral-laden fluid via a jet to the processing system through control nozzles built into the bag. Steam jets could serve also as a backup or emergency orbit control mechanism. Material fragments too large for transport by steam jet would collect inside the bag and be subjected to secondary mining, if economically justified. Secondary mining could consist of explosive, or perhaps impact, fragmentation within the bag.

*Hard Rock.* Two mining approaches suggest themselves at this stage: whole-body rubbleization, and sequential fragmentation.

Whole-body rubbleization mines the asteroid as a unit, fragmenting it to an approximately uniform particle size *in situ* using a series of closely timed explosive blasts. This method requires sufficient operating platforms over the asteroid surface to drill the holes necessary for distributing the explosive agent spatially throughout the asteroid [6]. Complete enclosure of the asteroid in a bag would enhance fragment control; a

variation on this theme could use two smaller bags instead of one.

Partial sequential fragmentation is a more common mining technique. Either mechanical mining machines or individual blasts would fragment and excavate the material, throwing the broken rock into a bag anchored over only a section of the asteroid. The ore could then be transported, still within the bag, to a processing module or a storage docking facility.

*Metal and Metal-Rock Mixtures.* The surface layers of a nickel-iron asteroid are expected to be brittle in shadow, but more ductile in sunlight. Fragmentation is more easily accomplished in brittle materials, so control of the rotation period would become an important supplement to the fragmentation process. In stony-iron asteroids, differential strain due to contrasting thermal characteristics of rock and metal under focused solar energy could initiate spalling-type fragmentation. Like terrestrial open pit mines, mining would proceed inward in lifts (benches).

**Processing Operations:** The first step in processing – comminution – is begun by the fragmentation accomplished in the original mining. All subsequent beneficiation depends on achieving the proper particle size, to isolate grains of valued material as individual particles. Then the valued particles must be separated from the waste particles using one or a combination of properties sufficiently different between the two.

The valued particles are concentrated in appropriate form to provide feedstocks for the target market processes. One form of metal concentration, for example – smelting – will require that the metal be fully melted, then drawn from the three-dimensional molten puddle, transported, formed into appropriate shapes, and delivered to the next step, possibly a mass driver.

**Transport to Markets:** The value of the material being mined will control the methods by which it is shipped, and the distance across which it is feasible to ship. Valuation of the orebody model will, in the planning stages, determine for example whether it is more cost-effective to move the asteroid near a market before processing, or process it on site and ship the smaller mass of product.

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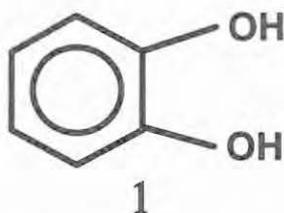
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**ORGANIC-BASED DISSOLUTION OF SILICATES: A NEW APPROACH TO ELEMENT EXTRACTION FROM LUNAR REGOLITH.** S. L. Gillett, Dept. Geol. Sci./172, Mackay School of Mines, University of Nevada, Reno, NV 89557, gillett@seismo.unr.edu

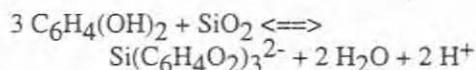
**Introduction:** *In situ* resource utilization is widely recognized to be critical for the establishment of a space-based infrastructure. Terrestrial mining processes are of limited relevance because they assume abundant O<sub>2</sub> and water as well as anomalous natural feedstocks ("ores"). In particular, silicate minerals, the most abundant chemical compounds on any rocky planet, are not generally exploited as element sources on Earth despite making up nearly all common rocks. Several processes have been studied experimentally for extraction of elements from lunar regolith, the surface layer consisting of rock comminuted over geologic time by meteorite impact. However, these processes all have serious disadvantages. Direct pyrolysis of silicates or electrolysis of silicate melts are extraordinarily difficult because of the extreme temperatures involved. Although approaches based on dissolution of silicates in hydrofluoric acid (HF) or fluorine avoid this difficulty, they have severe problems due to the extreme toxicity and corrosiveness of HF.

**Silicate dissolution in organic "cocktails":** An alternative approach to low-temperature silicate processing merits investigation. Outside the space-interest community, several research groups have studied the dissolution of silicates in organic-based reagents at low temperature and ambient pressure.

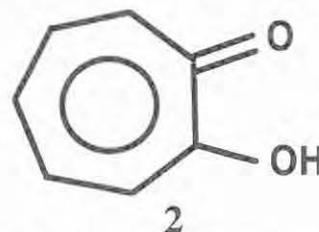
**Chelate-based dissolution.** A number of organic ligands form extremely stable complexes ("chelates") with Si and so can disrupt a silicate crystal structure.



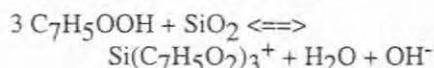
For example, catechol (1,2-dihydroxybenzene, 1) reacts with silica according to the following stoichiometry:



Obviously, this reaction is driven to the right at high pH. Low pH disrupts the silicon catecholate complex to yield silica gel and regenerate catechol. Corriu and coworkers[1] have also examined silicon catecholates as precursors for organosilicon synthesis.

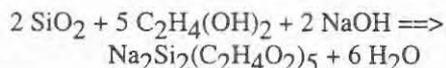


Tropolone (2-hydroxy-2,4,6-cycloheptatrien-1-one, 2) reacts with silica as follows[2]:



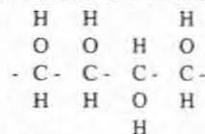
Note that this reaction is driven to the right at low pH.

**Basic diol solutions.** Laine and coworkers[3] have investigated the dissolution of various forms of silica, including beach sand(!), in basic solutions of simple 1,2 diols such as ethylene glycol (C<sub>2</sub>H<sub>4</sub>(OH)<sub>2</sub>) to form silica glycolates, e.g.:



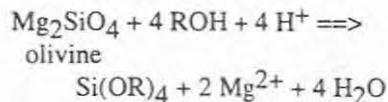
These can be used as precursors for ceramic[4] or zeolite synthesis[5]. Glycolates are better raw materials than catecholates or tropolonates as they are more reactive due to containing 5-coordinate Si.

**Polyalcohols with threo configuration.** In basic solution, polyalcohols having at least 4 adjacent OH groups with the middle two in *threo* configuration:

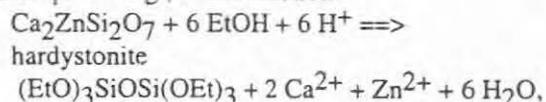


are excellent complexing agents for Si, yielding 5- and 6-coordinate aqueous species. Examples include threitol, mannitol, sorbitol, xylitol, and so on[6].

**Acidified anhydrous alcohols.** Kenney and coworkers[7] have synthesized silicate esters (silicon alkoxides) by dissolving inorganic silicates in acidified alcohol mixtures, e.g.:



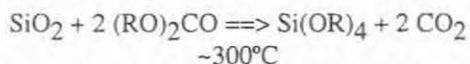
In many cases the oligomeric silicate "backbone" is not disrupted. E.g., in the reaction:



the Si<sub>2</sub>O<sub>7</sub> unit is preserved.

These reactions obviously are driven to the right by "scarce water" conditions. They provide a direct route to silicon alkoxides, which can be used directly in low-temperature "sol-gel" ceramic syntheses. Alkoxides can also be converted into monomers for synthesizing siloxane ("silicone") polymers.

**Dialkyl carbonates.** Akiyama, Ono, & Suzuki [8] have shown that dialkyl carbonates will react directly with amorphous silica to yield alkoxides under relatively mild conditions:



Whether other highly polymerized silicates, such as glasses or feldspars, will react in this fashion is evidently unknown.

**Triethanolamine.** Most recently, Kemmitt & Henderson[9] have shown that amorphous silicas, including geothermal silicas, will react with triethanolamine ~210°C to yield silatranes. These can then be converted into alkoxides or other organosilicon products.

**Implications for natural mixtures.** Such silicate dissolution has not been investigated as an approach to processing natural silicate mixtures, although it promises to combine the considerably less energy-intensive approach of fluorine-based systems with considerably lower reagent toxicity. Moreover, the organosilicon compounds produced are themselves useful raw materials. Alkoxides in particular are of intense interest in the low-temperature "sol-gel" fabrication of ceramics[10]. Finally, the thorough comminution of the regolith makes it an attractive feedstock because crushing and grinding will not be required.

Hence, regolith dissolution might provide a cheap and relatively safe way of preparing silica sols and gels for (e.g.) cement, fiber, or ceramics fabrication. Furthermore, H<sub>2</sub>O and/or alcohols outgassed on curing of such materials could be recycled automatically by the life-support system.

**Hydrometallurgy:** Such dissolution also may provide a way of solubilizing metals for subsequent extraction. The metals in silicates are present as included cations that provide charge balance by compensating the negative charge of the silicate anions. On dissolution of the silicate structure these metals also go into solution. Solution-based extraction of metals, such as Au and Cu, is of growing importance on Earth[11] and is a focus of much research worldwide; much of this research should be relevant. Also, on dissolution in complexing reagents, small highly charged metal ions (e.g., Al<sup>3+</sup>[12] and Ti<sup>4+</sup>[13]) will

themselves be complexed, and the potential utility of such complexes should also be investigated.

**Conclusions:** Obviously, organic-based silicate processing still has the disadvantages of requiring reagent importation and H<sub>2</sub>O recycling. These reagents, however, are considerably less toxic than HF, so that they fit in better with life-support systems. The organic reagents are also potentially susceptible to microbial degradation, whereas fluorine-based reagents are not. Moreover, the organosilicon compounds produced are themselves useful raw materials, unlike fluorides which are merely intermediates from which HF must be regenerated.

Finally, in the longer term silicates are a promising alternative, of particular relevance to carbon-poor bodies like the Moon, for molecular nanotechnology (MNT)[14]. Making silicate sols from pulverized rock debris is also an approach toward generating silicate molecular "building blocks" for MNT.

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## HISTORIC FRONTIER PROCESSES ACTIVE IN FUTURE SPACE-BASED MINERAL EXTRACTION.

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**Introduction:** The forces that shaped historic mining frontiers are in many cases not bound by geographic or temporal limits. The forces that helped define historic frontiers are active in today's physical and virtual frontiers, and will be present in future space-based frontiers. While frontiers derived from position and technology are primarily economic in nature, non-economic conditions affect the success or failure of individual frontier endeavors, local "mining camps" and even entire frontiers.

Frontiers can be defined as the line of activity that divides the established markets and infrastructure of civilization from the unclaimed resources and potential wealth of a wilderness. At the frontier line, ownership of resources is established. The resource can then be developed using capital, energy and information. In a mining setting, the resource is concentrated for economic shipment to the markets of civilization. Profits from the sale of the resource are then used to fund further development of the resource and/or pay investors. Both positional and technical frontiers develop as a series of generations. The profits from each generation of development provides the capital and/or investment incentive for the next round of development. Without profit, the self-replicating process of frontiers stops.<sup>1</sup>

**Igniting Frontiers:** Anthropologists have long known that three non-economic "environmental" factors cause societies to expand or contract. These can be termed: Technology, Social Systems, and Ideology. Studies in historic mining have modified these terms slightly to: Technology, Legislation and Charisma (TLC). The status of these three environmental conditions in society either enhance or diminish the cost of entering frontier while simultaneously increasing or decreasing the probability of success. Changes to these environmental conditions have resulted in expansion of prehistoric societies, historic civilizations, and most recently have been operational in the expansion of the society into the virtual world. They have also been demonstrated to be in operation in space-based frontiers such as telecommunications, Remote Sensing and Global Positioning (GPS).

The ignition of a frontier depends on participant's ability to enter the wilderness, obtain control of resources, and then economically develop infrastructure to extract resources and transport them back to markets in civilization. When this is done at a

profit, the frontier is ignited. While investors can be persuaded to support frontier enterprises for several rounds of development, profits are the determining factor for the onset of self-replicating frontier development.

**Launch Bars.** The total perceived cost from first movement to first dollar can be termed the "Launch Bar". This is not a hard number, rather is a projection based upon business realities blended with assumptions on the nature of the undeveloped wilderness resource. If potential returns are judged to be adequate and sufficient investment capital is in place, then first movement into the frontier may take place. Each civilization / wilderness interface is unique and as a result, the development of a frontier is difficult to predict. However, understanding of the ramifications of Launch Bars provides some measure for the timing of events and even the ultimate success of frontier efforts.

Research in historic mining frontiers in the Northern Rockies has determined that there is a direct link between the speed of frontier development and the height of the Launch Bar. The higher the bar, the slower the frontier will develop. There is also a connection between the Launch Bar and the number of participants in a frontier. The higher the bar the fewer the participants. For example a space-based telecommunication venture currently requires about \$100 million to begin services. Business plans are measured in years and there are less than 100 companies active in this arena. On the flip side, a \$400 used computer and an Internet hook-up can set up a business trading on e-Bay. As a result, Internet businesses develop in months or even weeks with a vast number of e-commerce start-ups each day.

The TLC environmental conditions actively move the Launch Bar up or down. This in turn alters the pace of frontier development and changes the number of participants. The invention of the cyanide milling process is a prime example of how technology created a boom in western mining (Technology). The passage of the 1872 mining law regulating the establishment of mining claims allowed mining companies to effectively control the ownership of their mines and thereby have collateral for loans (Legislation). The cry of "GOLD" in 1849 caused men and women from around the world to drop what they were doing and rush to the California gold fields (Charisma).

Launching a frontier endeavor does not assure the sparking of a viable frontier. The American West has many examples of failed mills rotting in the

wilderness. There are as many reasons for frontier failure as there are failures. Under capitalization, overcapitalization, poor business practices, changes to markets during development are some of the more prominent causes of failure. When a prominent frontier enterprise fails, it often causes a catastrophic drop in the Charisma of the individual frontier. These were historically termed, "Humbugs"; however, this term has recently been replaced with "Iridium Effect". The effects of a humbug can sour a frontier's access to investment capital for a generation of investors.

**Frontier Mining Development:** Frontier mining has traditionally fallen into three categories: Subsistence, Speculative and World-Class. The size of the resource and the capital required to develop it determine which approach is used. Subsistence mining is typified by small-scale placers that supplement a single family's income over a long period of time. Speculative mining typically starts at Subsistence levels, but by a series of speculative steps develops the resource to an appropriate level. World-Class mining ventures utilize large capital reserves to study, plan and then develop large-scale facilities to process resources efficiently. Each of the categories has its place in development of mining resources. However, because of the high Launch Bar in any space-based mineral extraction, only the World-Class category would be applicable to open up the frontier.

Another ramification of the Launch Bar for World-Class ventures relates to failure rates. As the Bar moves up, failure rates move downward. Low Launch Bar mining endeavors in the American West had failure rates around 90 percent. High Launch Bar endeavors approached even money. Recently, in space, the \$5 billion Iridium frontier enterprise demonstrated that even extremely high Launch Bar attempts to open a new frontier can and do fail.

Part of Iridium's problem was market timing, by the time their business plan had unfolded; terrestrial-based cell phones had absorbed most of their potential market. However, any primary frontier endeavor will have a high initial Launch Bar and will carry high risk. Once a new (or primary) frontier has been established, the base of the launch bar is raised for subsequent secondary frontiers. For example, once the California gold mining frontier was established, the base level for the Launch Bar on the Nevada silver frontier was effectively raised. Once a single dollar of profit has been made from a new frontier, investors look at the frontier as a source for high return on investment, rather than a dubious venture into the unknown. Speculative development then becomes possible.

**Raising the Base:** While frontiers are extensions of society into new, previously untouched areas, they do not spring fully formed from the void. Nearly all frontiers result from the combination of unexplored aspects of several previous frontiers. The primary frontier of the California Gold Rush for example would not have been possible if not for at least three previous frontiers. The Beaver pelt frontier of the 1820s and 1830s established routes through the Sierra Nevada Mountains and established an American presence in California. The Oregon agrarian frontier in the 1840s put a wagon road across the continent and firmly placed the idea of Manifest Destiny in the minds of Americans - that America was destined to reach from Atlantic to Pacific shores. The Georgian gold rush of the early 1800s taught men the skills and developed the technologies of gold mining. Together these three frontiers raised the base of the Launch Bar so that middle-class, and even poor men and women, had the means to take part in the California Gold Rush.

While much of the hardware on the space frontier has directly evolved out of governmental programs, the current economic activity in space is as much or more the result of other previous technical frontiers that have created the equipment and, more importantly, the markets that make the frontier economically viable. Television, which exploded onto the scene in the late 1950s and early 1960s, is the direct parent of the space industry. Earlier communications frontiers stretching back to radio, telephone and even the modern version of telegraph messaging have played a role in creating the markets and technology of the current space frontier. Computers, both mainframe and personal, are also lending heat to the frontier fire. Telecommunications, GPS and Remote Sensing are generating revenue that is in turn being used to evolve transportation systems.

**Conclusion:** Significant advances in Technology, Legislation and Charisma must occur before the Launch Bar for Space-based mineral extraction becomes viable. Other space-related activities such as the International Space Station, robotic exploration and increase in the size of the world economy will raise the base of the Launch Bar. Because of frontier uncertainty, it is very difficult to predict when the Launch Bar will be shortened to the point an attempt at sparking a frontier can be made. Understanding the ramifications of Launch Bars may provide a tool for understanding when the time for such an attempt has arrived.

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**THE NEAR-EARTH SPACE SURVEILLANCE (NESS) MISSION: DISCOVERY, TRACKING, AND CHARACTERIZATION OF ASTEROIDS, COMETS, AND ARTIFICIAL SATELLITES WITH A MICROSATELLITE.** A.R. Hildebrand<sup>1</sup>, K.A. Carroll<sup>2</sup>, D.D. Balam<sup>3</sup>, J. M. Matthews<sup>4</sup>, R. Kuschnig<sup>4</sup>, P.G. Brown<sup>5</sup>, E.F. Tedesco<sup>6</sup>, <sup>1</sup>Department of Geology and Geophysics, University of Calgary, 2500 University Drive NW, Calgary, AB, T2N 1N4 (hildebra@geo.ucalgary.ca), <sup>2</sup>Dyancon Enterprises Ltd., 3565 Nashua Drive, Mississauga, ON, L4V 1R1 (kac@dyancon.ca), <sup>3</sup>Department of Physics and Astronomy, University of Victoria, P.O. Box 3055, Victoria, BC, V8W 3P6 (balam@beluga.phys.uvic.ca), <sup>4</sup>Department of Physics and Astronomy, University of British Columbia, 6224 Agricultural Road, Vancouver, BC, V6T 1Z1 (matthews@astro.ubc.ca;kuschnig@astro.ubc.ca), <sup>5</sup>Department of Physics and Astronomy, The University of Western Ontario, London, ON, N6A 3K7 (peter@danlon.physics.uwo.ca), <sup>6</sup>Terra Systems, Inc., Lee, New Hampshire, USA 03824 (etedesco@terrasys.com).

**Introduction:** In the closing decade of the twentieth century asteroid and comet discovery, tracking, and characterization have attained levels of interest and committed resources previously unparalleled. This is due in large part to the level of respectability that the impact hazard has attained, but also reflects fundamental interest in the small body population of the solar system and the perceived usefulness of asteroids and (extinct) comets as exploitable resources. The respectability of studying this population was also reflected by spacecraft missions which began to include asteroid or comet encounters, or were dedicated to their observation. Asteroid and comet sample return missions are imminent. With the exception of some experimental work, all small body discovery and tracking work has been ground based, although consideration and tests of what may be achieved with a space based detector have begun [1, 2]. The Near-Earth Space Surveillance (NESS) Mission, a microsat dedicated to observing near-Earth (NEO) and interior-to-the-Earth (IEO) asteroids and comets plus artificial satellites, is currently being studied under contract to the Canadian Space Agency.

**Science Goals:** The primary science goal will be to discover and derive orbits for enough IEO's to establish the population's dynamical characteristics to closer than 0.387 AU (Mercury's mean solar distance); this observing program will also add significantly towards delimiting the larger members of the Earth-crossing Aten class of NEO's. Pointing near the Sun will be limited by the capability of the baffle system, but an interior-to-Mercury small body population (vulcanoids) may also be sought if the spacecraft orbit has suitable eclipse geometry to allow significant observing time at near-Sun angles. The spacecraft will carry spectral measuring capability, probably in the form of a filter system, and the NESS mission will provide sufficient taxonomy of discovered objects to characterize the population and determine object sizes.

Defining the IEO population will provide constraints towards understanding the evolution of Venus and Mercury. For example, establishing the impactor flux and types at both Venus and Mercury will allow refining the age of the Venusian surface, and determining the rate of volatile delivery to the surface of Mercury.

Mapping a fraction of the IEO population and Aten-class objects now unobservable from Earth's surface will leverage science opportunities. For example, missions to the inner planets, such as Messenger to Mercury, will have more potential fly-by opportunities en route, and small body radar imaging/reflection opportunities will be available in the sunward hemisphere of the Earth. As well, the ability to obtain astrometric observations of any NEO at any time will allow improvement of ephemerides for any fast moving object to enable radar or other observations without the limitations of ground based systems. Finally, NESS will discover comets either unobservable, or earlier than may be observed, from ground based platforms. Cometary behaviour may also be tracked substantially inwards of the Earth's orbit depending upon a comet's orbital geometry relative to that of the Earth.

**Artificial Satellite Tracking:** Satellites are tracked to provide ephemeris information in support of mission operation functions, such as pointing high-gain ground station antennas, and on-board determination of magnetic field strength/direction for attitude control/estimation purposes. They are also tracked to predict and avoid potential satellite collisions. NORAD uses satellite tracking data to distinguish satellites from ballistic missiles. The Canadian Department of National Defence (DND), as part of Canada's contribution to NORAD, plans to develop an operational space-based tracking system. While satellites in low Earth orbits are efficiently tracked using ground-based radars, optical tracking has advantages

for satellites in higher orbits (e.g., geostationary or Molniya orbits). NESS will demonstrate satellite tracking technologies from a microsat platform.

**Advantages of an Orbital Platform:** Optical search and tracking for both asteroids/comets and satellites is done by comparing sequential star-field images to look for (typically faint) moving objects. Performing these observations from a space-based observatory offers operational advantages, such as continuous duty cycle, avoidance of weather/clouds, and reduced scattered light from the Sun, Moon and Earth. However, the relative expense of a satellite is most justified by its ability to observe the sky close to the Sun which is essentially unobservable from the ground. Combining the capabilities of Earth based searches and a spacecraft will result in mapping the potentially hazardous Earth crossing asteroids significantly faster than ground based surveys alone [2].

*Operational modes.* Reflecting the unique capabilities of an orbiting detector in its small body observing role, NESS will primarily be deployed in observing an "optical fence" eastwards of Earth and interior to Earth's orbit to the limit of its sunward pointing capability. While not limited to the eastward looking geometry, it is convenient for the spacecraft design. In this orientation it will perform its discovery, astrometry and colour survey functions. The secondary operating mode will consist of looking at targets of opportunity such as fast movers in the near-Earth environment, artificial satellites, or potentially

hazardous asteroids (PHA's) that need lengthened orbital arcs. An example of a fast mover with a poorly determined orbit is 1994 NM1, which on December 9, 1994 passed close by the Earth with an orbital solution that allowed intersection with the Earth.

**Spacecraft Design:** The NESS mission is based on the spacecraft telescope and bus developed for the MOST (Microvariability and Oscillations of Stars) mission [1]. The microsatellite is only 50 kg in mass with dimensions of about 60 x 60 x 24 cm. The design is 3-axis stabilized with 10 – 20 arcsecond pointing precision. MOST carries a 15-cm aperture f5.88 Maksutov telescope with a 2° square field of view. The current design is capable of at least magnitude 19 resolution with reasonable exposure lengths for a search program. The modifications required to optimize the MOST design for the NESS mission include a baffle, on board processing capability, consideration of increasing mirror size, and reducing the pointing wobble to sub-pixel size on the imaging CCD. The large data quantities generated by imaging and photometry probably require increased ground station support.

**References:** [1] Carroll, K.A. et al. (in press) *Proceedings 14<sup>th</sup> AIAA/USU Conference on Small Satellites*. [2] Tedesco, E.F. et al. (in press) *Planetary and Space Science*.

**Privatized Space Resource Property Ownership.** Dennis M. Hope, The Lunar Embassy, 6000 Airport Road, Rio Vista, CA, 94571. (707) 374-6445 (dmhopetd@aol.com)

In the fall of 1980 a vision for the future was born. Privatized ownership of planetary bodies has been debated and yet skirted by most space enthusiasts for the past 15 years or so. This abstract is an attempt to lay all ideas of privatized ownership to rest. The concentration of efforts to place technological events ahead of property rights and ownership have been the calling card of all the space advocacy groups in recent history. For what ever reason the advocates have decided that this is an issue best left to another time. "Maybe we can sneak up on it and it won't feel so bad when we find that we are too late." This seems to be the general consensus from the conventions I have participated in over the last few years.

The intent of this abstract is to point out a few facts that, like it or not have been put into place some twenty years ago. My name is Dennis M. Hope. I own a company called, "The Lunar Embassy." The main purpose of this business is to offer for sale claimed celestial properties. In 1980 the idea germinated and grew to reality in early 1981. The original claim of ownership sent to the United Nations General Assembly, The United States of America, and the former Soviet Union was for the Moon of Earth and the other eight planets and their moons. This document was sent to each of the above governmental bodies with a letter attached stating that my intent was to subdivide and sell to anyone that desired these types of properties at any time. It was also mentioned in the letter that if any of these governing bodies had a legal problem with us doing this to inform us. We have never heard form any of them.

Since the initial offering of these properties for general public consumption took place we have currently some 217,000 property owners on the Moon of Earth, Mars, Venus, and IO. In the summer of 2000 the Lunar Embassy will offer for sale properties on Mercury and Neptune. Eventually we will offer all but one planetary property for sale and that is Europa. Our property owners list includes two former Presidents of the USA, politicians from around the world, scientists, journalists, doctors, attorneys, astronauts from both the USA and USSR, celebrities like Harrison Ford, Tom Hanks, Tom Cruise, Nicole Kidman, John Travolta, Eddie Murphy, Johnny Carson, David Letterman, Mick Jagger, Johnathan Frakes, Patrick Stewart, Leonard Nimoy, William Shatner, Marina Sertes, Brent Spiner, and a total of 408 well know personalities. We are represented in 123 countries around the world and have implemented a reseller program as of 1998 in October. We currently have 23 reselling representatives in the world and 2 Ambassadors who have purchased exclusivity rights for their countries. We have fought legal battles in Germany and won. We have been scrutinized in more than 6000 publications around the globe in the last 4 years and we have come out positive and unscathed. We are the recognized force behind property rights on celestial bodies. We have agents in Hungary, currently working up a proposal for a seat on the United Nations through a group called the, "First Lunar Republic."

Our group of property owners for the most part are educated individuals from around this planet letting the rest of us know they are following their pioneering spirit and providing for the future. They are serious individuals that see the next frontier as their tapestry to create as they see fit. The property owners need you all to know that the issue of property rights has been decided and if you wish to join us, all the better. If you decide that you need to ignore what has been accomplished here already then you will find that we are not easily dissuaded from our quest of complete property rights as lined out in the original claim of ownership in 1980. I, as the spokesman for the property owners have a duty to inform all space advocates that the time is at hand for all of you to know that we are intent on continuing our sales and marketing. You all could benefit from a group our size and would be wise to allow us to be heard.



**THE FABRICATION OF SILICON SOLAR CELLS ON THE MOON USING IN-SITU RESOURCES.** A. Ignatiev, Space Vacuum Epitaxy Center, Science and Research I, University of Houston, Houston TX 77204-5507, USA (Ignatiev@uh.edu).

The exploration and development of the solar system depends critically on the availability of electrical energy. In addition, the long term potential for humans to settle space requires self-sufficiency and therefore, self-sustaining electrical power systems in space locations remote from the Earth. It is projected, based on data from average power usage in developed countries (including an addition allocation for life support), that 6 to 10 kW of continuous power will be required per person to support humans in space. Robotic outposts would require less, but if expanded to incorporate significant space presence, could grow to nearly the 100 kW to 1 MW values required for human outposts. The ability to supply such power to remote space locations is currently quite limited. The presently permissible power technology for space is solar power. However, considering the large mass requirements for solar power systems (~ 20-30 kg/kW) and high launch costs, it is doubtful that the current approach of fabricating and assembling solar power systems on Earth, and then launching them into space will be viable for major outposts. What is required is an electric power system, the kernel for which is a fabrication facility which can be installed on remote moons and planets, which will utilize the resources of the moon or planet to fabricate solar cells on location, and will be self replicating in that it will use the power that it produces to produce more solar cells.

Such a revolutionary power system utilizes the indigenous resources present on moons and planets accompanied by an *in situ* electric power system fabrication approach based on the production of solar cells by a thin film growth technology. For

the case of the Earth's Moon, thin film silicon-based solar cells can be fabricated in the vacuum environment of the surface of the moon utilizing raw materials generated from the processing of the lunar regolith. The thin film solar cells will be vacuum deposited directly on the surface of the Moon by a facility that incorporates both regolith processing and solar cell fabrication. Such a facility can have the capacity to fabricate a 1 MW power system on the surface of the Moon in several years.

This unique approach for the emplacement of a safe electric power system would require transportation of a much smaller mass of equipment to the Moon than would otherwise be required to install an electric power system, and would result in a power system that was repairable/replaceable through the simple fabrication of more solar cells. This approach of supplying only the robotic fabrication facility to generate remote power capability would also result in significant major cost reductions through the major decrease in required mass to target. A similar technical approach could also work on Mars with modification. This new autonomous electric power system architecture will allow for human and robotic presence in space independent of Earth.



**A New strategy for Exploration Technology Development: The Human Exploration and Development of Space (HEDS) Exploration/Commercialization Technology Initiative.** John C. Mankins, Advanced Projects Office, Office of Space Flight, NASA Headquarters, Washington, D. C. 20540 (jmankins@hq.nasa.gov)

In FY 2001, NASA will undertake a new research and technology program supporting the goals of human exploration: the Human Exploration and Development of Space (HEDS) Exploration/Commercialization Technology Initiative (HTCI). The HTCI represents a new strategic approach to exploration technology, in which an emphasis will be placed on identifying and developing technologies for systems and infrastructures that may be common among exploration and commercial development of space objectives. A family of preliminary strategic research and technology (R&T) road maps have been formulated that address "technology for human exploration and development of space (THREADS). These road maps frame and bound the likely content of the HTCI. Notional technology themes for the initiative include: (1) space resources development, (2) space utilities and power, (3) habitation and bioastronautics, (4) space assembly, inspection and maintenance, (5) exploration and expeditions, and (6) space transportation. This paper will summarize the results of the THREADS road mapping process and describe the current status and content of the HTCI within that framework. The paper will highlight the space resources development theme within the Initiative and will summarize plans for the coming year.



**SPACE RESOURCES FOR SPACE TOURISM.** G. E. Maryniak, X PRIZE Foundation, 5050 Oakland Avenue, St. Louis MO 63110, USA (gmaryniak@xprize.org).

**Introduction:** Markets have replaced governments as the engines of technological change throughout the world. Unfortunately, world space programs, particularly those involving human spaceflight, are still running on inertia and mythology from the Apollo era and often concern themselves with "flags and footprints" activities which, if supportable at all, could only be funded by large governments.<sup>1</sup>

Alternative space activities with a sustainable economic basis have been suggested. The provision of baseload electrical power from high orbit has been one of the most interesting of these as it is based upon the fundamental need for energy. After an initial favorable review of the concept by NASA and the US Department of Energy in the 1970's and early 1980's and an 18 year period of dormancy, the concept is once again under study by NASA. O'Neill proposed that solar power satellites could greatly benefit from the utilization of lunar resources. Subsequent studies by MIT, the Convair Division of General Dynamics and the Space Studies Institute indicated that between 90 and 99% of the mass of such large scale power systems could be lunar in origin.<sup>2</sup>

But the sheer size and cost of such projects have proved a serious barrier to their implementation. A large portion of the problem has been a lack of confidence in our ability to significantly reduce launch costs. Furthermore, the uncertainties associated with the use of nonterrestrial materials have discouraged NASA from considering their use in recent space solar power investigations. And at the end of the day, the perceived abundance of present low-cost energy sources requires space solar power advocates to rely upon ecological arguments for the implementation of such systems. In short, there is not a near-term provable market for space solar power.

**Space Tourism:** There is a growing realization that providing the experience of spaceflight to the public is a market which will dwarf present projections for conventional commercial launches of telecommunications and remote sensing satellites. The early history of aviation provides an existence proof for this concept. Market studies throughout the developed world have proven surprisingly consistent in showing that about 7 out of 10 persons contacted profess an interest in taking a ride in space.

Initially the bulk of early space tourism is likely to be suborbital in nature. Orbital tourism in its earliest forms might well consist of missions of less than one

day duration. Although these first forms of tourism will be essential in creating a foundation for more ambitious business plans, they will not, at first be in a position to benefit from space resource utilization. However, the Japan Rocket Society's survey research indicates that people may be willing to pay as much for about one week in a space hotel as for they paid for the lift to orbit. If this is true then habitable volume, shielding mass, life support consumables and makeup materials will be needed in low earth orbit.

The history of human exploration and settlement suggests that the characteristics of the first local resources utilized will include:

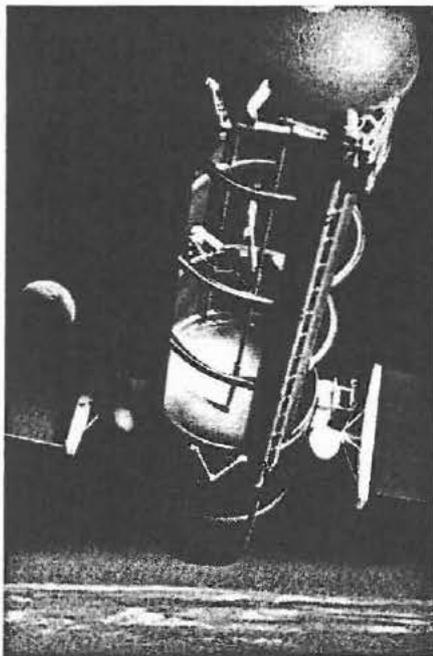
- **Proximity to the market**
- **Little or no processing required**
- **No uncertainty as to the availability of the materials**

Fortunately, there is one class of nonterrestrial resource which has precisely these characteristics. The resource is the Space Transportation System External Tank.

*Proximity to the market:* In the normal Space Shuttle mission profile the Shuttle's main engines are purposely shut down before the liquid propellants contained in the tank are exhausted. The tank is then jettisoned and the Shuttle is given an additional velocity increment with the Orbital Maneuvering System engines. The main engines could be operated longer and doing so would actually increase the payload which the Shuttle takes to orbit. However, the low density and large area of the tank would cause it to be de-orbited by atmospheric drag. Absent a user willing to take responsibility for maintaining the orbit of the External Tank, NASA is naturally unwilling to deposit these structures in orbit. In terms of delta v, the External Tanks are the most accessible form of materials available. Basically, the delta v requirement is zero for delivery of the tanks although stationkeeping is necessary during the life of the asset.

*Processing Requirements:* External tanks are useful as structural elements with little or no processing. Many including Spencer, Taylor and Gimarc have considered the use of External Tanks in creating habitable volume.<sup>3</sup> Although there has been some resistance to the notion of converting fuel tanks into habitats, the Skylab example (a pretty good station built from upper

stage tankage) tends to diffuse critics. In addition to considering the use of External Tanks as potential habitable volume, the Space Studies Institute has examined the use of tank materials as reaction mass and as potential feedstocks for space construction. Under SSI auspices, graduate students at the Air Force Institute of Technology developed systems designed to harvest the materials contained in External Tanks.<sup>4</sup> Figure 1 depicts such a system in operation.



**Fig. 1. External Tank Harvesting System**  
(photography and model by Ron Jones)

*Knowledge of the Materials:* In this regard, Shuttle External Tanks are the ideal resource. Since we built them we have specific knowledge of their composition.

**Long-term implications of space resources and space tourism:** Once the demand for space tourism is established, a variety of destinations exist which could benefit from utilization of space resources. The use of lunar resources to support Low Earth Orbit (LEO) operations and trans-LEO flight has been well researched. Using electromagnetic launch, material can be supplied to free space on an economical basis.<sup>5</sup> It is interesting to note that both lunar orbiting and lunar surface tourism are under study at this time.

Tourism could provide the rationale and the means to answer some of the most critical and questions which remain regarding human settlement of space. For example, late in his life Professor Gerard O'Neill considered the minimum size for self sustaining space colonies. The most critical parameter for these designs is the human pseudogravity requirements for indefinite

stays.<sup>6</sup> No present or proposed government space projects are planned which would provide an answer to the question of human gravity needs. The long-term staff of the first partial gravity space hotels may provide the clues which answer this question. Similarly, if the demand for propellant and other consumables is sufficiently large, tourism could provide the impetus for our species learning how to "live off the land" in the solar system.

#### **Getting started in space tourism - The X PRIZE:**

It will be necessary to prove the existence of the latent demand for personal spaceflight before large investments on the scale required for the use of space resources will be made. Initially, suborbital spaceflight is likely to demonstrate the existence of the space tourism market. Suborbital flight is roughly 25 times easier than orbital flight due to the relatively low energies required. The early history of commercial aviation suggests that large numbers of people will be willing to purchase tickets for spaceflights which simply permit them to directly experience spaceflight. This is likely to be true even though the flights are of relatively short duration and to not include a stopover at a space destination. Unlike the post World War I era, where there was a strong supply of surplus aircraft, we do not have a livery of ships available to meet the potential demand. To create an incentive for the development of the first spaceships which can fulfill the demand for the most rudimentary form of space tourism, the X PRIZE was announced by Diamandis, Lichtenberg et al in 1996. As of this writing, 19 teams in 5 nations including Argentina, Canada, Russia the United Kingdom and the United States have registered to compete for this \$10 Million prize. To monitor developments in this area the reader is encouraged to visit the X PRIZE Foundation's web site at [www.xprize.org](http://www.xprize.org)

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**RECOVERY OF VOLATILES FROM THE MOON AND ASSOCIATED ISSUES.** E. D. Mc Cullough, Boeing RSS, 10349 Brookway Place, Riverside CA 92505, USA (edward.d.mccullough@boeing.com).

Hydrogen and other volatiles were detected in the lunar regolith returned by the Apollo missions and in the data returned from the Clementine and Lunar Prospector satellites. The hydrogen concentration appears to vary by a factor of 34 between equatorial and polar crater locations. The recovery methods will vary with the nature of the deposits and the environmental conditions. Yields depend on process difficulty and available resources. Available resources include the H<sub>2</sub>/water concentrations, thermal gradients, vacuum, insolation and regolith fines. Process difficulty depends on water concentration, environment, characteristics of the equipment and logistics. Production rates depend on equipment characteristics and logistics. The distribution and disposition of volatiles and vapor mobilized elements at a fine scale are only known for a limited number of locations. Experience in terrestrial mining, beneficiation and processing has shown that small variations in the grade or associated contaminants of an ore can have a marked effect on the efficiency of these operations. These can range from operational impairment of machinery to degradation of process chemistry. The appropriate processing methods will vary with the location and the concentration of water. For equatorial and mid latitude locations, hydrogen production could be combined with a high temperature whole soil process like Magma Electrolysis both of which requires heating of the soil to high temperatures. It has been reported that free mercury in the lunar environment can also migrate to the poles. Potential chemical interactions of mercury and other volatile heavy metals is also addressed.



**Preliminary Analysis of a Small Robot for Martian Regolith Excavation.** Tim Muff, R. H. King, and M. B. Duke, Colorado School of Mines, 1500 Illinois St., Golden, CO 80401 (tmuff@mines.edu)

We are beginning the analysis of excavation systems for use on the surface of Mars, where the regolith is known to contain 1-2% water. If the water can be economically extracted, it may provide the basis for producing propellants on Mars or producing stores of water that could reduce the risks of long-term human occupancy on the surface. Because the amounts of material that must be excavated are large in proportion to the product generated, mining efficiency and the total power required are important.

For an excavator, the two main contributors to power consumption are soil breaking and transport. The power required to extract the soil is dependant on the geometry of the cut. The power for soil transport depends on distances the equipment has to travel within the mine. We have created a computer simulation of a regolith excavator, based on a bucket wheel concept, which will eventually allow us to vary mine characteristics (such as strength of the regolith) and determine optimum excavation rates and associated power requirements. We have done a normalized force analysis of the difference between mining the same quantity of material in a circular and rectangular mine layout. From this analysis we are able to derive requirements for an excavator that could be included on a Mars robotic exploration mission within the next decade.



## THE REGISTRATION OF SPACE-BASED PROPERTY

By Declan J. O'Donnell, Esq.\*  
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### Abstract

Any form of property interest to be held in outer space will need to be registered in order to provide notice and for the purpose of protecting it from appropriation by others. Some such property may include space resources, such as orbits and land on the Moon and Mars. Common Law Estates have been recommended as legitimate possessory property interests in space resources. However, the public registration of those interests, (however acquired), has never been defined. The legal estate is separate from the resource affected and it is a man made space object as a matter of law and fact. As such there is both an opportunity and a duty to register same with the State and with the United Nations under Article II of the Convention on Registration of Objects Launched into Outer Space, January 4, 1975. This paper will detail how that works and what alternatives are available. A conclusion is suggested that the Treaty on Registration may be available for this purpose, but that other registration procedures should be utilized prior to Treaty Registration for qualification and definition purposes. The Participating States need to work out a fair set of qualifications and standards lest they abuse this treaty which has no provision for arbitration, mediation, or other conflict resolution. The entire history of property rights and registration at common law is offered as an analogy.

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**CONTINUOUS PROCESSING WITH MARS GASES.** Clyde Parrish, NASA, Kennedy Space Center, FL (321) 867-8763 (clyde.parrish-1@ksc.nasa.gov), Paul Jennings, Florida Institute of Technology, Melbourne, FL (321) 867-8763, (paul.jennings-1@ksc.nasa.gov).

Current Martian missions call for the production of oxygen for breathing, and fuel and oxygen for propulsion to be produced from atmospheric carbon dioxide (CO<sub>2</sub>). Adsorption and freezing are the two methods considered for capturing CO<sub>2</sub> from the atmosphere. However, the nitrogen (N<sub>2</sub>) and argon (Ar), which make up less than 5 percent of the atmosphere, cause difficulties with both of these processes by blocking the CO<sub>2</sub>. This results in the capture process rapidly changing from a pressure driven process to a diffusion controlled process. To increase the CO<sub>2</sub> capture rates, some type of mechanical pump is usually proposed to remove the N<sub>2</sub> and Ar. The N<sub>2</sub> and Ar are useful and have been proposed for blanketing and pressurizing fuel tanks and as buffer gas for breathing air for manned missions. Separation of the Martian gases with the required purity can be accomplished with a combination of membranes. These membrane systems do not require a high feed pressure and provide suitable separation. Therefore, by use of the appropriate membrane combination with the Martian atmosphere supplied by a compressor a continuous supply of CO<sub>2</sub> for fuel and oxygen production can be supplied. This phase of our program has focused on the selection of the membrane system. Since permeation data for membranes did not exist for Martian atmospheric pressures and temperatures, this information had to be compiled. The general trend as the temperature was lowered was for the membranes to become more selective. In addition, the relative permeation rates between the three gases changed with temperature. The end result was to provide design parameters that could be used to separate CO<sub>2</sub> from N<sub>2</sub> and Ar. This paper will present the membrane data, provide the design requirements for a compressor, and compare the results with adsorption and freezer methods.



## Drilling and Logging in Space; an oil-well perspective

Max Peeters<sup>1</sup>, James Kovats<sup>2</sup>

### *Abstract*<sup>3</sup>

Growing interest in extraterrestrial subsurface exploration has prompted an examination of advanced technologies for drilling slim holes and obtaining geophysical data in these holes. The borehole surveys with geophysical measurements called "logging", complement, and under favorable conditions, replace soil sampling. Very shallow drilling systems were used extensively during the Apollo lunar missions, and are in the planning stages for use on Mars. The prime objective is to gather scientific data, but these data could eventually provide a basis for the commercial use of space mineral resources. Given the strong scientific interest in water on Mars and the Moon, subsurface characterization with geophysical methods is attractive, because these methods can cover a much larger volume than soil sampling. Space technology has boosted the development of borehole geophysical instruments because both in space and in boreholes the instruments have to function in hostile environments, in confined spaces, and to be able to withstand large g-forces.

This paper reviews oil industry drilling and geophysical borehole techniques that could be adopted for space applications. Coiled tubing drilling has many advantages because the surface facilities are compact, and an electrical cable in the tubing can transmit power and data. Moreover geophysical sensors can be embedded in the drill collars, which ensures that measurements are carried out while drilling, and this avoids risky reentry of geophysical tools in the hole. If kevlar is used for the coiled tubing, a laser beam could be transmitted via optic fibers in the coiled tubing wall. Using this beam to cut the rock would virtually eliminate mud and downhole motor requirements, and save a lot of weight. The quest for water and the strict requirements for redundancy, simplicity, and rugged instruments led to the selection of electromagnetic wave resistivity, natural gamma radiation, geophones, and induced epithermal neutron instruments as detectors. All these detectors can in principle be fitted into a coiled tubing string, and a combination of these measurements can provide quantitative information on the porosity, water-saturation, seismic velocity, and lithology of the Martian or Lunar soil.

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<sup>3</sup> this paper was earlier presented during the SPACE 2000 conference (pp. 739 – 747) Feb. 27 – March 2, 2000, Albuquerque NM.



**LORPEX FOR POWER SURGES: DRILLING, ROCK CRUSHING.** Kumar Ramohalli, Mario Urdaneta, Massimiliano Marcozzi, and Vanessa Duke, Space Engineering Research Center, 4717 East Fort Lowell Road, Tucson AZ 85712, USA.

This paper presents a new concept in space power: the ability to generate high levels of power (power surges) for short durations, even when the average power level is quite low. This power surge is generated through In-Situ Resource Utilization (ISRU), where the low average power is used to extract and store fuel/oxidizer combinations that can be rapidly expended when needed. It should be recalled that power surges have always been the main limiting factors in space exploration, planetary rovers; without the high power, no duration (no matter how long in duration) of low power can do such simple operations as crushing a rock, drilling deep, hopping over an obstacle, or ascent to a waiting mother craft.

While the basic concept is straightforward, this paper presents results from an actual project that designed, built, and demonstrated (at Planetfest97, in Pasadena, California) the first robot. Called, LORPEX (for Locally Refueled Planetary Explorer) this 20 kg robot uses an array of silicon photovoltaic cells to harness solar energy through traditional means. Carbon dioxide (either from the atmosphere, or from a storage container) is dissociated into carbon monoxide and oxygen. These two gases are stored separately in two containers. When needed, these two gases are burned in a simple engine to generate a rapid power surge that is mechanical, but can be easily converted into electrical power (if needed) through a generator. As a simple variation, we have also explored carrying a high-density solid fuel on board and burning it with the ISRU produced oxidizer (i.e., a hybrid rocket for propulsion).

The photovoltaic array was thoroughly tested in our Mars chamber (simulating temperature, composition, and pressure in the martian atmosphere) including the day-night cycling.

At the time of the meeting, we expect to have more data on the power surge numbers. We have also developed (in cooperation with Jet Propulsion Laboratory) a novel ISRU unit that promises significant improvement over the much studied solid oxide electrolyzer cells. From various media produced segments, we will show a brief video tape.



**AN END-TO-END NEAR-EARTH ASTEROID RESOURCE EXPLOITATION PLAN.** K.L. Reed<sup>1</sup>, <sup>1</sup>BAE SYSTEMS, Mission Solutions, 16250 Technology Drive, MZ 6300-B, San Diego, CA 92127, kevin.l.reed@baesystems.com.

**Introduction:** The possible end result of the utilization of raw materials garnered from near-Earth asteroids (NEAs) has been well documented if often a bit fanciful (*e.g.*, [1]). Very few have put forward an end-to-end plan from prospecting to mine closure for any specific asteroid or for any particular asteroid resource. There are many aspects to planning for the mining of raw materials from asteroids that have never been encountered in terrestrial resource exploitation due to the dispersed nature of the asteroids. As an example from petroleum exploration, if a dry hole is drilled in a large geologic setting indicative of petroleum deposits, one only need pack the drill rig up and move it to a new spot. In asteroid exploitation, the problem of “moving to a new spot” is complicated, as the “new spot” is moving constantly and may be many millions of kilometers distant at great cost in time and rocket fuel.

This paper will outline a relatively low-risk, probable high-return, end-to-end plan for the exploitation and utilization of asteroid raw materials. All aspects of exploration and mining will attempt to be addressed, from prospecting, exploration, and evaluation of possible resources to initialization, industrialization, and closure of the mine. It will attempt to plan for the acquisition of not just the needed scientific knowledge, but also to plan for acquisition of the engineering and geotechnical knowledge needed for effective mining of a small planetary object.

**Prospecting:** This stage may be described as finding what resources may be available to a particular market. Asteroid prospecting is far different than looking for resources on a large, planetary body. Asteroids are dispersed both physically and geochemically, due to their orbits and also due to their diverse geologic provenance. One spacecraft can be flown to a single planet and, using remote sensing techniques such as spectrophotometry, radiometry, and radar, can map and identify the possible resources of the planet on a global scale. This cannot be done economically with the dispersed asteroids, as the cost of the hundreds to thousands of spacecraft needed would initially be prohibitive.

A method by which one may accomplish an initial prospecting of the near-Earth asteroids is through a ground-based, multi-sensor observational program [2]. Estimates are that after three years, a few hundred NEAs will have been observed, which is a reasonable population from which to choose possible exploration candidates. Data obtained from this program would

yield parameters such as bulk composition, mean grain size, compaction, and other values needed to estimate the rheology of the body and to model the engineering possibilities for exploitation of possible resources. This modeling will assist in planning the spacecraft-based next stage—Exploration.

**Exploration:** This stage is examining in detail what resources actually are available. To locate these resources, not just to a specific asteroid but to specific locations on a particular asteroid, and to study them from an exploitative and an economic viewpoint. All these data are used to decide in the Evaluation stage which resource (if any) should be mined from a specific asteroid.

From the hundreds of asteroids observed in the Prospecting stage, a smaller sampling (~5-20) may be selected as worthy of further attention if all the indications from remote sensing show that they may have suitable resources for exploitation. Unmanned spacecraft missions, either flyby or rendezvous, will then be designed to detail the composition and geology of each body. These initial spacecraft missions will be used to assess the presence of raw materials for exploitation on these bodies and to derive a shorter list of possible resource candidates for complex, detailed follow-up missions. These subsequent missions to the few candidates left for exploration will provide details from drill cores and other interactive analysis techniques. These data will then be used in the final analysis for evaluating what resource from what body will prove economical to exploit for what market.

**Evaluation:** The Evaluation Stage takes into account all the data from the Prospecting and Exploration stage and decides which of the resource/market combinations are economic to exploit. This stage will most likely be running concurrently with the previous stages and the decision will be very fluid until the arbitrary deadline set by program economics is reached. The decision as to what resource to exploit for a specific market should wait until this point, at which the maximal amount of data is available for review, in order to utilize best the program resources for a more focused effort.

**Decision:** This is the point at which “all the eggs are put into one basket”. A resource satisfying a growing, profitable market is selected. A target asteroid that has the highest probability for return on this resource is selected. Then the program is focused on providing the resource to that specific market from that particular

asteroid (e.g., H<sub>2</sub>O from asteroid Y for use as volatiles for the ISS).

The decision point has been postponed to this stage because most of the data that has been gathered on the NEAs so far has been rather general in nature, taking them from a greater geochemical and cosmochemical context and placing ever more specific needs on their detailed characterization. Any systems or geotechnical engineering effort up to this point has not been wasted, either, as it has been asking and answering general questions such as 'How do we drill?' 'How do we blast?' 'How do we shore up and reinforce?'. This is the point at which the entire endeavor is then narrowed down to the real project of extracting specific raw materials from a specific NEA.

The decision revolves around two inter-related questions: 1) What market/resource combination are you going to address?, and 2) What asteroids/minor planets are you going to exploit in addressing that market. The answer that must be had at this point, based on all the data that has been gathered, will form the basis for success or failure. This is the reason that Decision is given as a separate stage from Evaluation as they are separate actions, Decision being pivotal.

**Initialization:** This stage includes the focused actions leading up to, and including, pilot operations of raw materials extraction.

This will be the most expensive stage in terms of investment vs. return, as the investment at this stage will need to be high with the possibility of minimal or even no return due to lack of feasibility of pilot operations. The previous stages were much less expensive and their results, mainly scientific knowledge regarding the NEAs, could always be used for academic research with a possible public interest write-off in the small event of failure. Initialization is the stage in which all altruism is assuredly cut off. This stage is where most of the proprietary knowledge is generated leading to a successful pilot operation.

Once a pilot operation is set up on the target asteroid, materials may then be extracted and then sent on to its intended destination. This will provide the evidence that the asteroid resource exploitation plan may be profitable.

**Industrialization:** The Industrialization Stage takes the pilot operation and increases its scale and efficiency. This is the longest and most profitable stage in the lifecycle of the mining operation. The raw materials extracted will now enter into a balance of quantity versus market value in which the amount of material mined is not a function of technological achievement as much as it is driven by market forces.

**Closure:** Every mining operation must have the Closure Stage that ends its life as a useful source of

materials. Operations are ramped down to stoppage, equipment is disassembled and shipped out, personnel are transferred or furloughed, and the mine is "safed". It is a stage that must be completed in any event to keep the remainder of the asteroid and mine dross from posing a hazard to further resource exploitation and solar system exploration.

The actual timing of the Closure stage is dependent on the usage of the mined asteroid material. If the mining operation is planned to utilize the entire asteroid, with only minor dust and gravel components left as waste, then the Closure stage plans may be enacted throughout the Initialization and Industrialization stages.

**Discussion:** The stages outlined here are not sequential. The thinking they entail are aspects that must be addressed from the outset of the commitment to start asteroid mining operations. For the first asteroid mining operation to be successful, an end-to-end plan must be in place initially in order to guide the focused use of capital and resources to a true goal.

This entire scheme is not a huge leap forward in thinking on this subject. Much of what is presented here has been said in high-level analyses before (e.g., [3]). What is unique in the current work is the mindset of implementation and pragmatism. Practicality in this case is really a two-edged sword as one must have the focus to utilize budgetary constraints to provide results but must also have the will to budget adequately for those processes that require high capital investment. This is another reason for a well-thought-out end-to-end plan for the first asteroid mining operation. Steps requiring high investment may be identified at an early stage and a timeline and budget estimate may be imposed, with contingencies for deviations and variances. Steps previously thought to require high investment might also be planned in more detail so as to use to best advantage synergies between all aspects of the enterprise. The contents of this abstract are a synoptic view of an existing plan pared down to two pages of double column format. Such a plan is being derived and should be ready in the very near term for use in case implementation should become a reality.

**References:** [1] Bear G. (1995), *Eon (reissue)*, Tor Books, ISBN: 0812520475. [2] Reed K.L. (1998) *First Space Res. Roundtable*. [3] Stafford T.P. and the Synthesis Group (1991), US Government Printing Office.

**AN ENGINEERING AND COST MODEL FOR HUMAN SPACE SETTLEMENT ARCHITECTURES: FOCUS ON SPACE HOTELS AND MOON/MARS EXPLORATION.** C. M. Reynerson, Ball Aerospace and Technologies Corp., P.O. Box 1062, Boulder CO 80306-1062, USA (creyners@ball.com).

This paper addresses a concept-level model that produces technical design parameters and economic feasibility information addressing future inhabited Earth-orbiting and Moon/Mars Exploration platforms. In this context, the Mars exploration platforms considered include those currently chosen in the NASA Mars Design Reference Mission. Space hotels will also be examined.

This paper uses a design methodology and analytical tools to create feasible concept design information for these space platforms. The design tool has been validated against a number of actual facility designs, and appropriate modal variables are adjusted to ensure that statistical approximations are valid for subsequent analyses. The tool is then employed in the examination of the impact of various payloads on the power, size (volume), and mass of the platform proposed.

The development of the analytical tool employed an approach that accommodated possible payloads characterized as simplified parameters such as power, weight, volume, crew size, and endurance. In creating the approach, basic principles are employed

and combined with parametric estimates as necessary. Key system parameters are identified in conjunction with overall system design. Typical ranges for these key parameters are provided based on empirical data extracted from actual human spaceflight systems.

In order to provide a credible basis for a valid engineering model, an extensive survey of existing manned space platforms was conducted. This survey yielded key engineering specifications that were incorporated in the engineering model. Data from this survey is also used to create parametric equations and graphical representations in order to establish a realistic range of engineering quantities used in the design of manned space platforms.

Using this tool sample space hotels and Moon/Mars exploration architectures are examined and compared with emphasis on cost minimization through variance of key mission requirements. This paper is based on work Dr. Reynerson recently completed at George Washington University in fulfillment for the degree of Doctor of Science in Astronautics.



**THE DEVELOPMENT AND REALIZATION OF A SILICON-60-BASED ECONOMY IN CISLUNAR SPACE.** G. J. Rodriguez, Parker CO 80134-9589, USA.

*Abstract: This paper departs from past proposals which envision mining of Lunar regolith and ore separation, oxygen recovery and smelting operations. Proposed is the concept that after oxygen the second-most valuable extract is Silicon which would be processed in Lunar foundries into Si60 and other Silicon-based Buckminsterfullerenes.*

*The potential applications and resulting space economy are exciting in their scope. Unfortunately the concept and its' applications are somewhat tenuous: this author is unaware of any attempt to synthesize Si-60 to date. However, on the optimistic side, Carbon is a close analog to Silicon with similar properties, such as a valence of four. Several laboratories around the world have produced families of Carbon fullerenes, reflecting various topologies.*

*A myriad of Silicon Fullerene Products would include cable, extrusions and structural products all produced on the periphery of earth's gravity well in lunar and lunar-orbital foundries. A second tier of applications is expected from alloys and the doping of Si60 derivatives including new semiconductors, nanomachines and translucent / transparent glass.*

*The advantage of the lunar manufacturing plant is seen as significant to the development of earth-orbital space habitats, resorts and satellites of all types when compared to lifting costs from planet earth. The Silicon Buckminsterfullerene Economy is elaborated.*

*Curriculum Vitae*

A nuts and bolts technologist from 'way back, he designs and develops products with electronics or intelligence content for the industrial world. Raised to be a generalist and an artist in a long line of artists he is comfortable working in petrochemical, avionics, mining, systems peripherals, industrial automation and the like. His customers have produced his designs in oil well controllers installed on five continents, avionics flying in commercial and military fleets worldwide as well as the President's Helicopter Fleet. These devices are often, although not exclusively, embedded controllers.

His technical passion is lost and ancient technologies, a field which he characterizes as "*unearthing architecture*". His efforts in this arena include cross-disciplinary application of "*mis-placed*" technology.

He holds a Bachelor's degree in math and computer science, having grown up with computers since the sixties while still a teen-ager.



**OUR LUNAR DESTINY: CREATING A LUNAR ECONOMY** Christopher J. Rohwer, The Boeing Company, 222 129<sup>th</sup> Ave. NE, Bellevue, WA 98005, ctrohwer@integrityol.com.

“Our Lunar Destiny: Creating a Lunar Economy” supports a vision of people moving freely and economically between the earth and the Moon in an expansive space and lunar economy. It makes the economic case for the creation of a lunar space economy and projects the business plan that will make the venture an economic success. In addition, this paper argues that this vision can be created and sustained only by private enterprise and the legal right of private property in space and on the Moon. Finally, this paper advocates the use of lunar land grants as the key to unleashing the needed capital and the economic power of private enterprise in the creation of a 21<sup>st</sup> century lunar space economy.

It is clear that the history of our United States economic system proves the value of private property rights in the creation of any new economy. It also teaches us that the successful development of new frontiers—those that provide economic opportunity for freedom-loving people—are frontiers that encourage, respect and protect the possession of private property and the fruits of labor and industry. Any new 21<sup>st</sup> century space and lunar economy should therefore be founded on this same principle.

Our nation’s history also includes the use of land grants as a means to facilitate private property ownership and thus promote frontier expansion and the creation of new economies. Specifically, land grants have been used successfully in the development of the New World colonies (sometimes called Proprietary Grants) during the 17<sup>th</sup> and 18<sup>th</sup> centuries. They also were commonly used in the settlement of virtually all of the states in the 19<sup>th</sup> century, most prominently in the Northwest Territories and in the building of the railroads to facilitate migration to and settlement in the western states.

This economic treatise examines the development cycles of some of our noted historical economies and analyzes the characteristics and results of those economies (see Figure 1).

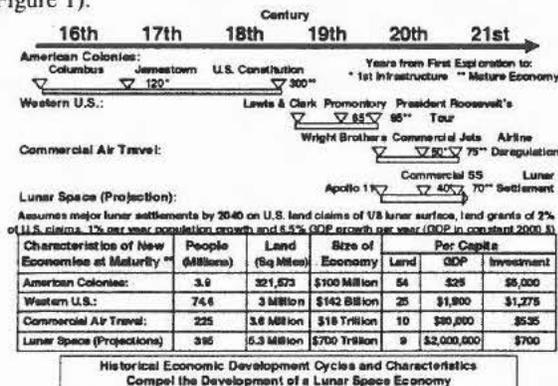


Figure 1 – Comparing Past Economies to a Future Space and Lunar Economy

It further evaluates the use of land grants and their contribution to the growth of those economies. It then estimates the benefit of land grants and accompanying government loans associated with the creation of a new space and lunar economy by projecting investment costs and revenues relative to the major infrastructure segments needed to create such an economy (see Figure 2).

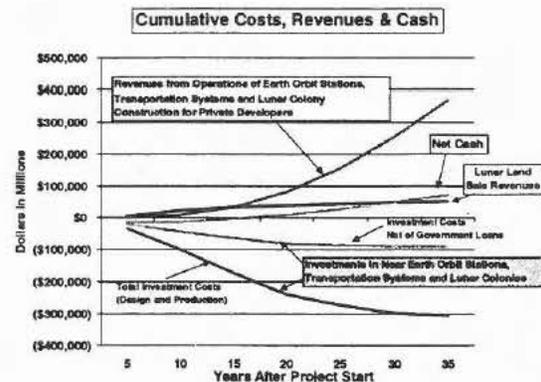


Figure 3 – Cumulative Cash for a Space and Lunar Economy; Lunar Land Sales Close the Business Case

This paper therefore offers a vision for our future in space based on an Economic Creation Model and a reasonable business case, both of which advocate private ownership of lunar property which in turn encourages and promotes private investment in near-earth space and ultimately lunar resources. Finally, it expresses the conviction that the simple act of granting lunar property to private enterprise would provide significant and early investment capital from lunar land sales, unleash tremendous entrepreneurial activity, incentivize technological breakthroughs, and lead to enormous economic expansion in the 21<sup>st</sup> century.

In conclusion, an initiative promoting commercial development of the Moon using lunar land grants would nourish a free market in near-earth space and create a new lunar economy of space travel, construction, touring, industry and science. This initiative would stimulate a powerful but recently weakened U.S. aerospace industry and enhance the development of science at all levels of our industrial and educational systems by inspiring interest in space science and engineering. Finally, this frontier expansion in space would carry our national heritage of freedom and opportunity for all into the 21<sup>st</sup> century.



**COST-EFFECTIVE APPROACHES TO LUNAR PASSENGER TRANSPORTATION.**

S. Rowland, 4753-B RR#1, Port Hope ON L1A-3V5, CANADA (simon@simonrowland.com).

A design analysis and cost model of an alternative to the chemical rocketry approach to lunar tourist transit. The performance leverage offered by combined electrical propulsion with microwave power beaming, and refuelling with in-situ space propellants, allows performance to be spent on many cost-reducing mission elements. High-speed transits, large margins, easy-to-work materials, safe propellants, simple and under-optimized design, redundancy for reliability, and a general elimination of gram-shaving all reduce costs, based on a large cost model. Air-launch from an airport using a ramjet aircraft developed as part of an incremental, independently profitable approach, in addition to optional mass-exchange tethers to move fuel, substantially enhance the system and derivative applications.



**LUNAR MINERAL RESOURCES: EXTRACTION AND APPLICATION.** S. Rowland, 4753-B RR#1, Port Hope ON L1A-3V5, CANADA (simon@simonrowland.com).

A discussion of the various uses and extraction techniques for useful but seldom-discussed lunar mineral resources. This talk comes both from the perspective of finding uses for materials and finding materials for an anticipated application. Includes indigenous propellants for chemical and electrical propulsion (beyond the obvious), metal extraction, leveraging imports, chemical extraction processes, things to do with lunar ceramics and glass fibres -- how to extract and use many materials on the Moon.



## SPACE RESOURCES DEVELOPMENT – THE LINK BETWEEN HUMAN EXPLORATION AND THE LONG-TERM COMMERCIALIZATION OF SPACE

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### Introduction

In a letter to the NASA Administrator, Dan Goldin, in January of 1999, the Office of Management and Budget (OMB) stated the following, "...OMB recommends that NASA consider commercialization in a broader context than the more focused efforts to date on space station and space shuttle commercialization. We suggest that NASA examine architectures that take advantage of a potentially robust future commercial infrastructure that could dramatically lower the cost of future human exploration." In response to this letter, the NASA Human Exploration and Development of Space (HEDS) Enterprise launched the HEDS Technology & Commercialization Initiative (HTCI) to link technology and system development for human exploration with the commercial development of space to emphasize the "D" (Development) in HEDS. The development of technologies and capabilities to utilize space resources is the first of six primary focus areas in this program. It is clear that Space Resources Development (SRD) is key for both long-term human exploration of our solar system and to the long-term commercialization of space since: a) it provides the technologies, products, and raw materials to support efficient space transportation and in-space construction and manufacturing, and b) it provides the capabilities and infrastructure to allow outpost growth, self-sufficiency, and commercial space service and utility industry activities.

### HEDS & HTCI Overview

The first of five goals stated in the recently updated HEDS Strategic Plan is "Explore the Space Frontier". Three primary strategic objectives to accomplish this goal are:

- Invest in the development of high-leverage technologies to enable safe, effective, and affordable human/robotic exploration
- Enable human exploration through collaborative robotic missions,
- Develop exploration/commercial capabilities through private sector and international partnerships

The goal of the HTCI program is to identify and develop technologies that have the potential to enable revolutionary new capabilities for both government sponsored exploration missions and commercial

development of space activities. Unlike previously implemented technology development programs which focused on technologies that were derived from proposed missions, the HTCI program focuses on technologies which can enable a broad architecture of potential mission destinations. The HTCI program is organized into six "Themes": (1) Space Resources Development, (2) Space Utility and Power, (3) Human Habitation and BioAstronautics, (4) Space Assembly, Maintenance, and Operations, (5) Exploration and Expeditions, and (6) Space Transportation. To support the HEDS Strategic Plan, the HTCI program also utilizes two major programmatic guidelines to help focus and shape the strategic plans, or "roadmaps", for each of the themes. These are, one, the use of time phasing objectives in the Near (2000-05), Mid (2006-11), and Far-Term (2012+), and two, the use of mission duration evolution from present (14 days Shuttle; 30-90 days ISS), to Mid-Term (50-100 days), Far-Term (300-1000 days), and Beyond (2000+ days). Mid-term mission objectives include lunar and libration point missions, and far-term mission objectives include Near Earth Objects and lunar outpost missions (300 days) and Mars and main belt missions (1000 days). Since the objectives of the HEDS Enterprise include both enabling affordable human/robotic exploration, and enabling human exploration through collaborative robotic missions, it is also the goal of the HTCI program to identify and develop technologies which can also support the robotic scientific exploration of space.

### Space Resources Development (SRD) Overview

It is fundamental to any program of extended human presence and operation on extraterrestrial bodies that we learn how to utilize indigenous resources, i.e. "living off the land". The goal of the Space Resources Development (SRD) theme is to develop technologies and capabilities to extract and process space resources to reduce the cost, mass, and risk of robotic and human exploration, enable the commercial development of space, and achieve long-term self-sufficiency from Earth. The approach used to achieve this goal is three-fold. One, synergize resource investigation, prospecting, and utilization activities with scientific and space commercialization interests. Evaluate both commercial and resource markets and Earth spin-off potential. Two, develop

high leverage resource and processing capabilities and products common to human and robotic exploration and space commercialization, and evolve to self-sufficiency. Develop technologies and capabilities that have the potential for multiple applications (life support, propellant production, fuel cell power systems, etc.) and/or multiple sites of exploration (lunar, Mars, asteroids, etc.) Three, develop SRD technologies and capabilities through extensive Earth-based testing and through mission incorporation evolution to minimize development and mission risk and cost.

The SRD theme is divided into six “capability” focused tasks: (1) in-situ resource assessment, excavation, & separation, (2) material & product transportation, (3) resource processing & refining, (4) in-situ manufacturing, (5) surface construction, and (6) surface cryogenic and product storage & distribution. Each capability-focused task is further divided into “technology” focused tasks. Roadmaps, including technology assessments, strategic technology approach plans, capability objectives and evolution, and goals, metrics, and benefits, have been created for each capability-focused task based on the time phasing and mission duration evolution programmatic guidelines. Also, both technology and product interaction and synergism with the other five HTCI themes have been identified. These capability-focused roadmaps and interactions with other HTCI themes were then combine to establish an overall SRD theme strategic plan.

As a result of developing the capability-focused task roadmaps, a number of core “building blocks” and common technologies have been identified which support the multiple destination focus of the HTCI program. The common building blocks identified include: fine-grained regolith excavation & refining, volatile furnaces and fluidized beds, atmospheric and volatile collection and separation, drilling, water & carbon dioxide processing, and surface cryogenic liquefaction, storage, and transfer. These building blocks must be low power, low maintenance, simple, reliable, and mass efficient since most operations will occur over a long period of time, under harsh conditions, and without human involvement or interaction.

#### **Rationale & Strategy for Space Resources Development and Flight Demonstrations**

A significant gap exists between analytical studies and reliance on technologies for mission critical events, such as utilization of space resources. Long-term and extensive ground testing of these technologies and systems under simulated mission environmental conditions is key to developing space resource utilization for future robotic and human exploration missions and the commercialization of space. However, without actual flight

demonstrations, mission planners and commercial investors will continue to perceive the incorporation of these capabilities into a mission as either high risk or not worth the potential benefits. It is the objective of the SRD Strategic Plan to combine the needs and capabilities of robotic and human exploration with the commercialization of space to minimize the cost and risk of future space resource utilization related activities, and to verify potential resources and demonstrate extraction viability. To meet this objective, flight demonstrations and missions which incorporate utilization of space resources must: (1) increase knowledge of the potential resources and mission environments, (2) increase confidence in space resource utilization technologies for use in future human missions, (3) enhance or enable science, human exploration, and commercial development of space, and (4) engage and excite the public. Possible near-term flight demonstrations and missions that have been identified that meet these common needs and capabilities include:

- Lunar polar hydrogen/water mission
- Near Earth asteroid/extinct comet prospector mission
- Mars surface water & deep drilling mission
- Mars sample return utilizing in-situ produced propellants
- Mars fuel cell rover mission

#### **Conclusions & Summary**

The goal of the HTCI program is to identify and develop technologies that have the potential to enable revolutionary new capabilities for both government sponsored exploration missions and commercial development of space activities. After examining the benefits and potential applications, it is clear that the development of space resource utilization capabilities is key to achieving this goal. To support the HTCI program, a Space Resources Development Strategic Plan was developed which includes both capability-focused and technology-focused development strategies. As a result of developing these roadmaps, a number of core “building blocks” and common technologies have been identified which support the multiple destination focus of the HTCI program. Also, the use of flight demonstrations and missions which utilize space resources are recommended to increase program manager and investor confidence and minimize mission cost and risk of utilizing space resources.

## TOWARD A MORE COMPREHENSIVE EVALUATION OF SPACE INFORMATION

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Humanity will face many challenges, some of which may threaten our very survival. Most of us want our kind to enjoy a good life here on a diverse and fertile earth, and as far beyond as we can reach. To attain this goal, we will have to get better at dealing with our problems before they happen, to paraphrase Lao Tzu. This requires having timely and pertinent information at hand. Therefore, it is in everyone's best interest to appraise it highly and encourage its collection. To this end, a new paradigm for dealing with information in the marketplace could prove useful. We will outline one such model and discuss how it applies to our greatest frontier - space. Our goal is to stimulate thought and dialog about long-range planning for humanity's future, and about present steps we can take to continue our progress to the stars.

To begin, we need to discuss some of the economical aspects of information, and describe a model of how it fits into the marketplace today. Information can be divided and classified in many ways, but we will limit this discussion to two. First, information can be categorized by whether it is held in the private sector or owned by the public. Examples of private information include an up-to-date database containing the names, addresses and spending habits of everyone living in a major metropolis, or recently analyzed seismic records showing a large, previously undiscovered oil reservoir. Public information is available to all, at usually no more than the cost of a book. It might be the product of government-sponsored research, or it may be public because it outlived its money-making relevance. Examples of public information include a database that lists the species, total number, and age distributions of fish living off the coast of New Zealand. Another example is the set of orbital parameters of a large asteroid that indicates a collision with earth will occur in 20 years. To improve readability of what follows, we will coin a few more words for information types; our justification being that we live in the Information Age. We will refer to the types of information described above as "privatein" and "publicin". There are two major distinctions between them: 1) as the names imply, the public has access to publicin while privatein is treated as private property; and 2) publicin is used by society to set policy, manage resources, and for general education, while privatein is used by individuals and businesses to make money.

A second useful classification divides information into two types: information about human creations and

activities, and about the rest of the natural universe. We will refer to the former as "createin" and the latter as "naturalin". There is some overlap at the borders - but for this discussion we shall lump information about human activities into naturalin if those activities significantly influence the natural state. A mass spectrometer furnishes examples of both types. How to build and operate the machine would be createin, while what the machine reveals about the isotopic ratios from rock samples would be naturalin. All 4 combinations of information occur: natural public, natural private, created public, and created private.

We are ready to examine how information flows during the life-cycle of a natural-resource harvesting/mining activity. Each resource activity has individual differences and complexities we will not mention, but all share most of the following essentials. A new natural resource is discovered, or a new demand is placed on a known resource. Not a lot is known about this resource, but as businesses and new methods develop around it, privatein blossoms. Claims and permits are usually freely given on a first-come basis, and those first there with efficient methods reap the harvest. With the passage of time, old privatein transforms into publicin, as business secrets become common knowledge, often in the setting of a public university. This is especially true in resource fields that require a high degree of technical skill to find and mine. As privatein grows, our skill at utilization grows until limited quantities of the resource disallow steadily rising yields. At this time, the need to collect natural publicin about the resource and its environs becomes apparent and resources are allocated to that end. However clumsily, the marketplace adjusts, tapering off to a lower yield.

A major problem with the way the present system works is that by the time we begin understanding a resource's place in the scheme of things, we have already excessively altered it. The information necessary to best value and manage the resource always lags behind the exploitation. One way around this situation is to modify the claim and permit granting process. By requiring naturalin be collected and given to society in return for a claim on the resource, the whole system is improved by providing more timely feedback. Instead of individual companies collecting what naturalin they think useful, and then hoarding it, naturalin collection is encouraged and shared by all. A more complete picture of the resource ensues, enabling more realistic

modeling. This is the paradigm shift mentioned in the first paragraph; it requires the consensus of society, and the cooperation of natural-resource industries.

From industry's point of view, this new business model would seem unfair, at first. They are forced to pay a new surcharge (the cost of naturalin collection) for what they used to get for free (permit/claims). Industries might also claim that making public the naturalin they collect gives their competitors an unfair advantage. However, the price of naturalin collection is a justifiable business expense and will be passed on to the customers. It is a long overdue example of economic externalities being internalized. Regarding unfair competition, two points: 1) any createin the industry owns is theirs to do with as they please. Industry-developed techniques and tools for naturalin and resource harvesting remain privatein. 2) Naturalin collected by one business cannot be used by other businesses to the disadvantage of the collector. The claim/permit system is set up to prevent this.

The best and easiest place to apply a new model for granting claims in return for naturalin is in space. There are two fundamental reasons for this. First, since we are just now venturing into space, we go there with no established business conventions - the slate is perfectly clean. Society is free to choose the best business arrangement that will work. Second, our very presence in space requires a high degree of knowledge. Science, the collection and analysis of information, will always be an integral part of all our activities in space. It makes sense then, to elevate the value of space naturalin to be equal to that of a natural resource. Exchanging naturalin for the rights to that resource naturally follows.

We will use the example of asteroid mining to illustrate this concept. To keep from straying too far into the genre of science fiction, we will assume no technology beyond that which we are capable of today. Spacecraft Helen A. Miner approaches Near Earth Asteroid #1829. As her orbit approaches its surface, she measures gravity and takes a broad spectrum of electromagnetic readings and relays the naturalin to other spacecraft in her sector; they are all connected to one another and to earth in a vast communication web. After landing, she takes a core sample, and anchors a beacon/seismometer in the hole. She kicks off the surface, relaying the resulting seismic signal. After some analysis of her data, she might be directed to repeat the procedure at another location on the same asteroid, or on another asteroid. In either case, she has already earned a claim for her grubstakers on NEA 1829.

There are two things to note about the above example. First, a financial transaction has been made in space with the transfer of very little mass. Naturalin

has been traded for a claim. This has great virtue because moving material around in space is costly given our present rocket technology. Having massless commodities (naturalin and claims) that abound in space is a real advantage for initiating space commerce. Second, using information as a medium of exchange requires a gauge to measure its value. Building this tool is no trivial task and will require careful consideration of many issues, including the value of redundant information, errors and noise in information, and the particulars of how a claim is matched to a naturalin set.

The long-term survivability of humanity requires us to be present in space. The only way we will occupy it is if we can make a living there, in other words, if commerce can be made viable. Space is not suited to naked human colonization and will always require our utmost scientific and technical abilities. In this paper we have outlined a method of drawing science and natural resource industries into a much closer symbiotic relationship. Together, and only together will they allow us to venture forth into space, to stay. Now is the time for space industrialists, scientists, policy makers, and the public to think about how we can best utilize space. A government program is, as we speak, relaying information from a close orbit around the asteroid Eros. Space industrialists are poised to visit others. The time has come.

**DEVELOPMENT OF METAL CASTING MOLDS BY SOL-GEL TECHNOLOGY USING PLANETARY RESOURCES.** L. Sibille<sup>1</sup>, S. Sen<sup>2</sup>, P. Curreri<sup>3</sup> and D. Stefanescu<sup>4</sup>, <sup>1</sup>University Space Research Association, NASA Marshall Space Flight Center SD48, Huntsville, AL 35802, Laurent.sibille@msfc.nasa.gov, <sup>2</sup>University Space Research Association, NASA Marshall Space Flight Center SD47, Huntsville, AL 35802, Subhayu.sen@msfc.nasa.gov, <sup>3</sup>NASA Marshall Space Flight Center SD47, Huntsville, AL 35802, <sup>4</sup>University of Alabama, Tuscaloosa, AL 35802

**Introduction:** Metals extracted from planetary soils will eventually need to be casted and shaped in-situ to produce useful products. In response to this challenge, we propose to develop and demonstrate the manufacturing of a specific product using Lunar and Martian soil simulants, i.e. a mold for the casting of metal and alloy parts, which will be an indispensable tool for the survival of outposts on the Moon and Mars. Drawing from our combined knowledge of sol-gel and metal casting technologies, we set out to demonstrate the extraordinary potential of mesoporous materials such as aerogels to serve as efficient casting molds as well as fulfilling numerous other needs of an autonomous planetary outpost.

**Aerogels as Multi-Use Materials:** Traditionally made from inorganic metal oxides or from the reaction of organic molecules, mesoporous materials such as aerogels share a common structure made of nanometer-size beads linked together in a low-density 3D network with a porosity of about 90%. They offer a remarkable combination of properties which are rarely used together on Earth but make them perfect candidates for widespread usage on a Martian settlement.

*Ultra low thermal conductivity.*

Applications: Insulation for habitats, laboratories, hydroponics green houses, liquid tanks, Metallurgical Casting molds

Aerogels are the best performing thermal insulators today. Silica aerogels typically provide thermal resistance per inch almost twice that of commonly used polyurethane foams. With thermal conductivities of 0.02 W/m.K (~R10/inch), they are nonflammable, nontoxic, lightweight (as low as 0.003 g/cm<sup>3</sup>), transparent and stable up to 650C. However, any convective heat transfer is virtually suppressed by the nanometer scale porous structure thus forcing any heat conduction through the tenuous solid network or by radiative process. For example, organic aerogels have thermal conductivities as low as 0.0045 W/m.K after they have been evacuated and can withstand temperatures up to 3650 °C if pyrolyzed.

*Selective Radiation Absorption.*

Applications: Radiation shielding, UV filtering for habitats, liquid propellant containment

Aerogels can become effective radiation shielding by proper selection of the elemental composition: Silica aerogels block UV and scatter X-rays while being 70% transparent to visible and IR wavelength. Incorporation of heavy elements by diffusion or doping of the porous solids can provide shielding from Gamma rays or solar flares. Moreover, demonstrated phenomena such as He densification in aerogel pores can be exploited for liquid propellant confinement and increased radiation shielding capability of the material, thus providing an ingenious solution for two major issues of planetary exploration.

*Impact Energy absorption.*

Applications: Micrometeorite shielding, acoustic insulation

The internal network of aerogels is capable of absorbing large kinetic energies by successive collapsing of its nanometer-size pores thus slowing down the incoming projectile. Such property is being used by investigators on NASA's Stardust mission, which will collect samples from the tail of comet P/Wild 2 in 2002 and return them intact to Earth.

*High Capacitance.*

Applications: Electrical Energy Storage

The extremely high surface areas resulting from the high porosity of aerogels make it possible to create extensive areas of charged double layers by selection of the right composition. Their low density and high internal surface area make it possible to fabricate high capacity batteries that are also lightweight and low volume. Companies like Powerstor are already manufacturing such products as heavy-duty capacitors. The same properties can be used for deionization of recyclable fluids as part of the life support systems. The additions of noble metals by diffusion into the porous network or by chemical incorporation make aerogels efficient and low volume catalytic materials for use in separation of components by gas chemistry.

The above list of properties and related applications shows how such materials could become cornerstones for a planetary settlement if a low cost, robust and efficient technique can be developed to extract and solubilize the silicates and metal oxides necessary to make them from planetary soils.

**Aerogels as Metal Casting Molds:** Terrestrial casting processes usually consist of producing a bath of molten metal and then pouring this liquid metal into the cavity of a ceramic or metal mold. Upon solidification, the poured liquid metal forms a shaped casting of desired dimensions. Typically, ceramic powders of mixed silicates, zirconia, and alumina are mixed with a resin binder, compacted into desired shapes and then cured at high temperatures. This process is both cumbersome and power intensive, thus ill suited for a Lunar or Martian base. If produced on Earth, the high cost of transportation to the base of these relatively heavy ceramic or metal molds would be prohibitive.

Ratke et al. have demonstrated the use of silica aerogels[1] as lightweight ceramic casting molds. Aerogels offer significant advantages in this application over traditional molds: reduced wetting of the crucible walls by the liquid, lower thermal conductivity and transparency in the visible and infrared allowing direct observation and measurements during casting. Most aerogel materials are made of either inorganic oxides or organic precursors. The composition of these chemical precursors determines such properties as refractive index, chemical reactivity or elasticity of the final product. For this study, the fabrication of a metal casting mold commands the choice of materials with good refractory properties at high temperatures. As such, silica, alumina and titania have all been found in Lunar and Martian soils. Iron oxides and Aluminum oxides are the two most abundant metal ores after silica found in both the Lunar and Martian soils. Several groups are conducting preliminary studies on the extraction and purification of these metals<sup>1</sup> to enable future planetary bases to create useful shaped parts for applications such as habitat structures, excavation tools, and metal antennas.

Wetting of liquid metal poured in an aerogel mold is lower than other ceramics because of the high pore volume provide only very small contact surfaces. The Fe or Al melt is poured into the cavity of the aerogel mold. By inserting a chill plate at one end of the aerogel mold, one can obtain high directionality in casting microstructure since the extremely low thermal conductivity of the aerogel (around 0.02 W/m.K) will inhibit radial or multidirectional solidification, an advantage over other sand and ceramic molds. Such directionality in casting microstructure is sought to obtain higher mechanical strengths in components such as turbine blades.

**References:** [1] Alkemper J., Diefenbach S. and Ratke L. (1993) *Scripta Metallurgica et. Materialia*, 29, 1495-1500.

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<sup>1</sup> D.M. Stefanescu, R.N. Grugel & P.A. Curreri, "In-Situ Resource Utilization for Processing of Metal Alloys on Lunar and Mars Bases", *Proc. of Space98* (1998), pp. 266-275.

**A NEW CONCEPT IN PLANETARY EXPLORATION: ISRU WITH POWER BURSTS.** Douglas Streibech, Mario Urdaneta, Patricia Chapman, Roberto Furfaro, and Kumar Ramohalli, Space Engineering Research Center, 4717 East Fort Lowell Road, Tucson AZ 85712, USA.

The concept of generating power bursts upon demand in space exploration is presented. As acknowledged by two NASA Novel Technology Report (NTR) awards, the concept is new and innovative. As a general background, it must be recalled that power has always been a major limiting factor in exploration, especially in the exploration of far off sites like Mars (contrasted with LEO or GEO). Without the high power ability, no amount of energy (that can only be expended at a low rate, i.e., low power) can accomplish such simple operations as: crushing a rock, hopping over an obstacle, drilling deep, and eventually ascent from the planet to an orbiting craft above, or even the return journey to Earth.

The concept presented here is an advance over the much studied In-Situ Resource Utilization (ISRU); we use ISRU for the extraction of the needed fuel and oxidizer from the local resources, store these gases, and expend them rapidly when needed. In the martian scenario, these gases will be carbon monoxide (fuel) and oxygen (oxidizer) extracted from the atmospheric carbon dioxide; subsequently, higher chemistry is possible after the discovery, and utilization of water which enables the production of an entire spectrum of hydrocarbons and carbohydrates. If nitrogen can also be added at a still later date, many more chemicals in the ammonia based family are possible. At SERC (University of Arizona) we have pioneered all of these chemical productions. In another award-winning innovation, an ultra-light weight material, popularly known as muscle wires, is used in a biology-inspired robot called BiRoD. The expenditure of energy in these materials produces power that results in mechanical motion. The short term power generation is thousands of times the average power that was used to harness the local resource in the first place.

At the time of this abstract, BiRoD has been designed, assembled, and shown to work in a primitive way, in its component form; new media have carried the high-profile story all over the nation. At the time of the Congress, we expect to not only have many more pieces of quantitative, engineering data from BiRoD but we still also attempt to bring that robot to the session for an actual demonstration.



**BOLD SPACE VENTURES REQUIRE FERVENT PUBLIC SUPPORT.** G. Jeffrey Taylor (Planetary Geosciences, Hawai'i Institute of Geophysics and Planetology, 2525 Correa Rd., Honolulu, HI 96822; gjtaylor@pgd.hawaii.edu).

**The Problem:** The idea of colonizing space and using space resources sounds like science fiction to most people. Few are interested in humans living and working in space, and very few are drawn to the prospect of living on another world themselves (though many have candidates they would like to send!). Why do it? they wonder. There's no need and it's dangerous. Americans are more concerned with raising their families, getting kids to soccer practice, paying for college, planning vacations, and the outcome of next week's NFL game.

Fortunately, there are times when space exploration seizes the public's collective imagination: Apollo 11 landing on the Moon, Mars Pathfinder bouncing to a safe stop on Mars, the first Hubble repair, John Glenn's flight on the Shuttle. The widespread interest in these events suggests that there is an inherent fascination with space exploration. The trick is to nurture that interest into zealous advocacy.

**Public Engagement Is Essential:** While one might argue that aggressive use of space resources and permanent habitation of space can be accomplished by influencing key members of national legislatures and corporate leaders, the fact is that strong public support is essential. People are the ultimate consumers of whatever companies produce in space; we must convince them that space manufacturing is important to their personal economic health and to that of their children and grandchildren. They need to feel that they are involved in the whole enterprise, thereby giving them a sense of ownership. Most important, their interest translates into financial support through investments in space-faring companies.

Strong public support will encourage politicians to support increases in government spending for space exploration. The role of government should be to develop the technologies necessary to reach space cheaply and to learn how to extract resources. It builds the infrastructure, provides essential seed money for developing resource extraction techniques, and can provide low-interest loans to commercial enterprises to do the rest. (In the United States, "government" is not necessarily just NASA, but the Departments of Defense and Commerce, and the Department of Energy National Laboratories as well.) In the end, we need strong political action, not just lobbying by our small (but enthusiastic) organizations. We need groups with the numbers and passion shown by the

American Association of Retired Persons and the National Rifle Association. This can happen only with widespread, enthusiastic public support.

Stockholders can influence corporate policies. This will become a more democratic process as individuals own greater amounts of stock--already half of American households own stocks. Universal public support for large, commercial space ventures coupled with widespread ownership of stocks could help spark industry investment in space resource utilization. Public enthusiasm could also translate into purchase of corporate bonds for space ventures.

**How to Engage the Public:** If we accept that it is essential to have widespread, ardent support for space colonization and the use of space resources, how can we achieve it? Here are some suggestions:

*Multifaceted, broadly based.* The effort must reach all segments of the population (children and adults, rich and poor, men and women, all ethnic groups). We must permeate society with the idea that living and working in space is normal, not merely the idea of a few crazy rocket scientists. It must involve movies, theater, literature, and art, not only science and technology.

*Involve the public.* People need to feel they are intimately involved with space exploration and resource utilization. This can start with the public voting on key decisions during missions (landing sites on the Moon and Mars, which rock to analyze, prioritizing experiments on the space station).

*Stoking our imaginations.* We must seize the imaginations of all but the most diehard dullards. This may be done most effectively through story telling, in words or art, about life on other planets, but not involving science fiction (e.g., no alien life forms, faster-than-light travel). Organizations could sponsor contests to produce works of fiction (short stories, novels, screen plays, plays, poems) and art (paintings, sculptures, computer generated scenes), judging in age categories. Magazines and publishers could be encouraged to feature the best entries. (For example, American Airlines features employee art on its menus in first-class. Why not open it up to space artists?) Ideally, compendiums of space-based literature will become so respected that they will be widely used in high school and college literature classes. Contests and publication will need financial backing. If the

publications are successful, publishers will be able to provide that backing.

*News media.* The news media are extremely important in any effort to reach hundreds of millions of people. However, there is a serious problem: Although science reporters do a credible job reporting space stories, the rest of the press tends to be pathologically uninterested. For example, in a brief statement on the South Lawn of the White House, President Clinton announced to the world that NASA scientists had found evidence for past life in a meteorite from Mars-- a startling discovery if proven correct. After his brief statement, the first question a reporter asked was about abortion. This was followed by another on that topic, then this question: "Where did you get that tie?" The President explained it was an Olympic tie. (Members of the 1996 U.S. Olympic Team had given it to him.) So, the White House press corps ignored life on Mars and focused on a political issue and a completely trivial matter. The lesson is that the utilization of space resources needs to be a compelling political or social story.

*Customers:* People must be convinced that there actually are useful, commercially viable space products. The usual ones mentioned are good (e.g., energy for Earth, fuel for space operations, microgravity products, tourism, satellite repair, national defense), but they have not yet been made compelling to the public. Perhaps experiments on the International Space Station will help show the way, but we need other more dramatic demonstrations, such as prototype solar energy satellites in orbit or water extractors on the Moon.

*Long-term effort.* Public engagement will not take place overnight. It probably requires decades of effort.

*Make space travel safe.* Space travel is dangerous. Most adults remember when the Challenger exploded; older ones remember that an Apollo crew perished just practicing for a launch. Until the public believes that space travel is as safe as driving their cars or flying in airplanes, nobody is going to sign up for a trip into Earth orbit, let alone to the Serenitatis Sheraton or the On-Orbit Omni.

*Educating while indoctrinating.* Space resource utilization and space colonization provide a host of educational opportunities. It is possible to develop exciting, engaging curricula for use in K-12 classes to make the next generations comfortable with the idea of living and working in space. However, to be successful in inspiring students to advocate the use of space resources, entire school districts must adopt such curricula. This will require an enormous effort. College curricula are also essential, not only for support but also for training the workforce that will accomplish what we envision.

**The Near Term:** MirCorp and the ISS may capture public attention, especially with the active participation from the media companies interested in space (Dreamtime, Kodak EyeOnSpace, etc.). People will be living and working in space. A potential problem is that their work and their lives in space might be boring to most people. If so, it will be important to try to turn that into an advantage: it shows how normal it is to work in space!

**Acknowledgement:** My thoughts on the importance of engaging the public in space exploration have been shaped by presentations and remarks by Bob Rogers to the Mars Exploration Planning Analysis Group.

## HOT-PRESSED IRON FROM LUNAR SOIL.

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**Introduction:** The amount of iron in the elemental form ( $Fe^0$ ) is about 10X greater in lunar soil than in the rocks from which the soil was formed [1-2]. At first, it was assumed that this was meteoritic metal. However, it was later shown that the amount of meteoritic contamination to the soil is only about 2% at best. The majority of the native Fe in the lunar soil was formed by the auto-reduction, by solar-wind implanted hydrogen, of the FeO in the silicate melts formed by micro-meteorite impacts. The FeO in the melt is essentially reduced to elemental Fe which homogeneously nucleates into myriads of nanophase-sized (3-33 nm)  $Fe^0$ . This melt quenches, thereby forming the glass which binds together the aggregates of soil particles called 'agglutinates.' This fine-grained Fe (abbr. 'np-Fe') in the agglutinitic glass is not visible with an optical microscope.

**Formation of Lunar Soil:** The major factor in the formation of lunar soil involves micro-meteorite impacts. Larger particles are comminuted to finer and silicate melt welds together soil grains into glassy aggregates called agglutinates. These two competing processes complicate the formational characteristics of the soil. Recently, we have become aware of yet another set of processes that significantly affect lunar soils. This is the formation of surface-correlated "nanophase  $Fe^0$ " (4-33 nm), resulting from impact-induced vaporization and deposition of Fe-, Al-, and Si-rich patinas on all soil particles [3-6], as well as sputter-deposited contributions [7]. The average grain size of this nanophase  $Fe^0$  is substantially less than that in agglutinitic glass such that it causes the major portion of the space weathering effects to reflectance spectra [4-6; 8-9].

**Agglutinitic Glass versus Grain Size and Maturity:** It has been demonstrated recently that for a given mare soil, *the abundances of agglutinitic glass increase significantly with decreasing grain size*, as evidenced by the  $I_s/FeO$  values which increase with decreasing grain size. The maturity index,  $I_s/FeO$ , is used as an indication of the amount of iron in a sample that is present as np-Fe. As shown by Taylor et al. [5-6], the percentage increase in  $I_s/FeO$  and agglutinitic glass, from the larger grain sizes to the smaller size fraction is only on the order of 10-15%, whereas the  $I_s/FeO$  changes by about 100%. That is, *with a decrease in grain size, the change in agglutinitic glass content is relatively small compared with the change in  $I_s/FeO$* . This logically leads to the conclusion *that the large increase in  $I_s/FeO$  is direct proof of the presence of another source of nanophase  $Fe^0$ , in addition to the agglutinitic glass*.

**Surface-Correlated Nanophase Fe:** The thesis on vapor-deposited patinas [3] has also found supporting evidence in several subsequent studies [4-6; 8-10]. *The presence of nanophase  $Fe^0$  in the vapor-deposited patinas (rims) on virtually all grains of a mature soil provides an additional and abundant source for the greatly increased  $I_s/FeO$  values*. In fact, for grain sizes of lunar soils <45  $\mu m$ , the amount of np-Fe on the surfaces is large, possibly equal to that in the agglutinitic glass in these fine grains.

**Magnetic Separation of Lunar Soil Particles:** Taylor and Oder [11] performed studies on lunar soils in order to determine the optimum conditions for the beneficiation of soil components for in-situ resource utilization (ISRU) at a lunar base. Using a Frantz Isodynamic Separator, specifically calibrated for

susceptibility measurements, they studied various size fractions of hi-Ti and low-Ti mare soils, as well as some from the highlands. They were able to successfully beneficiate the soil particles with decreasing efficiency as grain size decreased, down to 45-20  $\mu\text{m}$ . However, with sizes <20  $\mu\text{m}$ , they determined that separation was not possible. It appeared that 'clumping' of these fine-sized grains was responsible. It was apparent that this size fraction behaved as if virtually all the particles had relatively higher magnetic susceptibilities than the coarser particles. In retrospect, this behavior is now explainable, with our new knowledge, that each of these fine grains contains a surface patina of ferromagnetic nanophase Fe<sup>0</sup>.

**Uses for the nanophase Fe:** Recent experimentation by the author with the <10  $\mu\text{m}$  fraction of mature hi-Ti mare soil 79221 has shown that a small hand magnet will easily attract practically all the grains, even those that are plagioclase, but have a thin patina of np-Fe. This fine fraction, along with the high-magnetic susceptibility agglutinitic glasses from coarser sizes can be easily beneficiated from the lunar soil to make a feedstock for roasting. The nanophase Fe present both on the particle surfaces, as well as in the agglutinitic glasses, is readily ripened by annealing at 1000 °C. This can render this product a valuable feedstock from which to retrieve the enlarged Fe grains even by rather crude magnetic separation.

The presence of extensive amounts of np-Fe on virtually all surfaces of soil grains is particularly advantageous where the grain-size of a soil fraction is small (e.g., <45  $\mu\text{m}$ ), since the surface to volume ration is largest and the concentration of agglutinitic glass is the greatest. It will be possible to easily shape and form the soil and to sinter it slightly by "hot pressing." The np-Fe will grow during this process thereby adding significantly to the ad-

hesion and strength of the aggregates. In addition, the nanophase Fe is located within a silicate glass, which being inherently unstable, will readily add addition fusion of the particles to each other. The 'discovery' of the abundance of this nanophase native Fe on the surface of lunar soil grains has potential for numerous uses for ISRU.

**References:** [1] Taylor, 1988, Proc. Space 88, ASCE, 67; [2] Taylor and Cirlin, 1985, In *IONICS - ESR Dating and Dosimetry*, Tokyo, 19; [3] Keller & McKay, 1997, GCA 61, 2331; [4] Taylor et al., 1999, LPSC 30, LPI-CD #1859, #1885; [5] Taylor et al., 1999, New Views of the Moon II, LPI; [6] Taylor et al., 2000, LPSC 31, LPI-CD #1697, #1706, #1842; [7] Bernatowicz et al., 1994, LPSC XXV, 105; [8] Keller et al., 1999, LPSC 31, LPI-CD 1820; [9] Keller et al., 2000, LPSC 31, LPI-CD 1655; [10] Taylor et al., 2000, MPS, in press; [11] Taylor and Oder, 1990, Proc. Space 90, ASCE, 143.

## THE LUNAR DUST PROBLEM: A POSSIBLE REMEDY

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**Introduction:** Those of us who were around during the early Apollo days know well about the "Gold Dust Theory," that cost NASA beaucoup dollars. And the electrostatic fluffiness of the lunar soil was not a problem to landing on the Moon, but may contributed to the dust that was observed to cling to the astronauts' suits, as well as to the "rock boxes" such that they all leaked. However, the fine-grain nature (50 wt% = <50  $\mu\text{m}$ ) of the lunar soil, in the presence of the 1/6<sup>th</sup> gravity of the Moon, with the potential for extensive beneficiation of lunar soil has the 'EPA' and astronomers upset. They envision huge clouds of dust flying around the Moon, covering telescopes and solar cells. In addition, the large glass contents (up to 100%) of lunar soil makes the abrasive properties of the dust a great concern for any moving parts. However, a possible solution to many of these fears involves use of the magnetic properties of the lunar soil [1] and results of recent studies of the Lunar Soil Characterization Consortium (LSCC) [2-7].

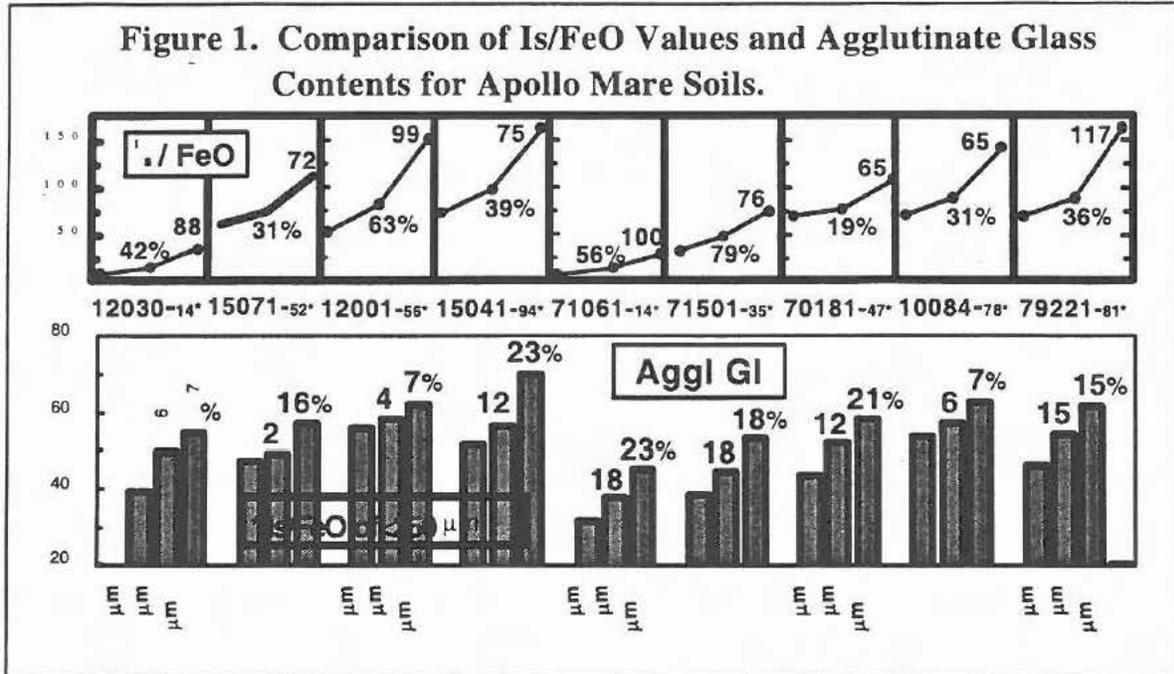
**Formation of Lunar Soil:** The major factor in the formation of lunar soil involves micrometeorite impacts. Larger particles are comminuted to finer and silicate melt welds together soil grains into glassy aggregates called agglutinates. These two competing processes complicate the formational characteristics of the soil. Recently, we have become aware of yet another set of processes that significantly affect lunar soils. This is the formation of surface-correlated "nanophase  $\text{Fe}^0$ " (4-33 nm), resulting from impact-induced vaporization and deposition of Fe-, Al-, and Si-rich patinas on all soil particles [8-12], as well as sputter-deposited contributions [13]. The average grain size of this nanophase  $\text{Fe}^0$  is substantially less than that in agglutinitic glass such that it causes the major portion of the space weathering effects to reflectance spectra [5-7; 9-12; 14-15].

**Agglutinitic Glass versus Grain Size and Maturity:** The data shown in Figure 1 were derived from studies by the Lunar Soil Characterization Consortium [5-7; 9-12]. In a given mare soil, the abundances of agglutinitic glass increase significantly with decreasing grain size. In spite of the different abundances of agglutinitic glass in the different size fractions, the average composition of the agglutinitic glass for each grain size of a given soil is similar, as shown in Taylor et al. [7].

**$I_s/\text{FeO}$  versus Grain Size and Maturity:** A comparison of soils of different maturities, as measured by  $I_s/\text{FeO}$  [16], shows that for any given grain size, the amount of agglutinitic glass increases with maturity. This is a direct reflection of the duration of surface exposure of a soil to micro-meteorite gardening, with its space-weathering effects. Therefore, as shown in Figure 1 by the values after the sample numbers (e.g., 71061-14) 12030, the  $I_s/\text{FeO}$  values of soils increase as a function of maturity [16]. As also shown in Fig. 1, within a given soil, the  $I_s/\text{FeO}$  values increase with decreasing grain size. In Figure 1, the percentage increase, in  $I_s/\text{FeO}$  and agglutinitic glass, from the larger grain size to the next smaller size fraction, is given above the respective sizes. An increase of 100% for  $I_s/\text{FeO}$  indicates that the amount of nanophase  $\text{Fe}^0$  has doubled, relative to the total Fe. Notice that with a decrease in grain size, the change in agglutinitic glass content is relatively small compared with the change in  $I_s/\text{FeO}$ . This logically leads to the conclusion that the large increase in  $I_s/\text{FeO}$  is direct proof of the presence of another source of nanophase  $\text{Fe}^0$ , in addition to the agglutinitic glass.

The thesis on vapor-deposited patinas [8] has also found supporting evidence in several subsequent studies [4-7; 9-12]. The presence of nanophase  $\text{Fe}^0$  in the vapor-deposited patinas (rims) on virtually all grains of a mature soil provides an additional and abundant source for the greatly increased  $I_s/\text{FeO}$  values. For the same masses, the surface area of the soils increases by a factor of 4, as the grain size decreases by 50%. If the increase in  $I_s/\text{FeO}$ , that is attributable to the minor increase in agglutinitic glass, is accounted for in each change in grain size, the 'residual' is the possible surface-correlated  $I_s/\text{FeO}$  contribution. On average, there is still a 2-5X increase in  $I_s/\text{FeO}$  between size fractions, whereas a decrease in grain size of 50%, increases the surface area by 4X (i.e., 400%). Therefore, as a first approximation, the increase in  $I_s/\text{FeO}$  of 2-5X correlates well with the predicted 4X increase in particle surface area (i.e., surface-bound nanophase  $\text{Fe}^0$ .

**Magnetic Separation of Lunar Soil Particles:** Taylor and Oder [1] performed studies on lunar soils in order to determine the optimum conditions for the beneficiation of soil components for in-situ resource utilization (ISRU) at a lunar base. Using a Frantz Isodynamic Separator, specifically calibrated for mag-



netic susceptibility measurements, they studied various size fractions of several mare and highland soils. They were able to successfully beneficiate the soil particles with decreasing efficiency as grain size decreased, down to 45-20  $\mu\text{m}$ . However, with sizes <20  $\mu\text{m}$ , they determined that magnetic separation of particles was not feasible. It appeared that 'clumping' of these fine-sized grains was responsible. It was apparent that this size fraction behaved as if virtually all the particles had relatively higher magnetic susceptibilities than the coarser particles. In retrospect, this behavior is now explainable in that each of these fine grains contains a surface patina of ferromagnetic nanophase  $\text{Fe}^0$ , thereby increasing its magnetism.

Recent experimentation by the author with the <10  $\mu\text{m}$  fraction of mature hi-Ti mare soil 79221 has shown that a small hand magnet will easily attract practically all the grains, even those that are plagioclase. This is the basis for a possible solution to the "lunar dust problem."

**Solution:** The finest grain sizes of lunar soils have higher magnetic susceptibilities than their obvious mineralogy would seem to predict [1]. This is due to the presence of ferromagnetic  $\text{Fe}^0$  on the surfaces of most soil grains. This added property, a product of space weathering, is especially effective for the finest grain sizes where the surface/volume ration is largest. It is hereby proposed that a "magnetic sweeper" would clean most surfaces of the fine grains of lunar soil that

may cover various installations. Even "magnetic filters" could prove invaluable for improving the healthiness of breathing air, a non-consequential problem.

**References:** [1] Taylor & Oder, 1990, SPACE 1990 Proc., 143; [2] Taylor et al., 1998, LPI-958, New Views, 71; [3] Pieters & Taylor, 1998, New Views, LPI-958, 6; [4] Taylor et al., 1998, LPSC 29, LPI-CD 1160; [5] Taylor et al., 2000, SPACE 2000 Proc.; [6] Pieters et al., MPS, in press; [7] Taylor et al., MPS, in press; [8] Keller & McKay, 1997, GCA 61, 2331; [9] Taylor et al., 1999, LPSC 30, LPI-CD 1859; [10] Taylor et al., 1999, New Views of the Moon II, LPI; [11] Taylor et al., 2000, LPSC 31, LPI-CD 1842; [12] Taylor et al., 2000, LPSC 31, LPI-CD 1697; [13] Bernatowicz et al., 1994, LPSC XXV, 105; [14] Keller et al., 1999, LPSC 31, LPI-CD 1820; [15] Keller et al., 2000, LPSC 31, LPI-CD 1655; [16] Morris, 1976, LPSC 7, 315.

**CONSIDERATIONS ON USE OF LUNAR REGOLITH IN LUNAR CONSTRUCTIONS.** Y. C. Toklu<sup>1</sup>, <sup>1</sup>Eastern Mediterranean University, Civil Engineering Department, Famagusta, T. R. Northern Cyprus, yct@bigfoot.com

Lunar regolith has a primordial place among in-situ lunar resources for lunar constructions. It can be used as tout-venant material (screened or not), or after being processed at some level.

Completely nonprocessed, even without screening, lunar regolith can be used for shielding, just by piling or damping. In a more elaborate way, it can be used after being packed in cages or sacks made of special plastics and fibers, like gabions and sandbags. This form can be used for protection purposes, or for constructing wall type structures.

Other levels of processing may lead to bricks, cement, mortar, concrete and materials involving more chemical decomposition and synthesis. It would of course be possible to produce reinforced-concrete or prestresses-concrete elements, but this will involve the use of tendons different than steel, which is so widely used on The Earth.

An interesting way of using lunar regolith would be reinforced-regolith (re-re) as compared to reinforced-earth. This technique, which is relatively recent on the Earth, would efficiently be used on the Moon, for infrastructural works and for shielding. In the latter use, there would be an important economy in the amount of material used.

Excavation of lunar regolith will go together with the problem of insufficient weight, due to 1/6 g level gravity, and also due to the economy in transporting machines and materials from Earth to the Moon. This problem could be tackled by creating net downward forces on the constructing machines. These forces can be created by applying surcharges, by anchoring systems, and by plates and tendons to force the machines down.

Some other issues in lunar construction with or without using in-situ resources will be the use of tele-controlled robots, and extensive planning with very high penalty functions.

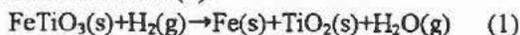


### Experimental Study on Water Production by Hydrogen Reduction of Lunar Soil Simulant in a Fixed Bed Reactor.

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**Introduction:** Human habitation on the moon will require utilization of lunar resource materials because of reducing cost of their transportation from Earth. Especially, oxygen is vital for life support and spacecraft propulsion. To this end, oxygen production from locally derived materials is of significance for future lunar exploration.

Over 20 processes of the oxygen production on the moon have been proposed.<sup>[1]</sup> Among them, oxygen production by hydrogen reduction is most feasible.<sup>[2]</sup> In the oxygen production process, ilmenite contained in lunar soil is reacted with hydrogen for water production (1), and then oxygen is produced through electrolysis (2). Hydrogen produced in reaction (2) can be reused in reaction (1).



The reaction (1) is endothermic with 11 kJ/mol at 1,300 K. Since free energy formation in this reaction is relatively low, ilmenite is easily reduced. Investigation of the hydrogen reduction mechanism of ilmenite is quite important to maximize water production from the lunar soil.

The purpose of our work is to discuss the possibility and reaction mechanism of the water production. Experiments and numerical simulation have been carried out to investigate the reactor characteristics.

**Experiments:** The schematic diagram of the experimental setup is shown in Fig. 1. Moisture meter is used to measure amount of the produced water every 0.5 seconds. The experiments are conducted with changing of reaction temperature, mass and particle size of the simulant sample, and flow rate and inlet pressure of hydrogen. The experimental conditions are specified in Table 1.

**Experimental Results and Discussion:** Effect of temperature on the water production is illustrated in Fig. 2. Under these temperatures except 1323 K, higher temperature leads to higher water production rates. This would result from the occurrence of partial sintering at 1323 K. The water production is enhanced with increasing hydrogen flow rate. Therefore, hydrogen mass transfer in the boundary layer around each of the sample particles is considered to be the rate-controlled process.

**Conclusion:** The experimental results indicate that the water production from Lunar Soil Simulant is feasible process, and also the water production is possible on the moon. The optimized reactor operation is available at a reaction temperature of 1,273 K, a hydrogen mass flow of 6 l/min, and a processing time of 10 to 15 min.

**References:** [1] L. A. Carrier. (1992) *AIAA Journal*, 30, 12, 2858-2863. [2] R. A. Briggs and A. Sacco, Jr. (1991) *J. Mater. Res*, 6, 3, 574-584.

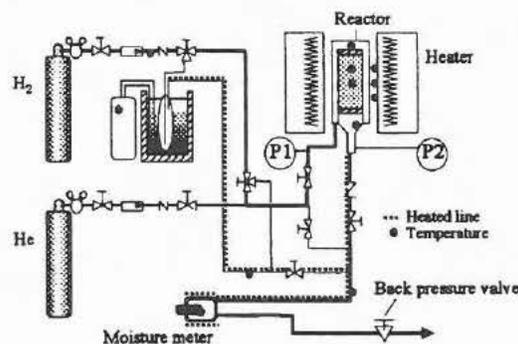


Fig. 1 Schematic diagram of experimental setup.

Table 1 Experimental conditions.

Sample Weight [ g ]	20, 40, 60
Reaction Temperature [ K ]	1173, 1223, 1273, 1323
Inlet Pressure [ kPa ]	303, 404, 505
Hydrogen Flow Rate [ l/min ]	2, 4, 6
Particle Size [ μm ]	all, 30, 90, 150, under75, over75

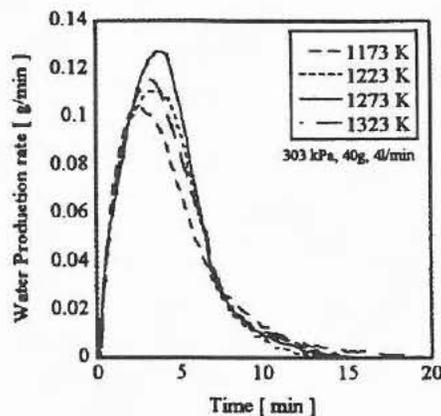


Fig. 2 Effect of temperature on the water production rate.

