SPACE RESOURCES ROUNDTABLE VIII

COLORADO SCHOOL OF MINES
OCTOBER 31–NOVEMBER 2, 2006

PROGRAM AND ABSTRACTS

LPI Contribution No. 1332

SPACE RESOURCES ROUNDTABLE VIII

OCTOBER 31–NOVEMBER 2, 2006

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LPI Contribution No. 1332

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Abstracts in this volume may be cited as

Author A. B. (2006) Title of abstract. In *Space Resources Roundtable VIII*, p. XX. LPI Contribution No. 1332, Lunar and Planetary Institute, Houston.

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ISSN No. 0161-5297

PREFACE

This volume contains abstracts that have been accepted for presentation at the Space Resources Roundtable VIII, October 31-November 2, 2006, Colorado School fo Mines, Golden, Colorado.

Publications support for this meeting was provided by the staff of the Publications and Program Services Department at the Lunar and Planetary Institute.

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PROGRAM

Tuesday, October 31, 2006

7:30 a.m.	Continental Breakfast and Registration
8:00 a.m.	Opening Remarks
8:30 a.m.	M. B. Duke Colorado School of Mines *Scientific Context for the Exploration of the Moon: A National Research Council Space Science Board Study*

ISRU AND THE LUNAR ENVIRONMENT

8:45 a.m.	K. Heiss, A. Ignatiev, and P. van Susante *Development of a Lunar Water Astroparticle Observatory Using In Situ Resources*
9:00 a.m.	G. A. Smithers, M. K. Nehls, M. A. Hovater, S. W. Evans, J. S. Miller, R. M. Broughton, Jr., D. Beale, and F. Kilinc-Balci *A One-Piece Lunar Regolith-Bag Garage Prototype*
9:15 a.m.	B. Boldoghy, J. Kummert, I. Szilágyi, T. Varga, and Sz. Bérczi *Feasibility Concept of Creating Protected Spaces with Great Size and Balanced Interior Temperature for Industrial Activities on the Moon*
9:30 a.m.	J. Diaz and B. Ruiz *Comparative Study of ISRU-based Transportation Architectures for the Moon and Mars: LOX/LH2 vs.LOX/Methane*
9:45 a.m.	B. Blair, B. Damer, D. Rasmussen, and P. Newman *Design Simulation in Support of Exploration and ISRU for NASA's Lunar Exploration Program and the Mining Industry*
10:00 a.m.	**Break**
10:15 a.m.	J. S. Halekas, G. T. Delory, T. J. Stubbs, W. M. Farrell, R. R. Vondrak, and M. R. Collier *Lunar Electric Fields and Dust: Implications for In Situ Resource Utilization*
10:30 a.m.	F. A. Slane and G. Rodriguez *Layered Architectures for Mitigation and Processing of Planetary Dust for Manned and Robotic Space Exploration*
10:45 a.m.	L. A. Taylor and J. T. James *Potential Toxicology of Lunar Dust*

INFRASTRUCTURE AND COMMERICAL

11:00 a.m.	C. D. O'Dale *Building Private and Public Sector Support for Space Resource Use*
11:15 a.m.	R. J. Kohl *Low Earth Orbit (LEO): Planning for the Necessary Infrastructure Services*

Tuesday, October 31, 2006 (continued)

11:30 a.m.	H. A. Thronson, S. Sharma, and A. E. Schweitzer *Future In-Space Operations Support of ISRU*
11:45 a.m.	R. M. Westfall *Galactic Mining Industries, Inc. — Business Plan Development — Market Definition and Revenue Streams*
12:00 p.m.	B. L. Fraser *Advanced Ultra High Displacement Compressor Technology for Space Industrialization as an Economic Tool for Space Exploration*
12:15 – 1:15 p.m.	**Lunch**

WORKING GROUP A
OVERALL PRIORITIES FOR DEMONSTRATING ISRU CAPABILITIES AND INFRASTRUCTURE DEVELOPMENT
1:15 – 3:00 p.m.

2:15 p.m.	**Break**
2:30 p.m.	*Working Group A Continues*

PROSPECTING

3:00 p.m.	B. L. Cooper *Craters and Channels on Malapert Mountain in the Lunar South Pole Region: Challenges Associated with High-Incidence-Angle Imagery*
3:15 p.m.	R. C. Elphic, D. J. Lawrence, P. Chu, and J. B. Johnson *Tests of the Utility of Neutron and Gamma Ray Probes for Resource Prospecting and Characterization*
3:30 p.m.	J. B. Johnson, R. Bates, E. S. Berney, IV, R. Elphic, B. J. Glass, R. B. Haehnel, and S. Taylor *CRUX II: Mapper-Decision Support System Project*
3:45 p.m.	K. R. Johnson and R. W. Easter *In-Situ Resource Prospecting, Assaying and Mapping*
4:00 p.m.	J. B. Plescia, P. Spudis, and B. Bussey *A Robotic Mission Strategy for Choosing an ISRU Prospect and Process*
4:15 p.m.	Halloween Reception w/ middle and high school students *(Provide attendees with bags of candy to give out, and students Trick or Treat?)*

Wednesday, November 1, 2006

7:30 a.m.	Continental Breakfast
8:00 a.m.	Opening Remarks
8:15 a.m.	Working Group A Summary

EXCAVATION AND MATS HANDLING

8:45 a.m.	D. S. Boucher *Planetary Mining: Planning the Dig and Digging the Plan*
9:00 a.m.	D. Glaser, G. Paulsen, K. Zacny, K. Davis, E. Mumm, and B. Glass *Autonomous Drills for Planetary Subsurface Access*
9:15 a.m.	K. Yoshida, K. Nagatani, G. Ishigami, S. Shimizu, K. Sekimoto, A. Miyahara, and T. Yokoyama *Soil Mechanics of Lunar Regolith Simulants for Probe Landing and Rover Locomotion*
9:30 a.m.	L. L. Johnson and P. J. van Susante *Excavation System Comparison: Bucket Wheel vs. Bucket Ladder*
9:45 a.m.	L. A. Taylor and B. Eimer *Lunar Regolith, Soil, and Dust Mover on the Moon*
10:00 a.m.	**Break**
10:15 a.m.	M. Berggren, R. Zubrin, S. Carrera, J. Kilgore, J. Campbell, H. Rose, N. Jameson, C. Boyll, and C. Roark *Lunar Materials Handling System*
10:30 a.m.	B. Blair *A Long-Endurance Retaskable Transfer Vehicle*
10:45 a.m.	S. Trigwell, J. G. Captain, E. E. Arens, J. E. Captain, J. W. Quinn, and C. I. Calle *The Use of Tribocharging in the Electrostatic Beneficiation of Lunar Simulant*

WORKING GROUP B
PRIORITIES FOR DEMONSTRATING ISRU EXCAVATION AND MATERIALS HANDLING CAPABILITIES

11:00 a.m. – 12:15 p.m.

12:15 – 1:15 p.m. **Lunch**

Wednesday, November 1, 2006 (continued)

RESOURCE EXTRACTION

1:15 p.m. E. H. Cardiff and B. R. Pomeroy
Development of Vacuum Pyrolysis Techniques

1:30 p.m. B. R. Pomeroy and E. H. Cardiff
A Proof of Concept of Vacuum Pyrolysis

1:45 p.m. K. C. Tripuraneni Kilby, L. Centeno, G. Doughty, S. Mucklejohn, and D. J. Fray
The Electrochemical Production of Oxygen and Metal via the FFC-Cambridge Process

2:00 p.m. T. Watanabe, S. Komatsuzaki, H. Kanamori, and S. Aoki
Kinetic Investigation of Water Production from Lunar Soil Simulant by Hydrogen Reduction

2:15 p.m. Break

2:30 p.m. G. Rodriguez and R. Westfall
An Integrated Lunar Manufacturing Plant. Building the Fleet in Support of Continuous Presence on Mars

2:45 p.m. G. S. Mungas, D. Rapp, R. W. Easter, T. Wilson, and K. R. Johnson
Sublimation Extraction of Mars H_2O *for ISRU*

3:00 p.m. A. Muscatello, D. Bruinsma, and R. Zubrin
Integrated Mars In-Situ Propellant Production System

3:15 p.m. E. Shafirovich and A. Varma
Metal-CO_2 *Propulsion for Mars Missions: Current Status and Opportunities*

WORKING GROUP C
PRIORITIES FOR DEMONSTRATING ISRU PROCESSING CAPABILITIES
3:30 – 4:45 p.m.

SRR BOARD MEETING
OPEN TO ALL
4:45 – 5:30 p.m.

6:00 p.m. Dinner

Thursday, November 2, 2006

7:30 a.m.	Continental Breakfast
8:00 a.m.	Opening Remarks
8:15 a.m.	Working Group B and C Summaries

REGOLITH SIMULANTS

8:45 a.m.	J. Richard, D. S. Boucher, and M. M. Battler *Lunar Physical Simulant: Evolution, Production and Use*
9:00 a.m.	H. Kanamori, K. Matsui, A. Miyahara and S. Aoki *Development of New Lunar Soil Simulants in Japan*
9:15 a.m.	D. Rickman, C. Owens, R. Howard, and C. McLemore *Requirements and Techniques for Developing and Measuring Simulant Materials*
9:30 a.m.	R. Gustafson, B. White, M. Gustafson, and J. Fournelle *Development of a Lunar Agglutinate Simulant*
9:45 a.m.	T. Kobayashi, H. Ochiai, N. Yasufuku, K. Omine, S. Aoki, H. Kanamori, K. Matsui, and A. Miyahara *Load-Settlement Characteristics of Japanese Lunar Soil Simulant in Partical Gravity*
10:00 a.m.	**Break**

WORKING GROUP D
PRIORITIES FOR REGOLITH SIMULANTS
10:15 – 11:30 a.m.

ALL WORKING GROUP SUMMARIES AS MODIFIED
11:30 a.m. – 12:00 p.m.

12:00 p.m.	Closing Remarks

LUNAR MATERIALS HANDLING SYSTEM.

Mark Berggren, Robert Zubrin, Stacy Carrera, James Kilgore, John Campbell, Heather Rose, Nick Jameson, Curt Boyll, and Christine Roark, Pioneer Astronautics, 11111 W. 8th Avenue, Unit A, Lakewood, CO 80215.

Introduction: The Lunar Materials Handling System (LMHS) is a method for transfer of lunar soil into and out of process equipment in support of *in situ* resource utilization (ISRU). The LMHS conveys solids to an ISRU vessel, protects seals from particle contamination, provides a gas-tight seal, and minimizes wear related to abrasive particles.

A six-month, NASA SBIR Phase I LMHS program was conducted in 2006 to identify valve and flange configurations suitable for repeated lunar ISRU operations, to develop seal cleaning methods, and to integrate LMHS concepts with lunar ISRU.

Laboratory experiments were conducted to characterize the flow and particle adhesion characteristics of JSC-1 lunar soil simulant. Additional experiments were carried out to identify methods to prevent or remove particle contamination from potential metallic, ceramic, and elastomer sealing surfaces. Candidate valves were identified and tested with respect to durability in the presence of lunar simulant.

Laboratory results were incorporated with process design considerations leading to the fabrication of a sub-scale Lunar Materials Handling System. The LMHS is largely automated, remotely operated, and was built to fit in Pioneer's one-cubic meter vacuum chamber. Figure 1 shows the Phase I LMHS in Pioneer's vacuum chamber.

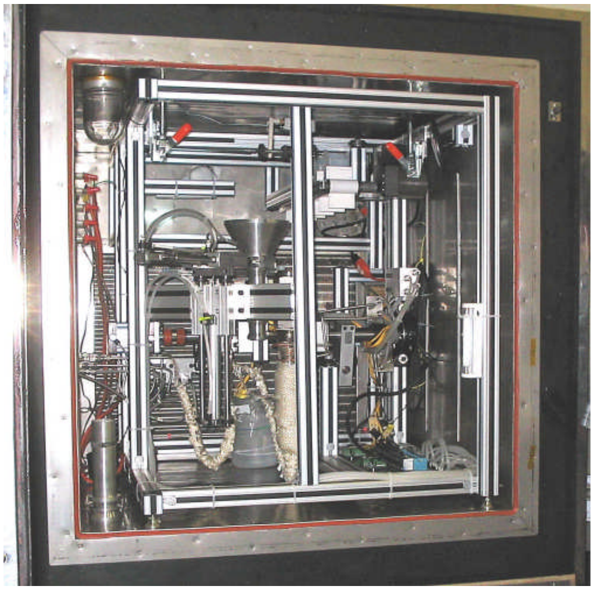


Figure 1: Phase I LMHS Demonstration Unit.

The LMHS was integrated with a near-term ISRU process, hydrogen reduction, to provide a realistic measure of the LMHS performance. Operations demonstrated feeding, sealing, water recovery for oxygen production, and residue discharging.

Valve Selection: Ball valves, knife gates, and flanges were selected as candidate Phase I seal mechanisms. These basic closures (and their variants) satisfied a sufficient number of the following criteria to warrant their evaluation.

- Ability to withstand or be protected from lunar and process temperature extremes,
- Ability to hold differential pressures of one bar or more,
- Ability to be operated over many cycles,
- Presence of a wide, clear flow path for transfer of feed soil and process residues, and
- Minimum rotation/abrasion of sealing surfaces.

Ball valves with Teflon seals (rated to 232°C) tested over dozens of feeding, compression, and pressure release cycles maintained a gas-tight seal. However, the rotating valve and seal surfaces showed clear signs of wear from contact with abrasive material, leading to eventual replacement.

A gate valve and its associated o-ring sealing system were also tested. This valve slides horizontally across the throat, but the seals engage perpendicularly to avoid abrasion. Gate valves and flanges are advantageous for their wide opening and low height profile. However, results showed that seals were prone to rapid failure by contamination by lunar simulant.

Protection of seals from exposure to abrasive lunar soils emerged as the preferred method for extending operating life. Each candidate closure type was amenable to the seal protection methods developed during Phase I and described below. Valve seal cleaning was employed as a secondary strategy.

Seal Selection: The LMHS application requirements pointed toward resilient materials such as elastomers for sealing elements. A number of elastomers have wide operating temperature ranges. For example, a Gore-Tex® formulation that performed well in Phase I has a temperature rating of –268 to +316°C. The LMHS-ISRU designs incorporate internal radiant heat barriers and cooling jackets to further protect valves and seals from environmental and process temperature extremes.

Particle Flow and Adhesion: Particle adhesion on clean, flat candidate metallic, elastomer, and ceramic substrates was characterized. Surface finish was a dominant factor related to flow initiation and particle adhesion. Materials that exhibited some of the best flow and adhesion properties, polished stainless steel and a resilient form of Gore-Tex, were tested under vacuum. Virtually all particles were shed from the Gore-Tex, except in regions with surface imperfections. The key finding was that most materials retain a durable layer of very fine particles. These particles can embed into elastomers, leading to seal failure. Electrostatic treatments helped prevent coarser particles from adhering, but a very fine layer of strongly adhered particles was still retained.

Surface Cleaning Experiments: Experiments were conducted to characterize effects of wiping, brushing, and vibration on particulate removal. Much of the focus was on removal of the durable fines layer adhered to substrates. Only the methods involving direct physical contact, such as wiping, were effective for removal of strongly adhered fines. However, this procedure causes abrasion to surfaces.

Magnetic and electrostatic cleaning methods were found to be effective in directly removing or enhancing the removal of all but the finest adhered particles. Even in cases where significant “fountaining” of particles was observed by electrostatic treatments, a persistent layer of fines remained.

Pneumatic pulsing was found to be very effective for particle removal. Short pulses (on the order of five milliseconds) could remove all particles, including adhered fines. Without optimization, a nozzle fed with compressed air (>100 psi) was found to entirely clean a surface with an efficiency of about 9 cm^2 cleaned per gram of gas consumed. Improved nozzle geometry, higher temperature, and faster-acting valves should substantially improve these results. Pneumatic cleaning has the potential for thorough, non-contact cleaning using only a small fraction of ISRU oxygen.

Seal Protection: Favorable materials handling techniques (polished surfaces, steep angles, and vibration) were integrated with insertable feed and discharge sleeves in the Phase I LMHS. The feed hopper and discharge sleeve were polished funnels to which a particulate sealing system was installed to fit above and below the process ball valve. Seals on the inserts mated with surfaces machined in the reactor above and below the ISRU process valve. The particulate sealing system is not gas tight (since the ISRU unit would be open to the lunar environment during feeding and discharging), but isolates the ISRU valve from abrasive particles during feeding and discharging. The insertable sleeves were fitted with an external wiper that removes any contamination that may occur as the sleeve is retracted before closing the valve. Figure 2 shows the LMHS discharge sleeve.

Figure 2: Insertable LMHS Discharge Sleeve.

LMHS-Hydrogen Reduction Demonstration: The best material flow, valve protection, and valve cleaning concepts developed in the laboratory were applied to a LMHS-hydrogen reduction demonstration unit. The hydrogen reduction process was integrated with a largely automated, remotely operated LMHS in Pioneer’s one-cubic meter vacuum chamber.

Lunar soil simulant (85 grams) was successfully fed through a ball valve, sealed inside the batch, down-flow hydrogen reduction reactor, reduced with hydrogen (at 850 to 870°C), and discharged without human intervention. The operations were repeated, making variations to particle size (minus 850 microns and 850 x 75 micron feed) and hydrogen flow rate (200 to 600 standard cubic centimeters per minute).

During Phase I, the reactor was inverted to discharge residue through the feed valve. The reactor interior was polished and tapered to encourage residue release. Future designs might incorporate insertable reactor components including a reaction basket and heaters to simplify the pressurized reactor design and to facilitate maintenance and replacement of components.

Oxygen yields of up to 2 percent were obtained with cycle times of about 5 hours, including feeding, heating, reduction, cooling, and discharging. Flow properties were improved by removing the finest particles, and reaction rate and extent were improved at higher hydrogen flow rates.

Acknowledgement: This work was sponsored through the NASA Small Business Innovation Research (SBIR) program. Landon Moore was the NASA JSC Contracting Officer’s Technical Representative.

Space Resources Roundtable 2006

Design Simulation in Support of Exploration and ISRU for NASA's Lunar Exploration Program and the Mining Industry

Brad Blair[1], Bruce Damer[2], Dave Rasmussen[3], Peter Newman[4]
DigitalSpace Corporation, 343 Soquel Ave, Suite 70, Santa Cruz CA 95602 USA

Abstract: DigitalSpace Corporation has been building an open source real-time 3D collaborative design engineering and training platform called Digital Spaces (DSS) in support of NASA's Exploration Vision. Real-time 3D simulation has reached a level of maturity where it is capable of supporting mission engineering design and operations using off-the-shelf game chipsets and open source physics and rendering technologies. This paper will illustrate several examples of state-of-the-art real-time design simulation utilizing DSS for the upcoming NASA lunar exploration programs and the mining industry.

I. Introduction

For several years, DigitalSpace Corporation has been building and utilizing an open-source real-time 3D collaborative engineering, design and training platform called Digital Spaces (DSS) in support of NASA's new exploration vision. This platform has been deployed into several NASA centers and other institutions to deliver innovative applications in almost every program, ranging from ISS training to Mars exploration.

II. Early Mobile Robotic Design Simulations

In late 2005, DigitalSpace Corporation was invited to join the NASA RLEP2 (robotic lunar exploration program, surface mission) to support the design simulation of "pre-phase A" rover concepts for a planned 2011 mission to explore cold, dark traps on the Lunar south pole. Our earlier work on a real-time simulation of the Colorado School of Mines' prototype lunar bucket wheel excavator[1,2], was employed to study future In-Situ Resource Utilization (ISRU) regolith handling operations (Figures 1, 2) and paved the way for our RLEP2 participation. Funding for the effort was covered under a NASA SBIR Phase I grant. A second phase continues to support refinement of the core DSS simulation platform as well as to develop specific applications for current NASA programs.

Figure 1. Colorado School of Mines' prototype lunar bucket wheel excavator.

Figure 2. DigitalSpace model of excavator operating on moon with dust simulation.

---

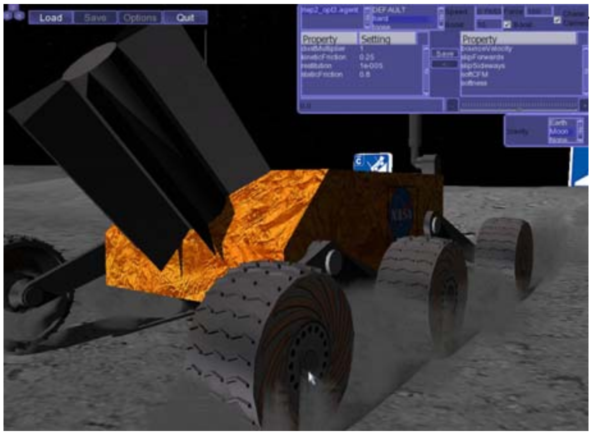
[1] Consulting Engineer and Economist, Golden, Colorado.
[2] President and CEO, DigitalSpace, 343 Soquel Ave, Suite 70, Santa Cruz CA 95062.
[3] Director, DM3D Studios, DigitalSpace Corporation.
[2] Chief Architect, DM3D Studios, DigitalSpace Corporation.

III. The RLEP2 Simulations

This section will describe our experience using DSS to create a real-time simulation of vehicles proposed during the RLEP2 surface mobility trade studies. To begin the effort, the DigitalSpace team developed a ‘moon hazards yard’ simulation environment and placed four vehicles within that environment for calibration of the real-time lunar physics model as well as to analyze the effectiveness of robotic vehicle configuration. Following the RLEP2 Mid-term Review in January of 2006, the team completed a newly rigged “V2” heavy RTG-powered six wheeled rover and placed it into an upgraded hazards yard environment, derived from the earlier work. Figures 3 through 12 below depict operation of this simulation within the newly designed moon hazard terrain, intended to test the RTG rover under variable conditions of crater wall traversal and hazard navigation. Note the physics engine input interface in the upper right hand corner of the simulation, which enabled NASA engineers to calibrate model parameters in real-time.

The V2 simulation allowed NASA engineers to calibrate, test and demonstrate elements of the design including:

- Set and calibrate physics engine parameters including gravitational force, static and dynamic friction, engine speed and torque, and damping coefficients.
- Articulate the mobility system to allow raising and lowering of the center of gravity for obstacle avoidance and instrument placement.
- Drive and steer the vehicle in the simulated lunar ‘hazards yard’ environment in real-time.
- Navigate hazards including crater walls, boulder fields, and negative hazards (small craters).
- Actively steer the view camera, using both static and ‘follow the rover’ modes.



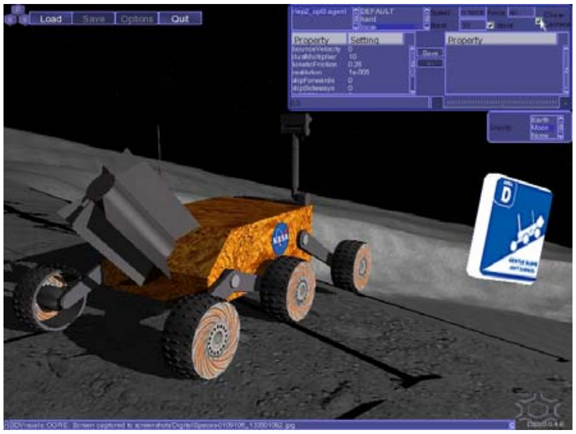


Figure 5. Vehicle traversing toward crater rim (note “dust” effects on wheel/surface contact).

Figure 6. Approaching crater rim.

A Long-Endurance Retaskable TRANSFER VEHICLE

Bradley Blair[1] and Justin G. Rodriguez[2] and Gary 'ROD' Rodriguez,
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Abstract: *Existing publications cite the need for a rocket which could be reused and retasked to a variety of near and distant orbits, from LEO to LLO. The ideal vehicle would be powered by Lunar-derived cyogenic propellants. Hauling a sixth of the propellant mass fraction (Hydrogen) from Earth and extracting the remainder (Oxygen) from the Moon is a compelling idea. Since the Moon already has substantial orbital velocity and a small gravity 'curb,' studies have shown that Lunar production can be shipped to LLO for 2-3% of the energy required to ship to the same orbit from Earth. By slight extension, to ship from the Lunar surface to LEO requires only 5% of the energy necessary to launch to LEO from Earth. Water-rich asteroids are another visionary source of propellant* on-orbit.

In the meanwhile it would be very useful to have the services of a rocket which could connect to any number of satellites and other space platforms to exchange fuel, payloads or electric power and serve as an orbital 'tug.' As a tug the rocket may serve to push another tug as an 'upper stage' to an even loftier orbit. The over-arching methodology collects solar power over a relatively long interval and, after conversion consumes that power quickly, generating thrust or electicity.

Such a vehicle would require regenerative capture of vented fuel and liquification facilities to return it to the venting tank. Transfer of cryogenic fluids in a hard vacuum is also sobering engineering task with all sorts of hazards. Any misaligned fitting could send a rocket flying off in an uncontrolled manner. Hydrogen is elusive in any form, seeping through most containers given sufficient time. A fuel needs to be well-behaved in bulk and yet have a credible ISP. A fuel which is inert and well-behaved prior to electrolysis is water. There are problems to be solved for the realization of the Water Rocket but they seem less formidable than long-term cryogenic management.

A water rocket would keep the bulk of it's fuel mass in an already-oxidized form and use solar-power to electrolyze whatever amount of water is forecast to be used in the near future plus a healthy reserve. This would shrink the volumes of the L02 and LH2 tankage which would be offset by a large-capacity water reservoir. Fuel cells would be available to generate peak power for specialty payloads.

*There are shortcuts available to the implementation of the Water Rocket. The Boeing Delta Cryogenic Upper Stage (*DCUS*) and the Lockheed Martin* Centaur *Upper Stage are obvious starting points. The Centaur is used as a 'stalking horse' in this paper because it has a familiar legacy and can be extensively researched through Internet public resources. The Centaur engine, the Pratt & Whitney RL10, is known to have been tested to seventeen restarts.*

Rather than develop an entirely new 'airframe' the Centaur can be relieved of it's single-use attributes and it's tankage reconfigured, adding gas recovery, refrigeration, zero-G electrolysis, fuel cells and deep space avionics. Someday photoelectrolysis may be available for direct conversion from solar energy. Water Rocket *can be a practical demonstration of the value, if not the mechanics of* In-Situ Resource Utilization (ISRU), *generating a prime customer for ISRU-derived oxygen and water.*

FEASIBILITY CONCEPT OF CREATING PROTECTED SPACES WITH GREAT SIZE AND BALANCED INTERIOR TEMPERATURE FOR INDUSTRIAL ACTIVITIES ON THE MOON

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Problem to be solved: Under Lunar conditions the outer temperature fluctuation on the surface is extremely wide, abt. 300 K near the equator. Due to the lack of atmosphere the outer cosmic radiation is considerable as well and it reaches the surface without diminishing, and the probability of meteorite impact is great as well. It is a factor to be considered from the point of view of long term human stay, as well as from the point of view of any industrial activity to be carried out on the Moon.

Joining to previous publication: We described in our previous publication, that if pre-fabricated modules are placed in the suitable Lunar surface formations (ditch, valley, crater) in such a way, that they are covered with Lunar regolith in a thickness of abt. 10-15 m, then an environment of balanced temperature is created for the module. *(see ref 1)*

Main steps of our proposal:

- Producing of building "brick" elements from Lunar regolith by pressing, using adhesives, melting etc.
- Creating of load bearing structures, primarily arches inside Lunar surface formations (valley, ditch, crater) of suitable size
- Covering of this load bearing structure from above in a proper thickness (10-15 m or more) by Lunar regolith for insulating purposes,
- So a thermally protected and insulated interior space of great size is created, with an interior temperature free from fluctuations of exterior irradiation and due to the inner heath flow the interior temperature is balanced, respectively fluctuates to a small extent around an average temperature of abt. –20C.
- The interior space of great size formed this way is suitable to house industrial technology and/or dwelling modules and it is protected from external cosmic radiation and meteorite impacts as well.

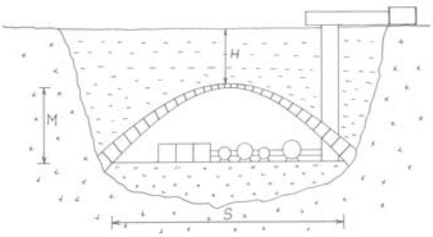

Fig. 1. *Cross section of a protected interior space of great size and of balanced interior temperature formed in a Lunar valley or ditch made suitable for industrial activity.*

Feasibility aspects: The domed spaces formed this way can be of strikingly great size, as Lunar rocks are of great solidity similarly to earth rocks, and are loaded by Lunar gravitation, which is only 1/6 G.

So for example a span of 80 m, height of 30 m can be achieved with unlimited length. The thickness of the covering protecting local soil can be 10-15 m ensuring balanced temperature protected space in accordance with our previous concept.

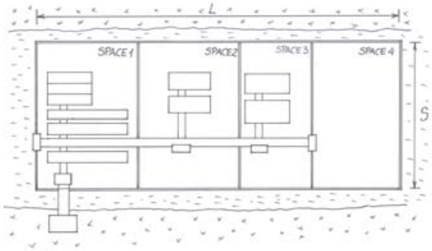

Fig. 2. *Possible lengthwise structure of a protected interior space of balanced inner temperature suitable for industrial activity as well, built in a Lunar valley or ditch lengthwise.*

Practical aspects: Forming of the arch takes place lengthwise on the lower surface of a Lunar ditch or valley, previously balanced in steps of a few meters or 10 meters with the use of a stave (arch frame) suitable for the purpose. The building elements of the arch made from Lunar materials on the Moon are placed on the surface with the help of robots. It is optional to use bonding material for connecting the building elements, but on basis of the earthly experiences an arch, which is properly built is self-supporting, its elements stand in themselves without a bonding material. The arch structure created this way is covered by the local Lunar soil – in the way described in our previous abstract – by a drag-line or excavator.

The arch-like roof structure formed in the Lunar ditch or valley can be further extended, expanded lengthwise. It can be limited by the local conditions only. So it is possible to create divided space of different sections going from outside towards the interior.

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Planetary Mining: Planning the Dig and Digging the Plan. Dale S. Boucher[1], [1]Northern Centre for Advanced Technology Inc. (NORCAT), 1400 Barydowne Road, Sudbury, Ontario, CANADA P3A 3V8 e-mail:dboucher@norcat.org.

Introduction: Terrestrial mining operations are basically brute force driven. In essence, a mine operator will solve excavation issues via a sometimes ad hoc increase in mass or power of the equipment in use. This range of decisions is based primarily upon the ready availability of resources (power, fuel, labour) and a time weighted element pertaining to capital cost, ROI, market forces, and labour rates.

Planetary mining activities must adopt a different approach. The biggest advantage is the time element. The biggest disadvantages are the availability of mass, power, and support resources (maintenance, refuelling,, other support logistics), and insertion resources (launch and landing, communications, etc.).

Planning the Dig:.Digging a hole does not make a mine. Mining is a well planned operation in logistics. The operation must optimize and coordinate infrastructure, services, transport, human interactions, ore body development, exploration and mining activities (drill, blast, muck). A very large proportion of an operating mine is devoted to managing the logistics required to access and extract the ore, then transport it effectively to the processing facility. Mine planning is used to develop and implement a viable, effective and dynamic strategy to optimize the mine operation on a macro scale.

Digging the Plan: Planetary mining operations, whether underground or surface based, require a well thought out and effective mine plan. Consider an excavator system which behaves as a trenching action. The trenches produced by the excavation process need be planned out in advance to ensure a minimum negative impact upon the extraction process. For example, consider a mobile excavator with 15cm wheels that excavates a trench to gain access to water ice on the lunar south pole (presently thought to be at depths greater than 10 cm below surface). This removal of overburden is a necessary step in the process. The problem arises when one considers a 10 cm deep trench into which the excavator must travel in order to access the high grade ore… with 15 cm wheels. Failure to adequately plan excavation paths could result in an excavator falling into or getting trapped in the trench before even one kilogram of ore is removed.

Many terrestrial open pit operations have fallen victim to mine planning errors. A large number have developed executed appropriate plans only to find that the high value “ore” may become inaccessible due to poor placement and sizing of early trenches (consider Homestake Open Pit in lead SD).

Equipment life and maintenance cycles require repair and refuel facilities or “dead unit” sidings. Roadways must be designed to ensure stability and transportability over the life of the mine. Finally, support and transportation logistics for the mine operation need be optimized to ensure efficient and effective utilization of the selected resources.

DEVELOPMENT OF VACUUM PYROLYSIS TECHNIQUES

E. H. Cardiff[1] and B. R. Pomeroy[2], [1]NASA Goddard Space Flight Center, [2]NASA Goddard Space Flight Center / The Pennsylvania State University.

Introduction: In Situ Resource Utilization (ISRU) is key to our long-term exploration of space. A number of ISRU-related techniques have been developed at NASA Goddard Space Flight Center. In the case of the Moon, the *in situ* resources include the vacuum and the solar flux, as well as the regolith. The focus of the team has been on development of the vacuum pyrolysis technique for the production of oxygen from the lunar regolith. However, a number of related techniques have also been developed, including solar and resistive heating of regolith, regolith sintering, melting, and boiling, and instrumentation development.

Demonstrations: In early work, a process was developed to sinter, melt, and vaporize regolith simulants in a vacuum using a concentrated solar flux [1]. This prototype device was used to test several different types of lunar simulants (MLS1A and JSC1A) and other minerals (ilmenite) [1]. These tests demonstrated the ability ot use concentrated solar flux to vaporize the regolith and produce oxygen via vacuum pyrolysis.

After several iterations of the design, spectra of the evolved gasses were obtained and illustrated the production of oxygen. Other authors have demonstrated the production of gasses, but did not demonstrate that the gasses contained oxygen, although the presence of oxygen was inferred from models [2]. In addition to the mass spectrometry detection of oxygen, the temperatures required for melting and vaporization were substantially lower than expected.

Analysis: The vacuum pyrolysis reaction was modeled to better understand the observed phenomena. Modeling of the chemistry of the vaporization/dissociation was performed via minimization of the Gibbs free energy with the HSC analysis package. Results of the analysis are shown here in Figure 1.

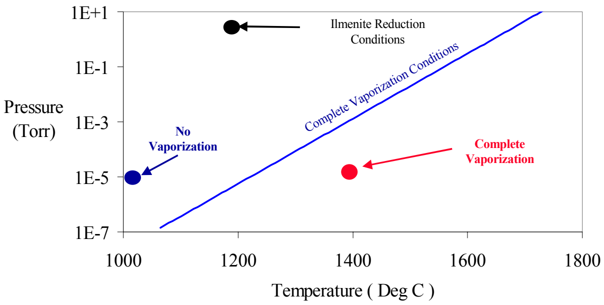

Figure 1. Conditions required to vaporize MLS-1A.

The temperature is significantly reduced at lower pressure, as shown by the curve in Figure 1 for the vaporization temperature of MLS-1A. The trends shown by the curve in Figure 1 were verified experimentally. Further description of these tests is given separately [3]. The tests (the data points in Figure 1) confirmed the trends for vaporization temperature.

Implications & Future Work: The reduced temperatures required to achieve vaporization at reduced pressures do not require the extreme heat made possible by direct solar heating. As illustrated in Figure 1, the temperatures approach those required for ilmenite reduction at lunar atmospheric pressures. For small amounts of regolith, such as those that would be obtained by a sample mission, it becomes feasible to heat the regolith resistively.

A new chamber has been designed to employ resistive heating to vaporize samples. The resistively-heated chamber derives much of its heritage from the Sample Analysis Module (SAM) on the Mars Science Laboratory. The SAM module is used to analyze the evolved gasses from pyrolysis of the martian regolith. SAM requires approximately 20W of power. The most significant difference between the two chambers are the pressures involved (SAM does not operate in vacuum), which drives the vacuum pyrolysis chamber to use more advanced materials. The resistively-heated chamber could easily be used for science applications (evolved gas analysis) on the Moon, as well as to demonstrate ISRU.

Conclusion: Vacuum pyrolysis has been used to demonstrate the production of oxygen in the laboratory. An experiment has been designed that could be used both as a scientific instrument and technology demonstration. Scaling up of the vacuum pyrolysis technique from this small-scale demonstration will require more power, and this is being examined with a 9.6 kW solar reflector and larger reactor design.

References: [1] E. Cardiff, B. Pomeroy, and J. Matchett, “A Demonstration of Vacuum Pyrolysis”, Space Resource Roundtable VII, October 2005. [2] Senior C.L., 1992, AIAA Space Programs and Technologies Conference, AIAA-1992-1663. [3] B. Pomeroy and E. Cardiff, “A Proof of Concept of Vacuum Pyrolysis”, Space Resource Roundtable VIII, October 2006.

CRATERS AND CHANNELS ON MALAPERT MOUNTAIN IN THE LUNAR SOUTH POLE REGION: CHALLENGES ASSOCIATED WITH HIGH-INCIDENCE-ANGLE IMAGERY.

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Introduction: Malapert Mountain[1] has been proposed as a location near the south lunar pole with the best conditions for line-of-sight communication with Earth, as well as nearly continuous sunlight[1]. Examination of currently-available images shows craters and channels of unknown origin near its peak, therefore Malapert Mountain is also of scientific interest.

Lunar Orbiter Data: Images of Malapert Mountain (85.5ºS, 0ºE) were obtained by the Lunar Orbiter IV spacecraft from May 17 through May 24, 1967 (Fig. 1a and 1b).

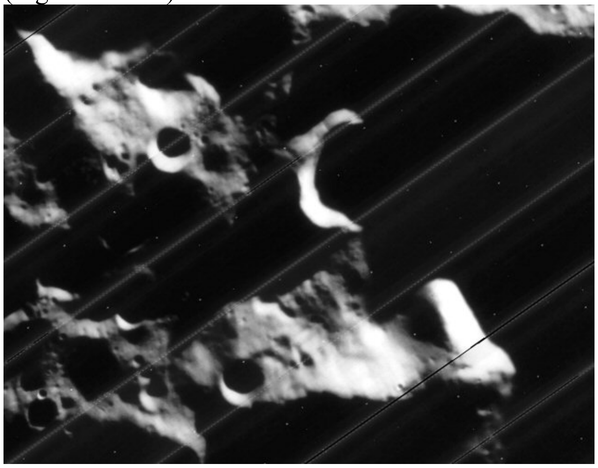

Figure 1a. Detail from LO IV 118 (1967/05/19), brightness and contrast stretched for clarity.

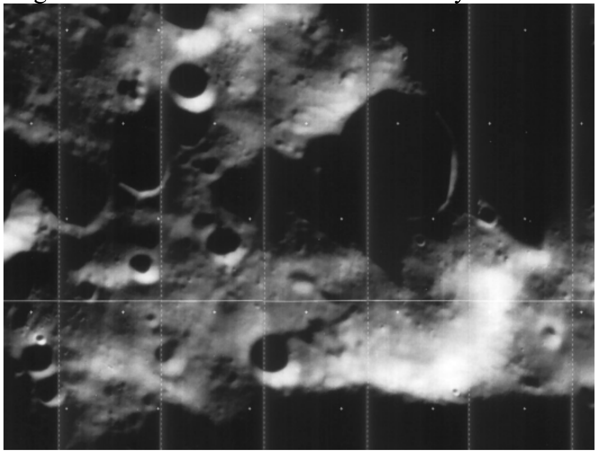

Figure 1b. Detail from LO IV 179 (1967/05/24), brightness and contrast stretched for clarity.

The incidence angle of the seven images studied ranges from 79.22º to 82.85º. Even though the changes in incidence and azimuth angle are small, the images show significant differences throughout the sequence.

A 7-km crater with a channel extending from it can be seen in the area west of Malapert Peak. Enlargements of this area are shown in Figs. 1c and 1d, corresponding to Figures 1a and 1b, respectively. The channel feature in the first image curves to the SE, whereas the channel in the final image is aligned ENE. It is likely that this difference is due to the slight changes in sun angle over the five days represented by the images.

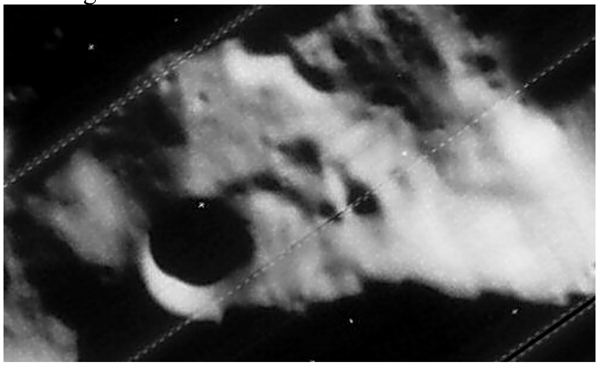

Figure 1c. Enlargement of crater at lower center of Figure 1a. Contrast and sharpness enhanced for clarity.

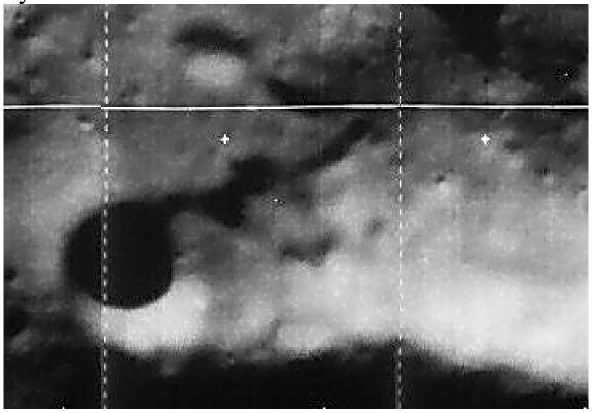

Figure 1d. Enlargement of crater as shown in Figure 1b. Contrast and sharpness enhanced for clarity.

Radar Data: A radar image of the area (Figure 2) was obtained from [2]. Textural differences are observed between the area nearest the crater and the area that is more distant. Mantling units exhibit low returns on depolarized 3.8-cm radar maps, indicating an absence of surface scatterers in the 1- to 50-cm-size range [3]. Mantling may be the cause of the change in texture which is observed in this area; however, the source of the mantling material is unknown.

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[1] Informal name given to this feature. It does not have a name assigned by the I.A.U.

Figure 2. Radar image (at 3.5 cm) of Malapert Mountain acquired in 1999, showing the crater and channel. Note increased roughness of terrain at the distal end of the channel.

Clementine Data: Clementine imagery from the Malapert Mountain area, acquired in 1994, is shown in Figures 3a and 3b. Figure 3a shows the ENE channel clearly, as does the radar image. The radar image and the Clementine image have a similar illumination angle to the final image in the Lunar Orbiter sequence (Fig. 1b).

The rationale for the standard Clementine multispectral ratio (false color) image processing of the Moon is described by [4]. The ratios employ 3 spectral wavelengths and combine these into a red-green-blue color image. This rendition and the wavelength ratios chosen serve to cancel out the dominant brightness variations of the scene (controlled by albedo variations and topographic shading) and enhances color differences related to soil mineralogy and maturity. The lunar highlands, mostly old (~4.5 b.y.) gabbroic anorthosite rocks, are depicted in shades of red (old) and blue (younger). The lunar maria (~3.9 to ~1 b.y.), mostly iron-rich basaltic materials of variable titanium contents, are portrayed in shades of yellow/orange (iron-rich, low titanium) and blue (iron-rich, higher titanium).

The Clementine ratio image for the Malapert Mountain area is shown in Figure 3b. Areas in shadow were masked out of this image, because the ratio information there is of dubious value [5]. However, the image information in the better-lit portions of the scene are likely to be accurate. The peak of Malapert Mountain displays dark blues and reds, indicative of highlands material. The ligher blue downslope could be due to (a) low light effects; (b) younger highlands material, or (c) high-titanium basalt. Interpretation (a) above seems most likely, because the lighter blue color appears not only on the lower slope of the peak, but also along the upper edge, where the light rapidly falls into shadow. Interpretation of the blue color is dependent upon context, and more information about morphology is needed in order to establish the geological framework.

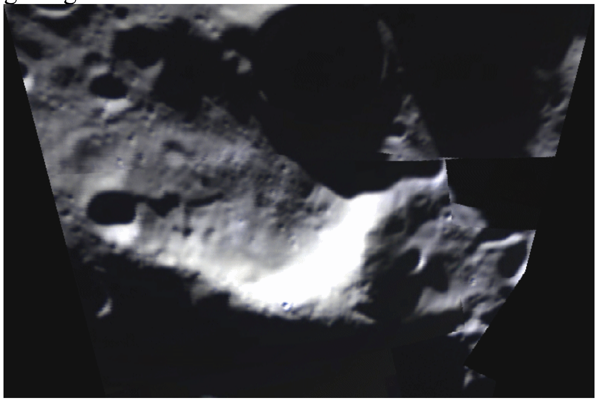
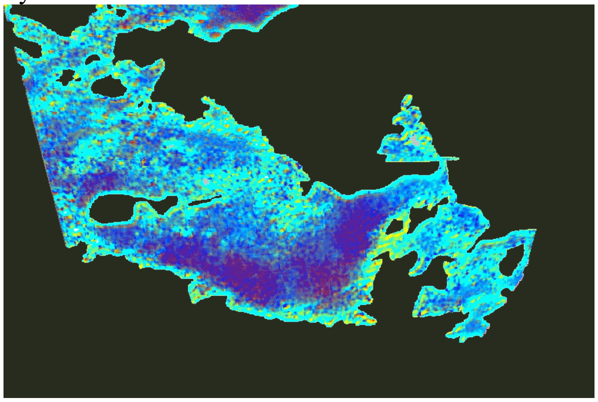


Figure 3a. Clementine color albedo image of Malapert Mountain. Brightness and contrast enhanced for clarity.



Fibure 3b. Clementine color ratio image of the Malapert Mountain area. Pixels with less than 30% brightness have been masked. See text for discussion.

Conclusions: It is too early to draw any conclusions from the available data. We await the Lunar Reconnaissance Orbiter to provide more and better information about this area. The DIVINER radiometer may detect temperature differences, which would suggest geothermal or volcanic activity. The Lunar Orbiter Laser Altimeter will provide improved information on the topography of the area, from which models can be constructed to understand how illumination angle and azimuth angle affect the appearance. The LAMP instrument will image the shadowed areas and give improved information on the overall morphology of the region. The Lunar Reconnaissance Orbiter Camera will provide meter-scale mapping over a two year period, which will show unambiguously how incidence and azimuth angles affect the appearance of features on Malapert Mountain.

References: [1] Sharpe and Schrunk (2002), *Space 2002*, 129. [2] Margot et al. (1999) *Science, 4,* 1658. [3] Gaddis et al. (1985) *Icarus, 61,* 461. [4] Pieters et al. (1994) *Science, 266,* 1844. [5] Lucey et al. (1998) *JGR, 103*, 3679.

COMPARATIVE STUDY OF ISRU-BASED TRANSPORTATION ARCHITECTURES FOR THE MOON AND MARS: LOX/LH2 vs. LOX/Methane.

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Introduction: Space exploration missions are dependent on large vehicles launched from Earth even when the payloads are small. Even though staging would increae the efficiency of missions to other planets and celectial bodies, the massive launch vehicles needed for the completion of such missions make them practically infeasible. If propellants can be produced and stored on the Moon, Mars, etc., the need for these massive systems disappears, making space exploration more feasible (technically and economically) and safe because redundant and emergency systems can then be created at lower costs and shorter times.

Background: Obviously, the availability of resources plays a mayor role as it does the performance of the current rocket engines. When studying the Moon and Mars there are two clear choices: oxygen/hydrogen, and oxygen/methane propulsion systems. We have chosen to use data from the Apollo missions to asses the availability of resources o the Moon and other data from NASA missions for the resources on the Moon and Mars, as well as other bodies. Table 1. provides an overview of the abundancy of resources on the Moon, Mars, and Phobos.

	Resource	Origin	Location	Abundance	Comments	Models
MOON	H_2O	Ice Deposits	Poles	~ 1.5% wt.	Hydrogen as water was assumed	1.0 % wt.
	H_2	Solar Wind	Everywhere	~ 50 ppm		50 ppm
	C	Solar Wind	Everywhere	~ 150 to 210 ppm		150 ppm
	O_2	Pyroclastic glass	Everywhere	~ 4% wt.		4 % wt.
MARS	CO_2	Atmosphere	Everywhere	~ 95% wt.		95 % wt.
	H_2O	Bound Water	Everywhere	~ 10% wt.		5 % wt.
	H_2O	Ice Deposits	Poles	Up to 90% wt.	Cover of dry ice during winter	0
PHOBOS	O_2	Carbonaceous chondrite	Everywhere	~ 12.6% wt.		12.6 % wt.
	C	Carbonaceous chondrite	Everywhere	~ 4.43% wt.		4.43 % wt.
	H_2O	Bound Water	Everywhere	~ 10% wt.	No ice considered	0

Table 1. Resource availability

The performance of oxygen/hydrogen rocket engines is superior to that of the oxygen/methane ones, but the technical difficulties for hydrogen storage and its impact on the mass of the architecture makes oxygen/methane propulsion systems attractive . Both options have been proven feasible for mission durations of a few months. Hopkins [1].

For a mission to the Moon with a small payload, the amount of material that needs to be moved and process on the Moon favores the oxygen/methane option as shown by Ruiz et al. [2]. In the case of a transportation architecture where reusable vehicles between the Moon and L1 are used, refueling at L1, the amount of methane to be produced is twice that of hydrogen, when a fixed payload is assumed. Should we choose to transport the oxygen from Earth and produce only the fuel in situ, the oxygen/hydrogen option proves to be better. However, if the oxygen and the fuel are to be produced in situ, the amount of material to be excavated is twice as much in the case of hydrogen (LOX/LH2) than in the case of methane (LOX/Methane). This advantages disappears if the ratio of the concentration of hydrogen to carbon is 2:3 or higher. Note that we have considered an equatorial location for this comparison (See Duke et al.[3]).

If we now consider a large scale lunar base or the propellant production capacity needed for a Mars reusable architecture, the only viable option is to use the hydrogen from the lunar poles, and therefore the LOX/LH2 choice is best.

Extensive research on these particular topics has been conducted at the Center for Space Resources in recent years, but we had not included the possibility of a reusable methane architecture. We have now compared the hydrogen and methane options under the reusability assumption.

References: [1] J. B. Hopkins (2005) *American Institute of Aeronautics and Astronautics AIAA 2005-6740* [2] B. Ruiz (2003) *Space Resources Roundtable V.* [3] Duke et al. (2004) *STAIF.*

SCIENTIFIC CONTEXT FOR THE EXPLORATION OF THE MOON: A National Research Council Space Science Board study. Michael B. Duke, Colorado School of Mines, (Center for Space Resources, 1500 Illinois St., Golden, CO 80401. mikeduke@earthlink.net.)

The National Research Council has been chartered by the NASA Science Mission Directorate to examine the opportunities for science that are embodied by the early period of lunar exploration in the Vision for Space Exploration. Scientific investigations will be an important part of the Vision, though not the driving force for exploration. NASA has requested that the NRC identify a prioritized set of scientific goals that can be addressed in the near term (~2006-2018) by robotic lunar missions and in the mid term (~2018-2023) by astronauts on the Moon. It has also requested that the NRC identify which scientific goals are most amenable to orbital measurements, in situ study, or terrestrial analysis via the return of lunar samples to the Earth. In addition to these primary goals, NASA also has requested the NRC to comment on those areas where there is a synergistic overlap between measurements addressing scientific goals and measurements required to ensure human survival; and collect and characterize possible scientific goals that might be addressed on or from the Moon in the long term (i.e., after ~2023). To constrain the study, NASA has asked the NRC to concentrate on the following topics: (a) The history of the Moon and of the Earth-Moon system; (b) the origin and evolution of the solar system, including the Sun; and (c) Implications for the origin and evolution of life on Earth and elsewhere in the solar system. Topics dealing with Earth observations and astronomy from the Moon, life sciences, and reduced gravity science on the Moon are not included. In order to undertake this study, the NRC has assembled a group of scientists with specialties in areas applicable to lunar science to gather information and prepare the report. An interim report has been delivered to NASA, which will be the baseline from which the study will evolve over the next year. This report will be available for comment by the scientific community.

Whereas NASA has limited the study to science, there are many places where lunar resource utilization and science have overlapping objectives. The Vision for Space Exploration includes a strong statement about the role of lunar resources. In order to carry the Vision out fully, the geological context, form, composition, and distribution of resources will have to be determined as well as the geomorphic and geotechnical properties of the lunar surface materials. These are typically also objectives for science, although levels of specificity may differ between science and applications requirements. The NRC and the committee solicits inputs on their study, including white papers describing key lunar science goals/opportunities suitable for implementation during the period 2006-2023; comments on the committee's interim report; and nominations for scientific and technical reviewers of the committee's final report.

TESTS OF THE UTILITY OF NEUTRON AND GAMMA RAY PROBES FOR RESOURCE PROSPECTING AND CHARACTERIZATION.

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Introduction: Future exploration of the Moon and Mars will include searching for in situ resources for living off the land, and assessing the ease with which such resources can be extracted and used. A key resource is hydrogen, especially in the form of water. So prospecting tools that detect and assess hydrogenous "ores" are needed before resource utilization can occur. Under NASA's Mars Instrument Development Program and the Exploration System-sponsored CRUX project we have developed instruments for *in situ* regolith resource assessment and characterization. Two neutron detectors, the Surface Neutron Probe (SNeuP) and the Borehole Neutron Probe (BNeuP) are designed to help locate and assess potential hydrogen-bearing deposits at the lunar poles and on Mars. Carried on a rover, SNeuP locates near-surface water or other hydrogenous materials in a lightweight (481 g) package. BNeuP determines the stratigraphy of hydrogenous subsurface layers to depths of 10 meters (or more if an integrated neutron source is used) while operating within a drill string segment. It weighs 517 g, and consumes 2.25 W. The instruments' heritage includes the Lunar Prospector neutron spectrometer and numerous programmatic space instrument applications at Los Alamos. We have tested the SNeuP and BNeuP prototypes and have demonstrated their ability to detect near-surface hydrogenous materials. One important application would be to assay near-surface water ice in permanently shadowed lunar polar craters such as Shackleton [1,2,3].

Surface Neutron Probe Testing: In October of 2005 we tested SNeuP's ability to detect near-surface deposits of 3- and 10-wt% H_2O in the Army Corps of Engineers Cold Regions Research Engineering Laboratory (CRREL) in Hanover, New Hampshire. Deposits with diameters of 25, 50, and 100 cm were buried at depths of 30, 15, 5 and 0 cm. The soil used in the test was silica-rich with a minor contribution from micaceous minerals. When dried the soil moisture content was 0.1 wt% H_2O, and the hydrous mineral contribution was equal to 0.39 wt% H_2O. The entire setup was cooled to -40° C for the tests, and a stepper-motor-driven sled carried the SNeuP instrument and neutron source across the test area. A map of the icy deposit layout is shown in the top panel of Figure 1.

By compiling the traverses (15 in all), we can bin the count rate data spatially and create a map of the HeSn (thermal + epithermal) neutron count rates. This is shown in the second panel of Figure 1. Separate measurements of epithermal and thermal neutrons permit determination of relative depth and water equivalent hydrogen abundance, as shown in the lower two panels of Figure 1. In a realistic lunar surface scenario, in which cosmic rays generate the neutrons and the overburden has <0.5 wt% H_2O, depth sensitivity of 70 cm or more can be achieved

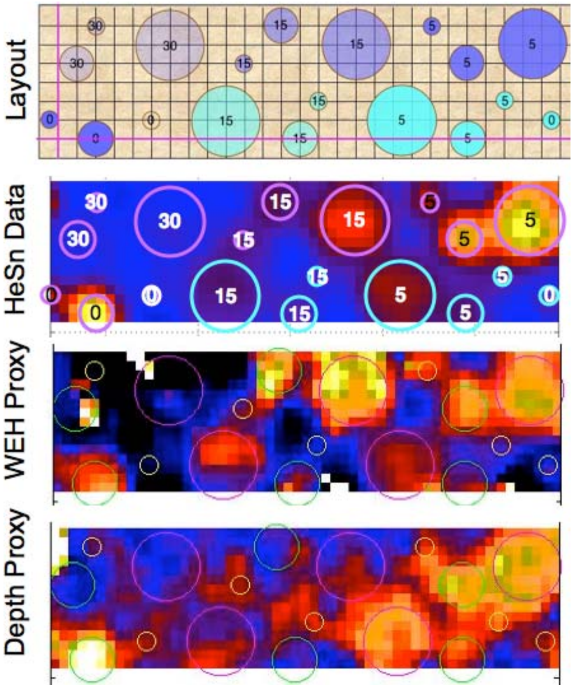

Figure 1. (1) Map of icy deposits and burial depths. Cyan and purple outlines denote 3 and 10 wt% H_2O, respectively. (2) HeSn count rates binned and smoothed using a gaussian with a 26-cm full-width at half-maximum. Icy deposit outlines are superimposed; numbers indicate depth of burial in centimeters. (3) and (4) show proxies for abundance and depth of burial.

Borehole Neutron Probe Testing: LANL and Honeybee Robotics have developed an experimental borehole setup for BNeuP. The drilling system is laid on its side and the BNeuP tool is advanced horizontally through blocks of dry limestone sandwiching layers of a target material. The test series was aimed at understanding the instrument's response to various thicknesses of polyethylene layers (polyethylene is a good proxy for water ice), and sensitivity to detection of hydrous minerals.

Figure 2 shows data from a subset of the tests. Test 1 (top panel) shows a log of BNeuP advancing through two 30-cm deep blocks of limestone and through a 15-cm thick layer of poly (light blue). The count rate rises to ~100 count/sec when the source, situated some 20 cm 'above' the detectors, enters the limestone. The peak counting rates are seen when the detectors are in the middle of the poly layer and the neutron source is above the layer. A local minimum in count rate is seen when the thick poly acts as a shield for source neutrons. When the source itself is in the layer and the detectors are below, a maximum number of neutrons are thermalized. A second peak is seen because some of these additional neutrons leak out and are detected. Test 5 shows the detection of a very thin seam (0.6 cm thick) of poly – a very large increase in thermalized neutrons is seen. Note that the ratio of thermal to epithermal neutron count rates places bounds on the vertical extent of the resource; less total hydrogen results in fewer thermal neutrons. Finally, the bottom panel shows a BNeuP log of a 15-cm thick layer of crushed gypsum. The signature of gypsum's enhanced hydration ($CaSO_4 \cdot 2H_2O$) is seen. Moreover, details of the count rate profile, epithermal-to-thermal ratio and peak thermal count rate provide clues on the vertical extent and quality of the "ore."

Conclusions: The instruments perform as designed, providing both localization and an assessment of "ore value," in terms of total hydrogen present. The neutron probes complement other *in situ* and remote sensing prospecting techniques in providing comprehensive situational awareness for mapping and decision making, both for surface operations and for drilling.

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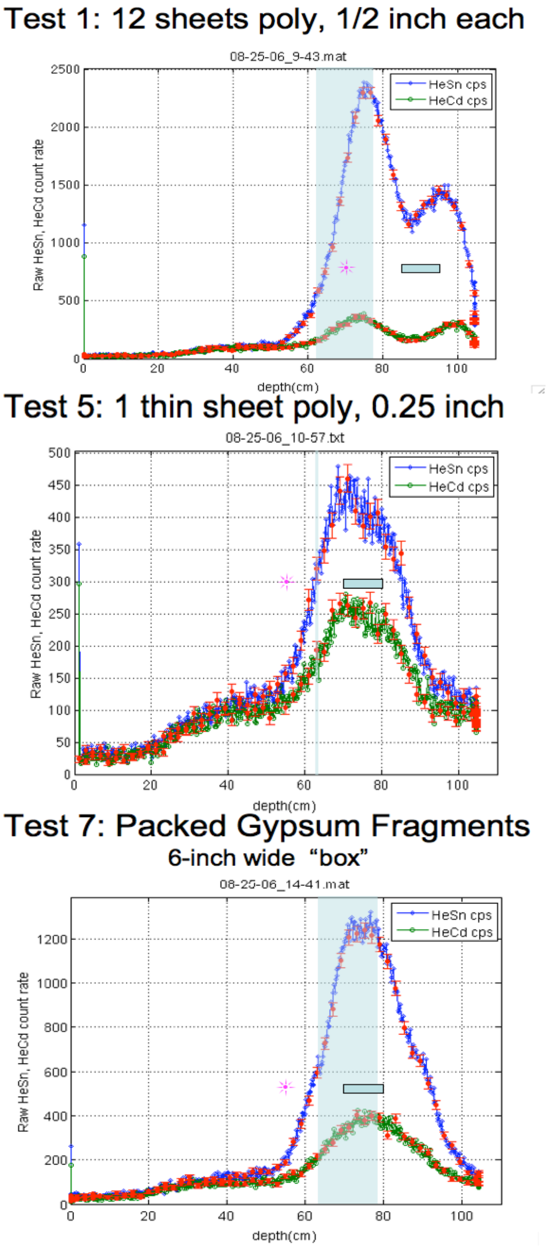
Test 1: 12 sheets poly, 1/2 inch each

Test 5: 1 thin sheet poly, 0.25 inch

Test 7: Packed Gypsum Fragments

6-inch wide "box"

Figure 2. Three BNeuP borehole tests. (top) Log of a 15-cm thick layer of polyethylene (proxy for water ice) sandwiched between dry limestone blocks; (middle) Log of a thin layer (0.6 cm thick) of poly between limestone blocks; (bottom) Log of a 15-cm thick layer of crushed gypsum.

Advanced Ultra High Displacement Compressor Technology for Space Industrialization as an Economic Tool for Space Exploration. Burt Lorren Fraser, 1998 S. Devinney St, Lakewood, CO 80228 (blfer1960@yahoo.com) Paul Larson, and Brett Weichers.

Introduction:

ARDL is in the process of developing new piston based devices which focus on being able to concentrate heat energy (as much as possible) and be able to use this heat energy as a co-generating power source thereby increasing the potential efficiency of the overall piston device. ARDL has concentrated on the Positive Displacement Piston design(s) because of it's vast technological history and proven wealth of development. We at ARDL believe that it has the most potential to help mankind in his journey to the moon and beyond.

ARDL is a small company dedicated to bringing about nothing less than a revolution in the field of Positive Displacement Piston Systems and Devices. ARDL has named the technology UHC-PCE [Ultra High Capacity – Pump(s), Compressor(s), and Engine(s)]. These combined Pumps, Compressors and Engines (or power input devices) will be able to run at standardized electrical industrial RPM speeds. We believe that today's material and micro-thermal technology revolution will allow our smaller sized positive displacement designs to do the same work of machines that are physically much larger. These large machines which, at this time, have no way of being economically transported into the realm of Space. ARDL's future devices will allow for smaller, cheaper, reliable piston based system modules which will be able to cooperatively combine both functions and applications in interchangeable modules. It is the interchangeability of these piston based modules which will allow piston based designs to do the equivalent work of machines much larger than ARDL's technology. Consequently, these designs will allow feasible industrial strength devices which are fiscal and economical for transport into the Realm of Space. This will greatly increase the potential of space resource industrialization and utilization to further the exploration of space. This, we believe, will initiate the beginning of the Space Industrial Economy thereby making space exploration economically and humanly viable.

Approach:

We will discuss both the design of the technology and potential applications. Advanced Rotary Division of Labor ARDL/LLC has a technology to build positive displacement Multi-Staged piston devices which will significantly reduce the size and weight of any compression design in use. These devices cover aerospace, terrestrial, and marine vehicles, and industrial manufacturing systems. Furthermore, multi-staged compression devices will have a significant impact on the cost of pumping and compressing materials (fluids and gases) for industries and manufacturers. Currently, companies in these markets design specific units for each different application. ARDL believes that it could commoditize this market to a modular unit design fits-all applications market. This method of unit modules unseats the present need for many pump and compressor designs to be manufactured into a system built by skilled labor. Currently these machines are very expensive in both materials (a large amount of materials are needed for manufacturing --- sometimes several tons) and long lead times for engineering and testing are often required. Such a design will have a significant impact on the markets in both application, function, and monetary terms. ARDL is the only company in the world which can provide multi-staged UHC-PCE units which are small and simple in mechanical design and operate at conventional output shaft speeds. We know of no other company investigating and researching this. Positive displacement piston machines are pumps, or compressors, or engines which use pistons to pump, or compress, or expand (positively displace) a material (working fluid). ARDL has a design which can combine positive displacement piston functions (pumping, compressing, or power input -- engines) into one unit.

Positive displacement piston machines are pumps, or compressors, or engines which use pistons to pump, or compress, or expand (positively displace) a material. ARDL has a design which combines positive displacement piston functions (pumping, compressing, or power input -- engines) into one unit. ARDL is calling the design UHC-PCE (Ultra High Capacity -- Pump, Compressor, Engine) Technology.

For instance:
Under normal conditions on the earth compressors are designed to function under what are known as ambient temperature-pressure loads. Heat generated from the compression of materials is considered to be a nuisance, something to be gotten rid of by venting the

excess heat into the atmosphere. This is not possible or practical in space.

Energy used in space cannot be wasted. This energy also needs to be used in a closed loop system. If at all possible, this heat energy should be used and re-used to its fullest extent. This means building a system in which a working fluid, in a closed loop system, cascades downward so that every last energy potential can be used.

ARDL's design is all about maximizing energy use potential: utilizing the available heat energy to perform real work in a closed loop steam cycle. The steam cycle can then cascade downward until the working fluid phase-changes from a steam back to a fluid. The process is then repeated over and over again.

ARDL has the ability to build such machines and incorporate an internal co-generation system to the compressor design WITHOUT increasing the mechanical complexity of the overall design/machine. Furthermore, we have the ability to do this in a modular system.

The modular system can be described as follows:
The Purpose of a piston is to provide linear reciprocative positive displacement for:
1. power input -- in the form of an expanded gas (be it burned or otherwise), or
2. fluid/gas movement -- in a pumped or compressed form.
These pistons can lay either in a Radial direction (perpendicular to the central axle), or Axial direction (parallel to the central axle).

The device consists of apparatus (cams) for converting rotary motion (Central Axle) to linear reciprocating motion (pistons) to rotary motion (cams), back to linear reciprocating motion (pistons) for displacement. This is accomplished by using Toroidal , Orthogonal Camed device(s).

The machine consists of:
The Central Axle:
This is the central core of the unit. Everything else inside the unit is built around the central axle. The central axle can be used in two different ways:

1. The central axle can be used to put power into the unit by coupling a shaft to it to provide rotary input power.
   Or,
2. The central axle can be used to take power out of the unit by coupling a shaft to it. The unit is then used to provide primary power to the shaft.

It all depends on how the user wants to configure the unit for use.

Figure #2 shows an example of the unit:

Figure #2

This design allows for a higher concentration of displacement area (i.e. Piston surface area) available to do work in the form of a pumped and/or compressed fluid than anything previously invented.

Displacement
The design's output is determined by:

$$\underset{\text{FOR RADIAL PISTONS}}{\text{PI} \times R^2 \times \text{SL} \times \text{S\#} \times \text{C\#} \times \text{RPM}} + \underset{\text{FOR AXIAL PISTONS}}{\text{PI} \times R^2 \times \text{SL} \times \text{S\#} \times \text{C\#} \times \text{RPM}} = V$$

Where:
PI=Pi, R = Radius Squared, SL=Stroke Length Height,
S#= The number of Strokes per turn of Cam,
C#=The number of Piston Cylinders (Radial or Axial),
RPM=Revolutions Per Minute, V=Volume.

In addition any of the pistons can be arranged by adding "Banks"- (or Modules) of pistons (Axial or Radial) for any application. As long as these working fluids are NEVER allowed to come in contact with one-another.

Additionally:
Many applications and examples of applications will be discussed --- to numerous to list here.

AUTONOMOUS DRILLS FOR PLANETARY SUBSURFACE ACCESS.

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Introduction: Drilling is arguably the most fundamental technique for exploring the unaltered in situ characteristics of any planetary subsurface [1]. While terrestrial drilling technologies are very mature and widely used in industry and science, extraterrestrial drilling experience is limited to the Apollo and the Soviet Luna and Vega missions. The lack of extraterrestrial drilling on more recent missions points to the difficulties of drilling in the environments of other planetary bodies. While providing some valuable experience in dealing with harsh drilling environments, the relevance of the Apollo, Luna, and Vega heritage to future drilling missions is limited because, in the case of Apollo, the ~ 500 Watt drill was human operated and, in the case of the Soviet drills, they had ample mass (~ 5000 kg) and power. High mass allows for a high reaction force on the drill bit (referred to as weight-on-bit or WOB) and high power translates into high drilling torque. Future robotic drilling missions to Mars or the Moon will not have the benefit of either high mass or power. (e.g. ~180 kg for MER and 500 kg for MSL). The key to drilling under these conditions lies in the automation capability, which must take into account all environmental and engineering performance parameters experienced by the drill and make “smart” decisions to mitigate faults that arise.

Honeybee Robotics, in partnership with NASA Ames Research Center (ARC), has developed two “sister” drills which have proven all of the necessary technologies for fully autonomous drilling. These drills were developed under the Mars Instrument Development Program (MIDP) as part of the Mars Analog Rio Tinto Experiment (MARTE)[2] and Drilling Automation for Mars Exploration (DAME) [3] projects.

The DAME Drill: The DAME drilling project focused on autonomous software for “smart” drilling. The drill itself has a fairly basic design (See Figure 1), with a simple mounting stand and motor controlled rotation (of the auger and drill bit) and vertical movement of the drill head. The DAME drill uses a full-faced bit for a primary cutting tool as its main focus is drilling, as opposed to sample collection. Deep drilling is accomplished by manually adding extra lengths to the drill string. Sensors in the drill, of most importance to the automation software, allow for the measurement of position and velocity of the drill head, total drilling torque, cutting torque, WOB, and bit temperature. The automation software was developed over a three-year period, with field tests at the end of each year. Field tests were conducted in Haughton Crater on Devon Island in the Canadian High Arctic. This particular site was selected because the impact breccia in this location is permeated with ground-ice and is currently in a relatively arid periglacial environment similar to what Mars is presumed to be like [4].

Figure 1 The DAME Drill.

The DAME control system consists of three hierarchical levels. The lowest level, the drill controller, is responsible for controlling actuators and force levels, protecting actuators and sensors, and passing sensor and actuator information to the next higher level. The second level consists of three modules. The Vibration Classification Module, developed and operated by Prof. Hanagud of Georgia Tech uses laser vibrometers to assess the operational state of the drill. The rest of the DAME drilling software was developed by NASA Ames. This includes the Model Based Diagnosis, which compares the sensor data to a nominal model of drill operations and the Rule Based Diagnostic module, which compares the magnitude and duration of certain sensor signals to a set of pre-defined thresholds. Information from all three second layer modules is evaluated and weighed by the highest level controller, the Contingent Executive. Based on criticality and past predictive performance of the diagnostic systems, the Contingent Executive determines whether drilling is proceeding normally, or whether a fault has occurred. If a fault is detected, the Executive selects a fault recovery procedure corresponding to the highest weighted probability. During all operations, the Contingent Executive also monitors and controls the low level Drill Controller.

At the conclusion of the third field test in July, 2006, the DAME control software was successful at identifying all six identified faults, and autonomously recovering from five of the faults [5]. The drill also operated for four continuous hours with no human intervention, including the successful identification of, and recovery from, a fault. Over the course of this field test, the drill, operating at a controlled limit of 110 W of power, penetrated through very challenging material to a final depth of 3.2 meters (a new Devon Island record).

The MARTE Drill: Complementary to DAME, the MARTE drilling project focused on autonomous capabilities for manipulating and assembling drill strings and for handling samples, but did not perform “smart” drilling. MARTE is also a coring drill, designed to capture core samples of rock. As such, it is more complex mechanically than DAME (See Figure 2), consisting of a drill platform, an indexed system for storing and manipulating ten one-meter long drill sections, and a system for capturing and transferring subsurface cores. In August of 2005, the MARTE drill was tested at a Mars analog site near Rio Tinto, Spain.

Automation for the MARTE drill focused on three major tasks. The first of these tasks was the automated assembly of drill strings. Secondly, the drill system had to be able to autonomously break and capture a 20 cm core. Finally, the drill system had to be able to hand the captured sample off to a core analyzing system.

In a six week field test, the MARTE system penetrated to a depth of 6.1 meters in clay and rock (Tuff, and Gossan) and was able to autonomously assemble and disassemble the drill tubes numerous times. Software for controlling the assembly of the drill tubes was robust enough to identify slight hardware misalignments which would prevent the drill strings from locking properly. The MARTE software also uses a hierarchical system. The Drill State Machine (DSM) has three levels of commands. The lowest level is concerned with basic movement and position of system components, the mid level with commands such as “add drill string” or “remove drill string” and the high level with commands such as “drill”, “break core sample”, or “retrieve core.” The same Contingent Executive that is used on the DAME project is also used for organizing and issuing the highest level commands to the DSM, as well as other systems that are beyond the scope of this paper. When a command is received from the Executive, i.e. “drill” or “break core”, the drill software is responsible for executing the high-level command, which in turn generates the necessary mid- and low-level commands.

Other functions of the drill control software enabled the drill to autonomously break, capture, and handoff cores with great success. Also, the software was able to identify situations where portions of the core would bind the mechanism within the core barrel and prevent the core from extruding from the core barrel properly.

Conclusion: Fully autonomous, low-powered drills for planetary exploration are now a reality, as demonstrated by the development of the DAME and MARTE drill systems. As a combined unit, these systems have demonstrated the ability to drill successfully with low power and low WOB, autonomously construct and deconstruct drill strings, capture and deliver cores, and identify and recover from faults during the drilling process. Although these two drills were highly successful, further development and testing are necessary to prove that such a drill system is flight worthy. A primary advance in capability should include the development and testing of a single drill which fuses the technologies demonstrated by the DAME and MARTE drills.

Figure 2 The MARTE Drill.

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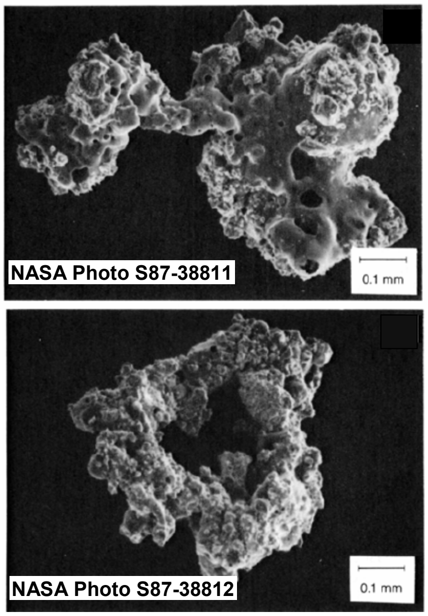
DEVELOPMENT OF A LUNAR AGGLUTINATE SIMULANT. Robert Gustafson[1], Brant White[1], Marty Gustafson[2], and Dr. John Fournelle[3] [1]Orbital Technologies Corporation (ORBITEC), 1212 Fourier Drive, Madison, WI 53717, gustafsonr@orbitec.com, [2]PLANET LLC, [3]University of Wisconsin-Madison.

Introduction: ORBITEC is developing a process to create agglutinate-like particles from various materials, including JSC-1 lunar regolith simulant. The ultimate objective of this work is to develop a large-scale production process that can be applied any lunar regolith simulant material to create agglutinate-particles that exhibit many of the unique features of lunar agglutinates. If successful, this process will significantly increase the fidelity of the existing and future lunar regolith simulants.

Definition of Lunar Agglutinates: Agglutinates are individual particles that are aggregates of smaller lunar regolith particles (mineral grains, glasses, and even older agglutinates) bonded together by vesicular, flow-banded glass. Lunar agglutinates have many unique properties, including: (1) a highly irregular shape, (2) presence of trapped bubbles of solar wind gases (primarily hydrogen) that are released when the agglutinates are crushed, (3) heterogeneous composition (due to the presence of individual regolith particles), and (4) the presence of metallic iron (Fe^0) droplets that are often very fine grained [1].

Importance of a Lunar Agglutinates: Agglutinates, shown in Figure 2, make up a high proportion of lunar regolith, about 50%wt on average, although their abundances may range from a rare 5%wt to about 65%wt. Agglutinates contain an appreciable amount of metallic Fe^0 in their glass. Two competing hypotheses regarding the mechanism of formation of Fe^0 are currently being debated. The prevalent hypothesis holds that Fe-bearing phases (e.g., ilmenite) in the agglutinitic melt are reduced by the solar wind hydrogen implanted in soil grains [2]. The other hypothesis contends that the Fe^0 forms from dissociation of Fe-bearing phases in a high-temperature (e.g., >3000 C) vapor produced by impacts followed by condensation of Fe^0 globules on the surfaces of exposed grains in lunar soils [3].

Currently, the only widely available lunar regolith simulants (JSC-1 and JSC-1A) contains few particles that match the shapes and morphologies of lunar agglutinates [4]. The presence of agglutinate particles will have a significant impact on the mechanical properties of the lunar regolith/simulant. The geotechnical properties that are most affected by the agglutinate particles include:



NASA Photo S87-38811

NASA Photo S87-38812

Figure 1. Examples of Lunar Agglutinates

Shear Strength: The particle shape and intragranular porosisty have a profound influence on the shear strength of the lunar regolith. Under the low confining pressures found on the surface of the Moon, the highly irregular and reentrant agglutinate particles tend to interlock and produce unusually high shear strength [1].

Compressibility: Lunar regolith is more compressible than current simulants due to the crushing of agglutinate particles under load [1]. The compression index and recompression index can be used to measure this property.

The mechanical properties of the lunar regolith change significantly based on the history of the regolith. High applied loads can cause many of the agglutinate particles to be broken into smaller particles. This is not true of current lunar regolith simulants. In addition, the presence of agglutinate-like particles with "nanophase" Fe^0 globules will significantly affect some of the thermo-physical properties of the simulant (including the absorption of microwave energy).

Current Status of the Lunar Agglutinate Simulant Development: Past efforts at producing synthetic agglutinates included plasma melting of MLS-1 lunar regolith simulant. This technique was evaluated using an in-flight sustained shockwave plasma (ISSP) reactor at the Mineral Resources

Research Center at the University of Minnesota. This testing concluded in products with unreacted mineral fragments, massive globular glass, and vesicular glass in a variety of textures that resemble some of the glassy components of lunar regolith. However, it failed to produce analogs of lunar agglutinates [5].

ORBITEC is currently developing two different methods to create agglutinate-like particles. Both methods attempt to mimic the fusion of individual grains that is observed in lunar agglutinates. The goal is to produce agglutinate-like particles that exhibit as many of the unique properties of lunar agglutinates as possible. Preliminary results are very promising, with the agglutinate-like particles having the same general size and shape as lunar agglutinates. Figure 2 shows some examples of the agglutinate-like particles produced by ORBITEC using JSC-1 lunar regolith simulant. Note how individual grains are bonded by in glassy melt regions.

When the surfaces of the agglutinate-like particles are examined closely, numerous "nanophase" Fe^0 globules can be seen (see the bright spots in Figure 3). Note how the Fe^0 globules tend to form in "trains" in both lunar agglutinates and the agglutinate-like particles. At least 50% of the Fe^0 globules in lunar agglutinitic glass are entrained in flow lines and many smaller globules occur in clusters. Approximately 99% of the Fe^0 globules in lunar agglutinates have a diameter of 1 µm or less [6]. In the agglutinate-like particles analyzed so far, the Fe^0 globules range is size from 10's of nanometers up to about 2 µm in diameter. The same Fe^0 globules have been found extending into the glassy melt regions. Energy dispersive spectrometry (EDS) and wavelength dispersive spectrometry (WDS) have verified that the iron globules are nearly pure Fe^0 and not iron oxide.

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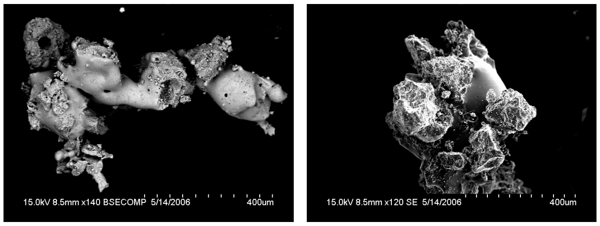

Figure 2. Examples of Agglutinate-Like Particles Produced by ORBITEC

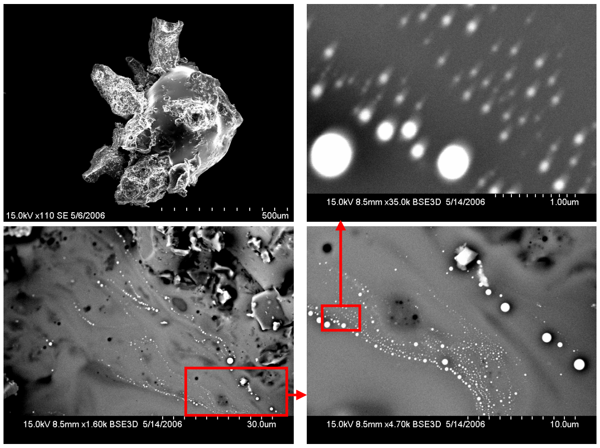

Figure 3. Nanophase Iron Globules on the Surface of an Agglutinate-Like Particle

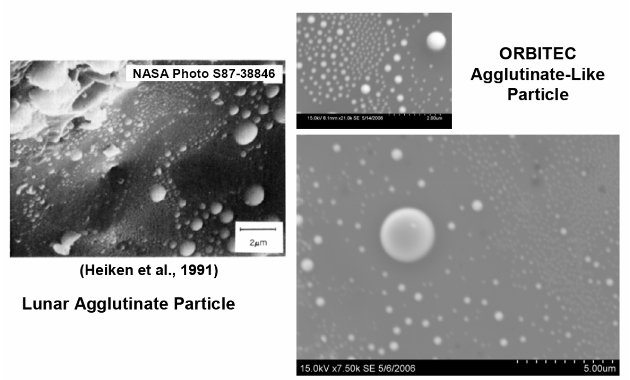

Figure 4. Comparison of Iron Globules on the Surface of a Lunar Agglutinate (left) with an ORBITEC Agglutinate-Like Particle (right) [Note that images are sized to the same scale]

LUNAR ELECTRIC FIELDS AND DUST: IMPLICATIONS FOR IN SITU RESOURCE UTILIZATION.

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Introduction: Although the lunar environment is often considered to be essentially static, it is in fact very electrically active. Measurements from the Lunar Prospector spacecraft imply lunar surface electrostatic potentials as large as 5 kilovolts during extreme space weather events. Surface electrification likely also affects dust, with observations from the Apollo era indicating transport of lunar dust to altitudes of ~100 km, and acceleration of charged dust grains to speeds of up to ~1 km/sec near the lunar terminator. Electrified dust grains can adhere to machinery, and large electric fields could also directly affect machinery.

All astronauts who walked on the Moon reported difficulties with lunar dust. These problems were likely worsened by the fact that the dust was electrically charged, enhancing its adhesive properties. Electrified dust is likely to have similarly significant effects on any machinery operating for prolonged periods in the lunar environment. Characterization of lunar surface charging and dust electrification and transport is therefore an important step in preparing for serious in situ resource utilization efforts.

Lunar Electric Fields: The surface of the Moon charges in response to currents incident on its surface, and is exposed to a variety of different charging environments during its orbit around the Earth, with charging currents spanning several orders of magnitude. On the sunlit hemisphere, photoelectron emission usually dominates, ensuring a small positive surface potential. On the night side, however, plasma currents dominate, and the lunar surface charges to a negative potential on the order of the electron temperature (typically ~50-100 V in the solar wind wake and magnetospheric tail lobes). See Fig. 1.

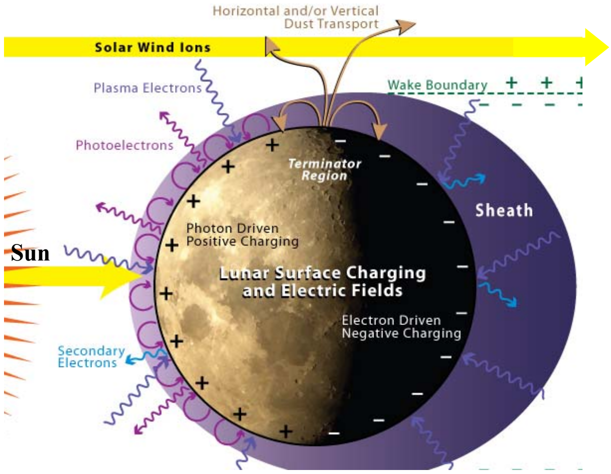

Figure 1: Schematic of lunar electric field environment (not to scale).

Apollo data placed some constraints on lunar surface potentials [1,2,3,4], and recent measurements by the Lunar Prospector (LP) spacecraft [5,6,7,8] have also added to our knowledge of lunar electric fields. Typical lunar nightside potentials are on the order of ~50-100 V negative. However, during some time periods surface potentials can reach much higher values. When the Moon is immersed in the energetic and turbulent plasma of the terrestrial plasmasheet, negative surface potentials of several kV have been observed [6]. Meanwhile, surface potentials as large as -5 kV have been observed during extreme space weather events. Our knowledge of the lunar electrostatic environment is still limited, though, especially in terms of how electric fields and dust are coupled.

Lunar Dust Transport: Dust is a significant component of the lunar environment that may affect both human health and system reliability [9, 10]. This was made apparent by the discovery of "lunar horizon glow" and "streamers" at altitudes of 10-100 km from orbit during the Apollo missions [11,12] and, more recently, Clementine [13]; as well as photographic evidence of levitated dust at much lower altitudes (<1 m) from the Surveyor 1, 5, 6, and 7 spacecraft [14]. Simple electrostatic levitation may explain some low altitude observations. Dynamic dust motion ("lofting"), on the other hand, may be required to explain observations of high altitude dust concentrations [15].

The Apollo 17 Lunar Ejecta and Meteorite (LEAM) experiment, meanwhile, though designed to measure hypervelocity micrometeorite impacts, instead mostly detected lower velocity (<1 km/s) dust impact, especially near the terminator regions [16]. These data provide compelling evidence for significant horizontal and vertical charged dust transport, raising the spectre of a "dusty sleet" which may persist for days at the surface each month near local sunset and sunrise. The effects of such accelerated dust on ISRU machinery should be carefully considered.

Lunar Dust Properties: Dust is defined as the finest component of the regolith (<100μm). The average lunar regolith grain size is ~70μm (too fine to see with the human eye), with roughly 10-20 weight percent smaller than 20μm [17]. The dust component from Apollo samples contains some grains as small as 0.01μm [18]. Grain shapes are highly variable and can range from spherical to extremely angular; with grains commonly somewhat elongated [19]. The sharp "barbed" shapes of many dust grains enable efficient mechanical adhesion to surfaces.

The low electrical conductivity of the regolith allows individual dust grains to retain electrostatic charge [19], thereby ensuring that the large lunar surface electric fields described above should result in significant dust transport.

Dust Adhesion and Abrasion: During the Apollo missions, dust adhering to spacesuits was a significant problem. Mechanical adhesion was likely due to the barbed shapes of the dust grains, which allowed them to work into the fabric. Alan Bean noted that "…*dust tends to rub deeper into the garment than to brush off*" [20]. Electrostatic effects due to charging of dust by photoionization, plasma current, and/or triboelectric effects likely only exacerbated this situation. It was found that the abrasive effect of adhered dust can wear through the fabric of a spacesuit, drastically reducing its useful lifetime [20, 21].

Problems were also experienced during Lunar Roving Vehicle (LRV) excursions, with dust being kicked up and covering exposed areas, leading to increased friction at mechanical surfaces [19, 21]. The resulting abrasive effect of dust increases wear and tear, significantly limiting the lifetime of surface equipment.

From the recovery and examination of parts from Surveyor 3 during Apollo 12, it was found that dust accumulation and adhesion were greater than anticiapted on both aluminum and painted surfaces [19].

When considering ISRU opportunities, which may require operation of machinery for long periods of time on the lunar surface - machinery which may itself be kicking up large amounts of dust during normal operation – it is therefore important to consider the abrasive effects of dust over time.

Necessary Measurements: So far, most observations of lunar electric fields and dust electrification and charging have been obtained from experiments not specifically designed to address this problem. To fully understand the coupled dust-plasma system around the Moon, it will be necessary to perform specific targeted measurement. Necessary measurements include:

1. Directly measuring electric fields, plasma parameters, and the mass, velocity and charge state of dust grains above the lunar surface.
2. Measuring lunar electric fields as a function of altitude, selenographic location, solar illumination conditions, and plasma conditions, and correlating these observations with dust measurements.
3. Determining the size and concentration of dust as a function of altitude, etc. in the lunar exosphere.

Conclusions: The lunar electrodynamic environment is complex, with plasma, electric fields, and dust tightly coupled. To date, few targeted measurements of this coupled system have been perfomed and our understanding is limited, especially regarding dynamical effects. However, dust is likely to have significant effects on ISRU efforts, particularly since it can become electrified and get accelerated. Therefore, an important step in preparing for ISRU is to close this gap in our knowledge and fully characterize lunar surface charging and dust electrification and transport.

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Development of a Lunar Water Astroparticle Observatory Using In Situ Resources

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Introduction: Astroparticle observatories have over that past 30 years contributed immensely to the knowledge of high-energy physics and origin of the universe. There remain, however, important gaps in parts of the electromagnetic spectrum when observing ultra-high energy gamma and cosmic rays from Earth. In the next decade and beyond, it has been proposed, amongst others by Spillantini [1], that this gap in observational data be closed by "water observatories" deployed on the Moon, where interference from the Earth's atmosphere and magnetosphere would no longer hamper measurements. Such water observatories would be deployed at the lunar North and South Poles by use of lunar In-Situ resources, which would encompass excavation of basins, lining of the basins with arrays of scintillation detectors, filling of basins with water, and collecting data. These observatories will consist, initially of an excavated basin 10m x 10m x 10m in size, to be filled with 1000 metric tons of water from the in-situ resources at the Polar Regions. The water basin would be constructed by fabrication of cavities out of the lunar regolith, which would be lined with a waterproof material containing scintillators, and then filled with water extracted from the adjacent permanently dark crater regions. These permanently dark regions are believed to contain water (ice) at a 1% to 5% concentration level. This water would be extracted by evaporation under microwave heating of the regolith. The microwave heating would be done with a localized source rastered over the ice field in a crater. The evolved water vapor and other gases would be captured, followed by condensation of the water vapor and storage/sorting of the other gases. The condensed water would be transported to the detector basins, and would fill the basins, which would then be covered/sealed to prevent evaporation to the Moon's environment. The energy for the construction of the cavity detectors and the water extraction would come from solar cell arrays fabricated on the surface of the moon from In Situ resources, and emplaced at the permanently lit regions of the Poles. The arrays would be integrated into an electric power system that would supply energy for the microwave melting of the ice, for the motive power for the cavity excavation and, later, for the operation of the detector and measurement systems deployed in and around the water observatory and for the processing and the transmission of the data to Earth.

[1] P. Spillantini, Moon Base Conference, Washington, DC, Oct 12, 2006

CRUX II: Mapper-Decision Support System Project. J. B. Johnson[1], R. Bates[2], E. S. Berney IV[3], R. Elphic[4], B. J. Glass[5]; R. B. Haehnel[2], S. Taylor[2]; [1]USA ERDC-Cold Regions Research and Engineering Laboratory, PO Box 35170, Ft. Wainwright, AK, 99703, Jerome.B.Johnson@erdc.usace.army.mil; [2]USA ERDC-Cold Regions Research and Engineering Laboratory, 72 Lyme Road, Hanover, NH, 03755; [3]USA ERDC-Geotechnical and Structures Laboratory, 3909 Halls Ferry Rd., Vicksburg, 39180-6199; [4]Space Science and Applications, Los Alamos National Laboratory, Los Alamos, NM 87545; [5]NASA Ames Research Center, Moffett Field, CA 94035-1000

Introduction: The success of future lunar and planetary surface operations (LPSO) will depend on identifying optimal sites for in situ resource utilization (ISRU), construction, environmental management, and surface mobility. LPSO requires knowledge of local surface relief and roughness, geotechnical properties and the concentration and distribution of resources.

We are in the first year of the CRUX II project to develop geographical information system (GIS) based display (Mapper) and decision support system (DSS) analysis tools to characterize regolith resources, surface conditions, and geotechnical properties.

The CRUX II is a scaled-down continuation of the Construction and Resource Utilization eXplorer (CRUX) project [1]. The CRUX was a NASA technology maturation project for the *Exploration Systems Research and Technology Program, Exploration Systems Mission Directorate* to provide critical technology for a return to the Moon and later planetary exploration. The CRUX project consisted of an integrated modular suite of instruments (Prospector-Surveyor) combined with Mapper) and DSS analysis tools (Figure 1) [1].

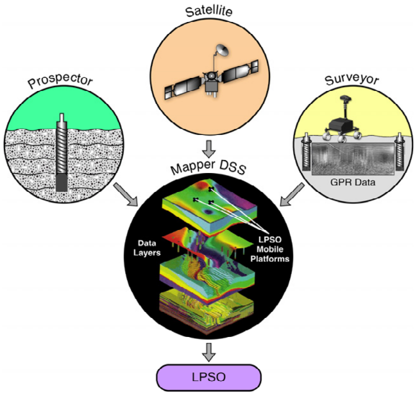

Figure 1. The CRUX architecture.

While development of Prospector/Surveyor instruments associated with the CRUX were eliminated from the CRUX II, the core Mapper-DSS was retained under the NASA's ISRU Projects Office.

CRUX II Architecture: The Mapper-DSS is a tool that will allow engineers and astronauts to combine measurements from resource prospecting missions with existing lunar and planetary data to plan and conduct LPSO. Mapper-DSS is a service-oriented approach for acquiring, managing, analyzing and disseminating near real-time geospatial data. The CRUX II Mapper-DSS architecture is shown in Figure 2.

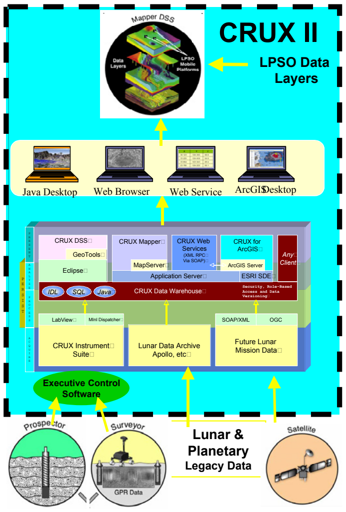

Figure 2. CRUX II Architecture.

We are still formulating the principal technical Principal technical components and requirements of the Mapper-DSS may change, but the general architecture will likely remain the same. It will consist of data input modules (shown at the bottom of Figure 2), data handling and DSS modeling modules at the data warehouse level. Several different user (clients) interaction capabilities will be used to produce desired data layer products. An executive controller will interface with instruments that perform surface measurements through a yet to be defined database structure.

Anticipated clients include a Java desktop application built upon the Eclipse framework that provides high-level computing capabilities. A web-based Mapper-DSS interface will provide the broadest possible audience access to data visualization and analysis tools. The web-based system, which is currently under development, will support geographic display and analysis of program data, and the display and query of models processed through the decision support system.

The delivered products from Mapper-DSS will be a series of science-based engineering guidelines and data interpretation protocols implemented in software. Engineering scenarios developed as needed by astronauts and engineers will drive these guidelines. As an example we consider the need to determine the concentration and distribution of ice and hydrogen (prospecting) in the polar lunar regolith (or only hydrogen elsewhere).

CRUX II Development Approach: We use the hydrogen prospecting engineering scenario incorporating integrated data collection and data fusion to guide and test the Mapper-DSS (Figure 3) [2].

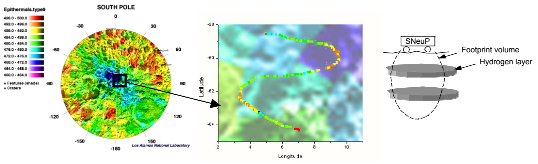

Figure 3. CRUX II hydrogen prospecting scenario showing Lunar Prospector satellite data (a) used by the Mapper-DSS to identify a region of interest for prospecting (b) with Surveyor instruments. The measurement footprint volume of a surface neutron probe over a hydrogen rich region is shown in (c) and hydrogen enhancement is shown along a Surveyor track in (b). These data would be used with other surface measurement data to characterize geotechnical properties, surface features, and the distribution of the resource (hydrogen in this scenario).

This process ingests legacy data for the moon from Apollo missions and satellites. The scenario also incorporates realistic synthetic data from hypothetical prospecting mission instruments to ensure seamless data fusion between different data types and to develop useful data retrieval and DSS capabilities.

Summary and status: The CRUX II team is in the process of setting project requirements and building preliminary Mapper-DSS capabilities. We have a WEB site containing preliminary lunar base maps. Selected Apollo 17 data, lunar geology, digital elevation maps and Lunar Prospector Orbiter data is being ingested. We are examining ways to develop flexible and interactive lunar base map displays and are asking the lunar science community and the terrestrial mining community for advice to help guide our effort. We encourage participants of the Space Resources Roundtable to help define data, data retrieval, and DSS capabilities that would be useful to the ISRU community.

A unique feature of this project is the ability to make available new Mapper-DSS capabilities rapidly since initial offerings will be browser based and later applications will be Java application based. The Java applications will be readily downloaded for local use with WEB-based data access.

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Introduction: Thar's gold in them thar hills!! We know it's there but we aren't quite sure where it is.

The Exploration Systems and Mission Division of NASA plans to develop In-Situ Resource Utilization (ISRU) technologies for the exploration of the Moon, Mars and beyond. It has been frequently suggested that in-situ resources might be beneficially used to provide consumables for astronaut survival (esp. oxygen and water), propellant for return vehicles (e.g., LOX, LCH_4, H_2), radiation shielding (using regolith covers and berms), and even to produce metals and ceramics for spare parts and solar photovoltaic cell substrates. These suggestions imply that if we can reduce the need to take all of the necessary supplies for a mission from Earth, there will be a net gain to a mission in terms of reduced Earth-launch mass, enhanced exploration duration, or the possibility of enabling long-term colonization. Initially, ESMD plans to focus on ISRU development for lunar applications.

Implementation of ISRU obviously requires in-situ resources of the type and composition that will be useful in satisfying an ISRU objective. The engineering design of equipment to gather and process in-situ resources requires some detailed knowledge of both the qualitative and quantitative analysis of the resources of interest. Analysis of the lunar samples returned by the Apollo and Luna exploration missions provided a wealth of qualitative and quantitative data about the mineralogy and the relative chemical composition of lunar surface regolith at different lunar locations. The Lunar Source Book provides a very detailed synopsis of the results of qualitative and quantitative analyses of those lunar samples. Table 7.15 in the Lunar Source Book lists the chemical compositions (wt%) of average soils at lunar landing sites. The soil is made up almost entirely of oxides of Silicon, Aluminum, Iron, Calcium, Titanium and Magnesium with small amounts of oxides of Sodium, Chromium, Manganese, Potassium and Phosphorus. Table 7.16 lists the major and minor element abundances (wt%) in bulk lunar soils as analyzed in five different particle size fractions (bulk, >90 µm, 20-90 µm, 10-20 µm, and <10 µm) to illustrate how the composition is distributed by particle size.. Table 7.17 lists the trace element abundances (parts per million) in bulk soils separated into size fractions analogous to Table 7.16. Tables A8.1 through A8.6 provide statistical summaries of lunar chemistry including data showing the very small concentrations of solar-wind implanted elements (H, C, N He, Ne, Ar, Kr, and Xe).

The major thrusts of the current NASA ISRU development program is to develop processes that can extract oxygen and volatiles from the lunar regolith. Various processes for extracting oxygen are under consideration but all of these processes face the daunting thermodynamic task of breaking the oxide bond by either electrolysis, hydrogen reduction or carbothermal reduction (with either CH4 or CO). The volatiles of interest are primarily considered to be solar-wind implanted gases hydrogen, helium and nitrogen which hypothetically can be released (desorbed) by heating the regolith up to 700°C. The products of these various processes are intended for use as propellants (O2, H2), consumables (O2, N2, H2O), nuclear reactor fuels (He-3) or reactants for intermediate processing (primarily H2 for reduction of oxides to form H2O which is subsequently electrolyzed to form H2 and O2; secondarily H2 to react with CO2 to form CH4 which is recycled in the carbothermal process).

Any lunar outpost that involves permanent or near-permanent human presence will require a significant amount of water for drinking and domestic use. Previous studies by JSC and others have estimated a water requirement of 10 kg/day per crew member for short term stays and 28 kg per day per crew member for long term stays. Assuming that it is possible to recycle up to 80% of the water (a fairly bold assumption), there would still be a water make-up requirement of about 6 kg/day per crew member. For a crew of four, for 365 days, the water make-up requirement would be at least 8760 kg, or nominally about 10 MT. If water recycle capability is limited or non-existent, about 40MT/yr would be needed. But the analyses of the lunar samples returned from the Apollo and Luna missions indicate that there is no trace of indigenous water in the lunar regolith. If water is not found on the moon, then the water requirement would need to be satisfied by deliveries from Earth at a cost that would clearly challenge the overall viability of a long-term manned base on the lunar surface. Therefore, it becomes clear that prospecting for and finding water on the moon are necessary precursor requirements for enabling a long-term manned lunar base.

The neutron spectrometer on the 1998 Lunar Prospector mission indicated that there was a higher concentration of elemental hydrogen in shadowed craters near the lunar poles than there was at other areas on the lunar surface. One would suspect that if the presence of hydrogen was due solely to solar-wind implantation then the concentration of hydrogen in the regolith would appear to be relatively uniform at all locations on the lunar surface. Since the Lunar Prospector neutron spectrometer data indicated that the hydrogen concentration was anything but uniform, it was then hypothesized that the permanently shadowed craters at the lunar poles were acting as 40 K cryotraps effectively freezing and containing any H2O molecules that may have found their way to the poles by molecular motion. These H2O molecules are thought to have originated from comet and meteor impacts on the lunar surface over millions of years. Because of the Lunar Prospector findings, it has been argued that it is important to send lunar landers and rovers to the shadowed lunar craters to collect "ground truth" data that can yield the unambiguous determination of the form of hydrogen (water ice, solar-wind implanted hydrogen, hydrates, organics, ammonia, etc.) that may exist in the permanently shadowed polar lunar craters and at what concentration and distribution (i.e., are there concentrated pockets of water ice, or is the water ice resource uniformly distributed throughout the crater). We must prospect for the mere presence of water and then analytically assay the content of the water once/if it's found. We also must map the area that has been prospected to provide a qualitative and quantitative basis for making subsequent decisions regarding the suitability of a particular site for constructing a long-term lunar outpost based upon the presence and quantity of water that is available at each particular site surveyed. Therefore, collecting "ground truth" data primarily for establishing the presence and concentration of water ice and/or solar-wind implanted hydrogen should be an initial and primary focus of the lunar ISRU program.

What are the tools needed to provide the water/hydrogen prospecting, assaying and mapping function? First and foremost, a neutron spectrometer is needed to measure the presence and relative concentration of elemental hydrogen at a particular site. Ideally, the neutron spectrometer would reside on a lunar rover and would be used as the first mode of prospecting for locating relatively high concentrations of elemental hydrogen. At locations of high hydrogen concentration, microscopic images and Raman spectrographic analyses of core samples would provide data regarding the form of the hydrogen detected by the neutron spectrometer (water ice, solar-wind implanted hydrogen, hydrates, organics, ammonia, etc.), along with an indication of how these hydrogen-bearing materials are distributed as a function of depth from the lunar surface. It has been hypothesized that it could be possible that there might be subsurface layers of water ice that are continuous over relatively large areas. In locations where water ice is located, a ground-penetrating radar (GPR) system could be used to first characterize the signature at that location. By comparing GPR readings at contiguous sites, the uniformity of the subsurface structure can be mapped. This mapping can yield important information that can help establish the boundaries of subsurface water ice fields if they exist. Knowledge of these boundaries can be used where to delineate regolith excavation activities for optimum recovery of available water ice resources.

Resource prospecting is the act of methodically and qualitatively searching for a particular resource of interest. For ISRU purposes, we would first prospect for the presence of water ice and solar-wind implanted hydrogen. Resource assaying is the act of analytically determining the composition of the desired resource in the bulk material once a resource containing a relatively high concentration has been found. For ISRU purposes, we specifically want to know the wt% of water ice and solar-wind implanted hydrogen as a function of depth below the lunar surface. Resource mapping is the act of providing a data base of resource composition as a function of location and depth. With the resource maps we can determine the best and most viable potential location for situating a long-term lunar outpost. By structuring a program that combines prospecting, assaying and mapping into a cohesive effort, we will maximize our chances of finding water and enabling the possibility of establishing a long-term manned outpost on the moon.

Excavation System Comparison: Bucket Wheel vs. Bucket Ladder.

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Introduction: the Vision for Space Exploration [1] calls for sustainable exploration and presence in space. For that reason NASA is looking into In-Situ Resource Utilization. This includes the equipment to mine and handle regolith. Tradestudies [2] have shown that two of the most efficient ways to excavate regolith are the bucket wheel and bucket ladder type excavators. This paper will compare the two types with respect to excavation metrics (e.g. production rate, power usage) in different types of simulant materials.

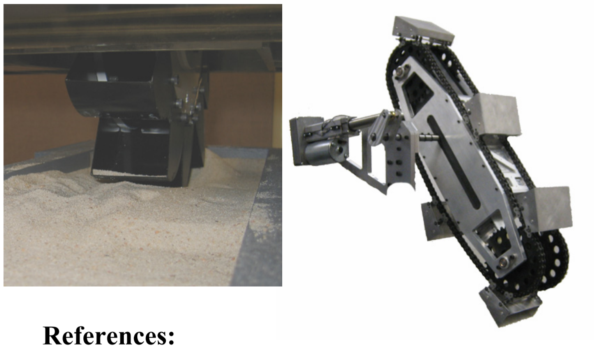
Bucket Wheel System Description: On Earth large scale mining systems often use bucket wheel excavators in combination with a transportation mechanism (e.g. conveyor belts). On the Moon the bucket wheel is beneficial because the digging forces pull the excavator down and allow for a lighter design of the mobility platform. A disadvantage of the bucket wheel system is that the wheel only digs, another system is required for transportation of the dug up material to the processing location. Because the scaling of large terrestrial systems to small scale planetary rover type systems is very difficult a prototype was built at CSM to test the small scale excavator system. The bucketwheel was designed to dig up 50 kg/hr and has 5 cm wide buckets that are mounted on a wheel of 20 cm diameter. The wheel is mounted on the end of a swinging boom that allows for vertical as wel as lateral translations of the bucket wheel boom. [3,4]

Bucket Ladder System Description: the bucket ladder is also based on a large scale terrestrial mining system that usually involves many cables. The lunar adaptation of this system consists of a rigid frame around which the chains circulate which eliminates the need for the use of cables but limits the length of the ladder. The buckets are directly mounted on the chains. The force directions for the digging part are very similar to the bucket wheel but the bucket ladder has the advantage that it also transports the excavated soil to another system (e.g. a dump reservoir or a hopper or even directly into the processing unit). The rigid frame is connected to an arm that connects the ladder to the mobility platform and allows the bucket ladder to be placed in various positions.

Study setup: Tests were conducted to compare the efficiency and excavation metrics of both excavation systems. A testbed was built that consists of a moving tray filled with different types (e.g. sand, cohesive material) of simulant materials for the different tests. Because the excavation systems were rigidly mounted, the tray could move to simulate forward motion of the mobility system.

Study results: results from the tests with the two different excavation systems will be presented and a comparison will be made. To compare the two systems some normalization is required. Power consumption, excavation rate and efficiency in the different materials will be presented for both systems.

Future work: future work will consist of integrating the excavation systems onto a mobility platform with a control system that allows tele-operation as well as autonomous operation. Further tests will be conducted with other types of materials such as ice-containing sands and lunar simulants. Improved prototypes are being planned and a study towards the effect of dust contamination on the machinery and operations will be done. Despite mitigation measures there will be intrusion of dust in the sensitive areas over time. A study to the speed of intrusion of dust and the effect on the machine efficiency is planned as well.



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DEVELOPMENT OF NEW LUNAR SOIL SIMULANTS IN JAPAN

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Introduction: Studies for developing various systems, devices and tools to be applied for lunar exploration missions in the near future are becoming active these days. Most of these studies require lunar soil simulant to investigate influences of lunar environment and to find the best solution for designing systems to be operated on lunar surface. The lunar soil simulants, such as MLS-1, JSC-1, and FJS-1 have been developed and used for these purposes up to this point, but they are almost out of stock now.

The FJS-1 was developed in Japan in 1995. This material was produced by crushing basaltic lava obtained from Mt. Fuji area, and well simulates bulk mechanical properties and approximates chemical composition of Apollo samples in lunar mare region. However, it contains very small amount of glasses, which may affect the chemical behaviors in ISRU processes. In addition to this, our next mission to the Moon could be performed in or near lunar highland region. Under these circumstances, we decided to develop new simulants.

Goals: Goals of our new simulants are as follows;

1. The simulants meet the regional needs, not only simulating mare soils but also highland soils.
2. The simulants are used for various purposes, not only mechanical studies but also chemical process studies.
3. The simulants are used internationally as one of the standard simulants.
4. The simulants are quickly supplied to investigators with reasonable amount and price.

Criteria for the Selection of Raw Materials: The most important process of developing simulants is the selection of raw materials. In this process, we put following criteria.

1. The materials, which approximate bulk chemical composition of lunar mare or highland soils. These materials are used as base (root) material of the simulants.
2. The materials, which contain pure minerals. They are used as additives of the simulants.
3. The materials, which are available to produce enough amounts of simulants.

Selected Raw Materials: Various possible materials were surveyed, and some of the samples were evaluated by fluorescent X-ray spectrometer analyses followed by the FeO determination (ISO 9035) tests, EPMA modal analyses, and particle density tests. So far, we have selected following materials as possible raw materials of new simulants.

As base materials:
- Bytownite (Minnesota)
- Albite (Norway)
- Labradorite (Madagascar)
- Anorthosite (Stillwater complex)
- Basalt (Hawaii)
- Basalt (Izu-Oshima, Japan)
- FJS-1 (Basalt / Mt. Fuji, Japan)
- Gabbro (Kohyama, Yamaguchi, Japan)
- Bytownite (Mexico)

As additives:
- Forsterite (Arizona)
- Forsterite (South California)
- Forsterite (Horoman, Hokkaido, Japan)
- Forsterite (Pakistan)
- Bronzite (California)
- Enstatite (Norway)
- Ilmenite (Australia)

Some of the samples are shown in Figure-1.

Bytownite (Minnesota)

Basalt (Oshima)

Gabbro (Kohyama)

Figure-1: Sample of the Obtained Raw Materials

Evaluation of Raw Materials: The selected raw materials were further evaluated by comparing chemical contents of SiO_2, TiO_2, Al_2O_3, MgO, CaO, Na_2O, and K_2O in the raw materials with those in Apollo samples. The factor R was calculated as a deviation of the material from Apollo samples [1]. The smaller R indicates better simulation.

$$R = \sqrt{\frac{\sum_{i=1}^{7} (Li - Ci)^2}{7}}$$

where, Li: Content of #i component in the Apollo sample, Ci: Content of #i component in a raw material.

Recommended Raw Materials: If a single material represents the simulant, following materials were recommended based on the factor R.

Apollo-11: Basalt (Hawaii), R=4.705
Apollo-12: Basalt (Hawaii), R=2.826
Apollo-14: Anorthosite (Stillwater), R=1.951
Apollo-15: Anorthosite (Stillwater), R=2.907
Apollo-16: Bytownite (Minnesota), R=3.941
Apollo-17: Gabbro (Kohyama), R=3.400

If the simulant is produced by mixing different raw materials, a better simulant can be obtained from the view point of chemical compositions as shown in Table-1.

Table-1: Recommended Mixture of Raw Materials

Mix Proportion: wt%	Bytownite (Minnesota)	Forsterite (S. California)	Forsterite (Pakistan)	Ilmenite (Australia)	Anorthosite (Stillwater)	Gabbro (Kohyama, Japan)	R
Apollo-11		1		18	81		1.336
Apollo-12				10	81		1.591
Apollo-14				5	76	19	0.737
Apollo-15		9		6	85		1.220
Apollo-16	87		8	5			2.728
Apollo-17			4	12	84		1.616

Table-2 shows recommended mix proportions of lunar mare and highland soils determined from the view point of modal abundances. In these cases, each raw material was first divided into mineral components, and then designed to have the same modal abundances of Apollo samples.

Table-2: Recommended Modal Abundances

(Mix Proportion: wt%)	Ilmenite (Australia)	Anorthosite (Stillwater) / Plagioclase	Basalt (Izu-Oshima, Japan) / Glass	Gabbro (Kohyama, Japan) / Olivine	Gabbro (Kohyama, Japan) / Opx	Gabbro (Kohyama, Japan) / Augite	Total
Mare	8.5	15.5	56.5	2.5	6.5	10.5	100
Highland	0.5	42.0	51.5	2.0	3.0	1.0	100

Future Works: New lunar soil simulants are now being produced from the raw materials obtained in this study. Simulating properties in the first stage will be the same as the FJS-1, i.e. bulk mechanical properties such as density, particle size distribution, and shearing strength. In the next stage, we will try to simulate agglutinates and grain level properties.

Conclusions: An analytical study on the raw materials for the new lunar soil simulant was conducted, and possible materials were selected on the basis of chemical compositions and modal abundances. The bulk mechanical model will be available soon, while the agglutinate models will be developed in the next year.

[1] Kanamori, H, et al., (1998), ASCE, Space 98, 462-468.

LOAD-SETTLEMENT CHARACTERISTICS OF JAPANESE LUNAR SOIL SIMULANT IN PARTIAL GRAVITY.

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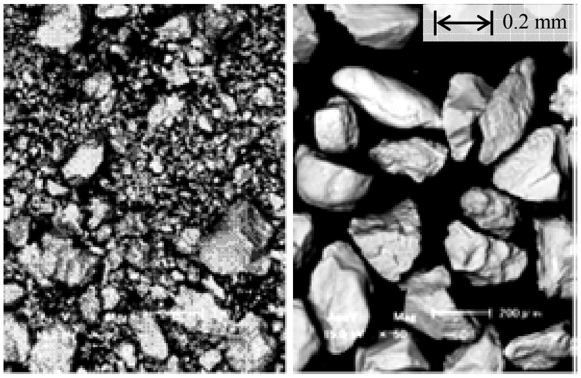
Introduction: From a viewpoint of the geotechnical engineering, predictions of lunar soil behaviors are of fundamental importance in evaluating the feasibility of lunar surface operations. This paper attempts to examine the effects of gravity on load-settlement characteristics of a shallow foundation through model tests in variable gravity conditions. This study is expected to be a pioneer work that provides a fundamental knowledge of regolith-structure interaction characteristics in reduced gravity environment.

Materials and Test Conditions: Two kind of oven-dried sands; the Japanese lunar soil simulant (FJS-1) and Toyoura sand were used. The lunar soil simulant is a terrestrial-based soil that mimics real lunar soil characteristics, including chemical composition, density, grain size distribution, and shear strength [1], while the Toyoura sand is widely used as a standard sand in geotechnical studies in Japan. **Fig. 1** shows SEM photographs of the materials. It can be seen that the grains of the FJS-1 exhibits very rugged and irregular shapes, while the surface textures of the Toyoura sand are comparatively smooth and the grains are chipped and rounded. Physical properties of the materials are listed in **Table. 1**.

Table.1 Physical Properties of the Materials

Soil property	FJS-1	Toyoura sand
Maximum bulk density, ρ_{max} (g/cm^3)	1.49	1.34
Minimum bulk density, ρ_{mim} (g/cm^3)	2.02	1.64
Maximum void ratio, e_{max}	0.46	0.62
Minimum void ratio, e_{min}	0.98	0.98
Soil particle density, ρ_s (g/cm^3)	2.95	2.65
Effective grain size, D_{10} (mm)	0.014	0.21
Mean grain size, D_{50} (mm)	0.10	0.26
Coefficient of uniformity, U_c	11.43	1.33
Coefficient of curvature, U_c'	1.30	0.98
Cohesion, c (kPa)	6.54	3.89
Friction angle, ϕ (degree)	51.2	39.4

The materials were compacted in soil boxes (W:400, H:160, D:50 mm) by a vibrator to give the relative density of 90 %. A model footing (Breadth, B = 20 mm, Length, L = 50 mm, base: rough) made of aluminum was penetrated to the model ground surface with constant loading rate of 3.0 mm/s. **Fig. 2** shows a schematic view of the test apparatus. The loading tests were conducted under variable gravity conditions (0, 1/6, 1/2, 1, 2G). **Fig. 3** shows a flight locus and the gravity variation during the parabolic flight maneuver. As shown in the figures, the partial gravity is kept for about 20 seconds with a convex track. Gravity components for airframe-axis, G_x and wing-axis, G_y are almost zero, therefore, it is unnecessary to concern for the effects of the flight posture.



(a) FJS-1 (b) Toyoura sand

Fig. 1. SEM Photographs of Grains

Test Results and Discussions: **Fig. 4** shows examples of load-settlement relationships obtained from the model tests. The FJS-1 exhibited the higher ultimate

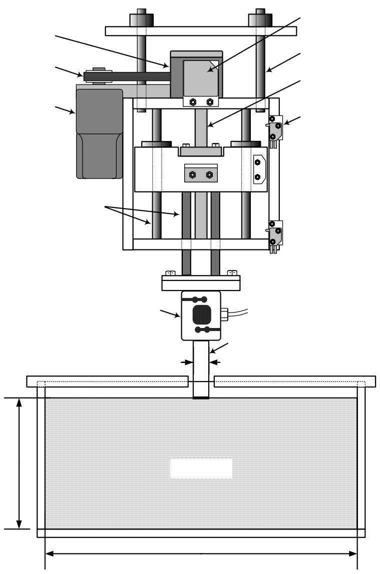


Fig. 2. Test apparatus

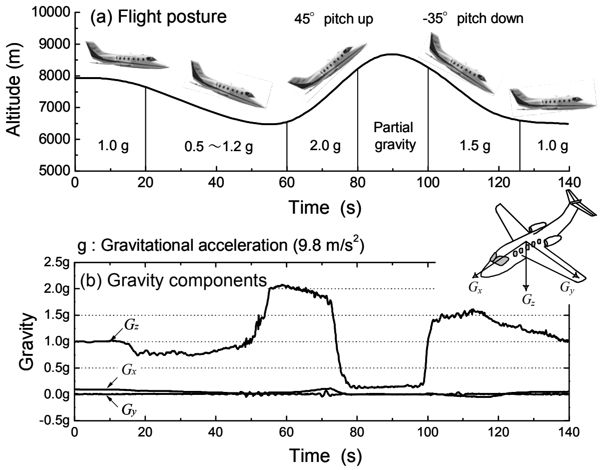


Fig. 3. Parabolic Flight and Gravity Variations

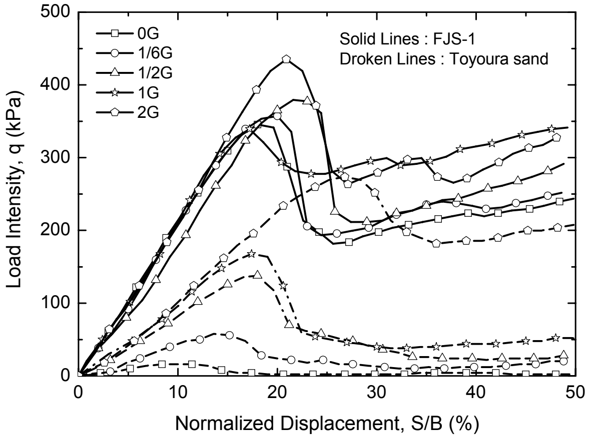


Fig. 4. Load-settlement Relationships

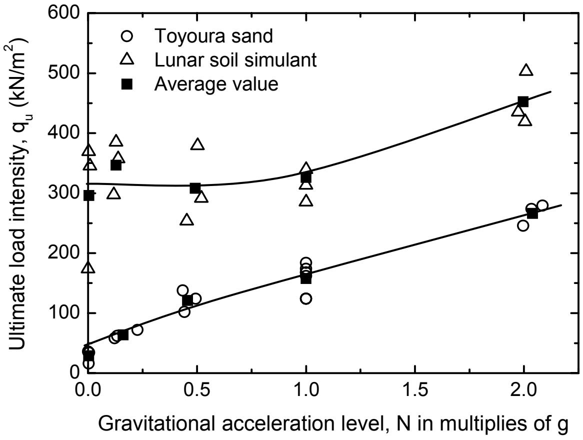


Fig. 5. Ultimate Load Intensity versus Gravitational Acceleration Level

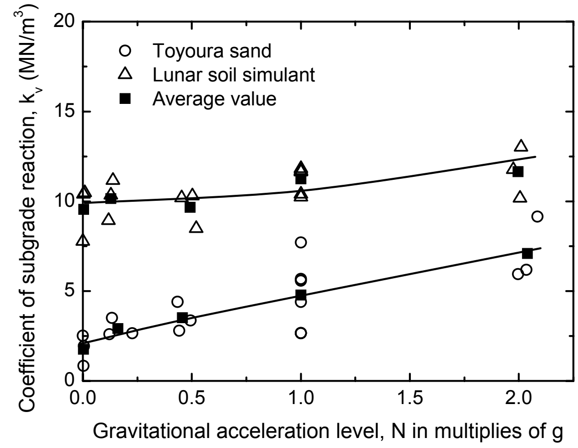


Fig. 6. Subgrade Reaction versus Gravitational Acceleration Level

bearing capacities (peak values) than the Toyoura sand. After the peaks, the more drastic drops are seen in case of the FJS-1 compared to the Toyoura sand. This implies that a densely packed lunar soil offers highly shear resistance but exhibits brittleness. Relationships between the ultimate bearing capacity, q_u and the gravitational acceleration level, N are given in **Fig. 5**. It can be seen that the gravity is reflected in q_u of the Toyoura sand, while the FJS-1 seems to have less effect when the gravity is smaller than 1g. **Fig. 4** shows the effects of gravity on the coefficient of subgrade reaction, k_v. It can be seen that k_v of the FJS-1 is larger than that of the Toyoura sand, and the effect of the gravity of the FJS-1 is comparatively small.

From a visual observation of soil behaviors through the front of the soil boxes, differences in the failure mechanism were seen between the materials. In the case of the Toyoura sand, slip surfaces generated in the model grounds immediately the model footings penetrated into the ground surface. On the other hand, in the case of the FJS-1, the compression process was seen for a little while and then the slip surfaces generated. The authors believe that this difference of the failure process results in the presences of the gravity effects as shown in **Fig. 5** and **6**. As a general rule, compressibility of the ground is determined by soil conditions and it is independent of the gravity. Therefore, q_u and k_v of the FJS-1 were mainly governed by the compression process even in the densely packed states. Consequently, the classical bearing capacity analysis based on the plasticity theory may not applicable to the lunar soil behavior predictions. Hereafter, the authors intend to develop an analytical framework for the bearing capacity problems on lunar surface.

Acknowledgements: This study is carried out as a part of "Ground Research Announcement for Space Utilization" promoted by JAXA and Japan Space Forum, and the authors are grateful for this support.

References:[1] Kanamori, H., Udagawa, S., Yoshida, T., Matsumoto, S., and Takagi, K. (1998). *Proc., 6th Int. Conf. Engrg. Constr. and Operations in Space*, ASCE, 462-468.

Low Earth Orbit (LEO): Planning for the Necessary Infrastructure Services

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Abstract:

As the many and varied space enterprises (e.g. space tourism, NASA's MMB, satellite repair, etc) formulate their travel missions, plans and schedules, there is now emerging information that suggests many of these space enterprises have LEO (Low Earth Orbit) in their plans. Some will come and visit LEO and then return to Earth (e.g. space tourism). Some will come to work in LEO and then return to Earth (e.g. tourism lodging services, On-Orbit Servicing/Assembly). Others, perhaps many others, will come to LEO, rest up and refuel, transfer payloads or crews and head off to other space destinations (e.g. MMB, Lunar commerce, Lunar tourism, etc). What is becoming clear is that LEO is becoming the preferred and likely location for a great diversity of space enterprises, space farers and other space 'stuff'. And as these various space enterprises further define and refine their concepts and missions, it is becoming possible to start to identify and even quantify the types and amounts of infrastructure services that will be needed in LEO (and perhaps other Earth Orbit zones). This paper will attempt provide a first look at and a broad insight into the variety and diversity of space enterprises and their plans for LEO and then to suggest an initial list of the variety of infrastructure services and capabilities needed to support these various LEO-related plans. This paper will also highlight some of the challenges and impediments that this need for 'architecting LEO' will present to global space community.

Sublimation Extraction of Mars H_2O for ISRU.

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Introduction: H_2O on Mars is an essential resource for future human exploration. H2O-based in-situ resource utilization (ISRU) on Mars will provide the necessary raw ingredients for propellant production and energy storage, oxygen and water for life support. The importance of H2O-based in-situ propellant production (ISPP) cannot be understated – there is no planned terrestrial launch vehicle in the near or longer term future that can deliver a fully fueled return launch vehicle to the surface of Mars.

Abundant, accessible Mars H_2O likely exists in the form of near-subsurface ice-filled porous regolith, particularly at latitudes ~50° and higher [1]. The upcoming 2007 Phoenix mission will provide an additional datapoint to confirm or refute this expectation.

Extraction of a permafrost ice in a regolith matrix may likely be complicated by the fact that a consolidated permafrost matrix forms a high-strength composite. Pure ice has the weakest compressive strength (~1-10's MPa). Permafrost in regolith increases the compressive strength of pure ice by about an order of magnitude (~10-100 MPa) in some cases approaching pure basalt (~100-1,000 MPa) [2].

Mars H_2O Resource Needs: Propellant mass requirements for ascent from Mars are likely to be ~ 40 metric tons (mt) for ascent to Mars orbit and ~ 100 mt for direct return to Earth [3]. Life support consumables required for a crew of six for 600 days on Mars are estimated to be ~125mt (Table 1). Recycling could reduce the need to bring resources from Earth, but the recycling plant is likely to weigh ~ 9 mt, and perhaps 20 mt of back-up cache might be needed. Recent studies [4] have shown that by utilizing indigenous Mars H_2O as a resource for H_2 and O_2 (through electrolysis) in combination with Sabatier reduction of atmospheric CO_2 to CH_4, large masses of propellants and life-support consumables can be produced with an ISRU plant of comparatively small mass. Since it takes roughly 5 mt in LEO to deliver 1 mt of payload to the surface of Mars [3] the required mass delivered from Earth to LEO can thereby be reduced by significant amounts - many hundreds of metric tons in many scenarios.

Table 1. Summary of consumables based on crew of six for 600 days. [3]

	Raw Consumable Need (without recycling)	
LSS Element	**kg/day**	**Kg for 600 days**
Oxygen	6.0	3,600
Atmospheric buffer gas	18.0	10,800
Potable water	24.0	14,400
Wash water	156.0	93,600
Food	6.0	3,600
Waste disposal	2.4	1,440
TOTAL	**212.4**	**127,440**

To provide a sense of scale, first order estimates indicate that three successive human Mars missions to the same site could be supplied with enough indigenous H_2O for all propellant and consumable needs from an ice resource that in 20% porous soil, would have an area about the size of a baseball diamond excavated to a depth of about 1 meter [3].

Mars Sublimation Extraction: Mission significant diffusive sublimation of an ice table boundary through a dry porous regolith into a saturated Mars atmosphere is possible even for ice table temperatures well below 0°C (Fig. 1).

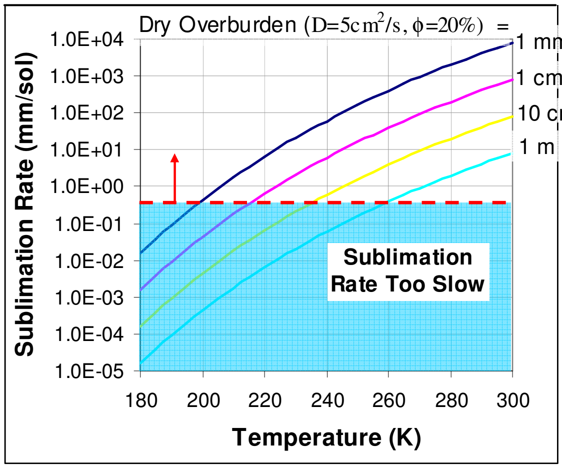

Figure 1. Ice table regression rates vs. ice table temperature and depth of dessicated overburden (*D* - soil diffusivity, ϕ – soil porosity).

The Mars daily solar thermal wave propagates into a dry insulating soil medium by ~10cm at Mars mid-latitudes (Fig. 2A) with seasonal variations that likely penetrate down to ~m's (depending on subsurface thermal conductivity and ice content).

By either excavating the dried and weakened soil overburden during sublimation extraction or decreasing the surface radiative IR emission (substantial loss of solar heat) in order to increase the average daily ice table temperature, it is likely possible to sublime H_2O

from Mars soils to depths of ~1m over reasonable mission timescales. Figure 2B illustrates an example of solar sublimation extraction at Mars midlatitudes by altering the effective surface emissivity, ε, to 0.03 while holding a surface albedo, α, of 0.2 over the course of 150 sols. Such a surface boundary condition could be met by deploying an optically transparent film (Fig. 3) that is capable of entraining an air space over the ground. This air space would be continuously "dried" to at least the saturation point to prevent accumulation of H_2O vapor in the surface boundary layer from inhibiting vapor diffusion or accumulating on the film. Even in the presence of surface dust, effective surface emissivity would likely be lower than current ground values due to intergrain radiative and convective heat transfer.

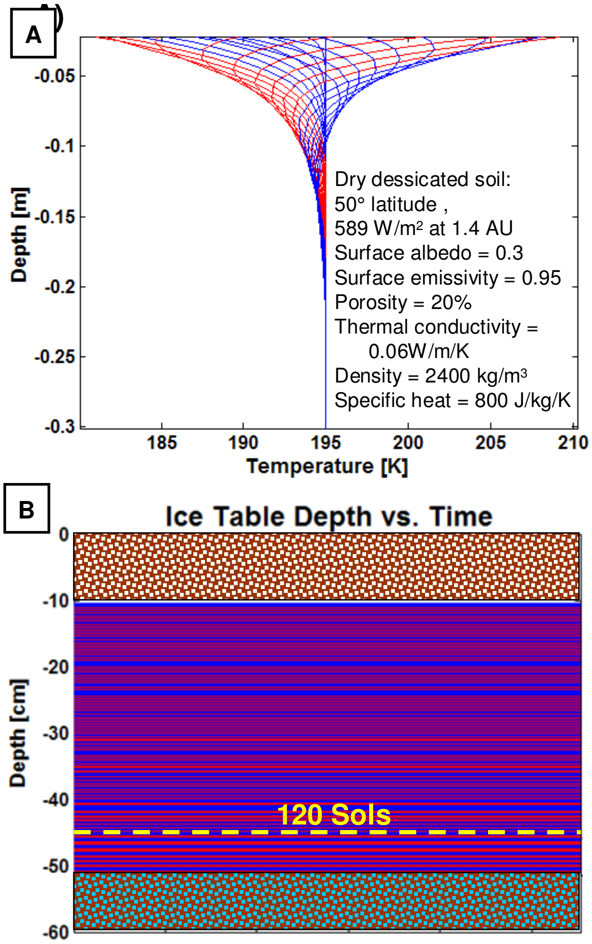

Figure 2. A) Typical Mars daily subsurface temperature profile in 1-hr increments (red/blue denote day/night respectively). B) Ice table regression over 150 sols with an initial 10 cm overburden (red/blue denote day/night ice table depth respectively) and a saturated local Mars atmosphere.

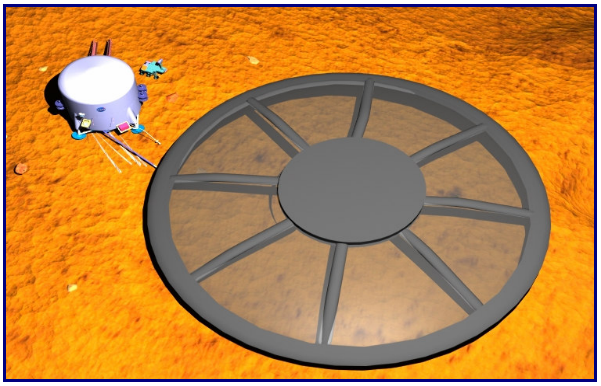

Figure 3. Large deployable film for solar sublimation extraction of Mars H_2O.

Improved knowledge of Mars near subsurface properties at a candidate extraction site would be required prior to being able to carefully implement an ISRU solar sublimation extraction plant. Highest priority measurements would be the vertical and horizontal distribution of ice, dry soil thermal conductivity, soil porosity and diffusivity, presence of salts in soils and basic soil chemistry. Secondary priority, but important measurements for engineering optimization, would include soil density and specific heat.

References:

[1] Rapp D. , Mungas, G. (2006*) Earth & Space 188,* 75. [2] Eustes III, A.W. et al. (2000) *Space Resources Roundtable II,* #7029. [3] Rapp, D., Andringa, J., (2005) *JPL Report* D-31340. [4] Rapp, D., et al. (2004). *JPL Report* D-31341.

INTEGRATED MARS IN-SITU PROPELLANT PRODUCTION SYSTEM.

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Introduction: Mars exploration can be greatly enhanced by the use of local resources to produce propellant. Producing rocket fuel for the return flight using *in-situ* resources greatly reduces the mass of the Mars lander. Combining the Sabatier reaction and the reverse water gas shift (RWGS) to convert hydrogen and carbon dioxide into oxygen and methane (with carbon monoxide as a waste product) provides a mass leverage ratio of 20:1. For example, a propellant payload of 500 kg on a Mars ascent vehicle delivered to the Martian surface as part of a Mars sample return mission can be replaced with 25 kg of hydrogen and an *in-situ* propellant production (ISPP) system. The goal of this phase II SBIR project is to develop such an ISPP system.

The Sabatier reaction converts hydrogen and carbon dioxide into methane and water according to the following reaction:

$$4H_2 + CO_2 \xleftrightarrow{-165\ \mathrm{kJ}} CH_4 + 2H_2O \qquad (1)$$

The water can be electrolyzed into hydrogen that can be recycled and oxygen that can be burned with the methane. The oxygen to methane weight ratio in equation (1) is 2:1, whereas stoichiometric combustion requires a ratio of 4:1 and optimum performance requires a ratio close to 3.5:1.

This problem can be resolved with the addition of the RWGS reaction:

$$H_2 + CO_2 \xleftrightarrow{+41\ \mathrm{kJ}} CO + H_2O \qquad (2)$$

To produce an oxygen to methane ratio of 4:1 twice as much carbon dioxide needs to be converted with the RWGS reaction than with the Sabatier reaction. This ratio leads to the following net exothermic conversion:

$$6H_2 + 3CO_2 \xleftrightarrow{-83\ \mathrm{kJ}} CH_4 + 2CO + 4H_2O \qquad (3)$$

The goal of this project is to acquire carbon monoxide from a simulated Martian atmosphere and to convert it into rocket propellant according to equation (3) using an electrolyzer to convert the water into oxygen and hydrogen.

System design: The system was designed from the standpoint that the Sabatier and the RWGS reactions occur in a single reactor. This design maximizes heat conservation within the system and minimizes ancillary equipment. A single reactor design requires only one membrane separator, one condenser and one recycle pump whereas separate reactors would require two of each of these units. Hence the benefits of a single reactor are readily apparent.

A simplified schematic of the single reactor ISPP system is shown below with the omission of the carbon dioxide acquisition and the oxygen liquefaction systems.

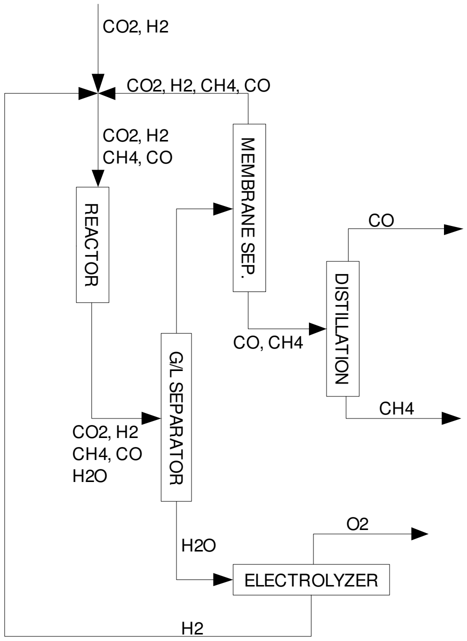

Figure 1: Schematic of ISPP system

Reactor optimization. Several reactor designs were tested with the most successful being a tube-in-tube reactor. A schematic of this the reactor is shown in Figure 2. The conversion of the Sabatier reaction was controlled by limiting the amount of catalyst in the reactor to 0.5 gram and sufficient catalyst (130 grams) was added to reach equilibrium conversion with the RWGS reaction. The Sabatier catalyst is 0.5 % ruthenium on alumina and the composition of the RWGS catalyst is $CuO(57)/ZnO(31)/\text{-}Al_2O_3(11)/Promoter(1)$ where the values in parentheses are weight percentages.

Results: The system shown in Figure 1 was built excluding the distillation column. The distillation column and the oxygen liquefaction system will be integrated using a single cryocooler and this system is currently under construction. The system was built to produce about 1 kg of propellant per day.

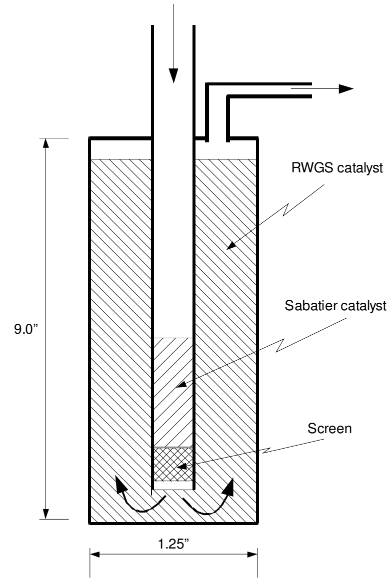

Figure 2: Schematic of tube-in-tube reactor.

Chemical conversion. Initial tests were performed with an electrolyzer integrated into the system to ensure that the hydrogen from the water could indeed be recycled back into the reactor. Some maintenance issues, however, prevented the integration of the electrolyzer for further testing.

The system was tested with a CO_2 feed of 0.63 SLPM and a H_2 feed of 1.26 SLPM. The outlet gas stream of the reactor was maintained at 3 bara and 375 ^{o}C. And the recycle rate was set at 10 SLPM which produced a permeate pressure of 1.2 bara. The concentrations of the reactor feed, the dry reactor products, the membrane permeate and membrane retentate are presented below in mol fractions.

Table 1: Compositions in mol fractions of gas streams

	Reactor inlet	Reactor outlet	Permeate	Retentate (final product)
H_2	0.5834	0.5538	0.5917	0.0000
CO_2	0.2789	0.2316	0.2441	0.0015
CO	0.1000	0.1486	0.1188	0.6444
CH_4	0.0376	0.0661	0.0454	0.3541

These results reveal several important aspects about the operation of the ISPP system. First of all, the low concentrations of H_2 and CO_2 in the retentate show 100 % conversion of the hydrogen and 99.5 % conversion of CO_2. Secondly, the ratio of CO to CH_4 is 1.8:1, which is close to the anticipated ratio of 2:1. The discrepancy is attributed to errors in the flow controllers. And third, the performance of the membrane separation is excellent. The permeate is enriched in H_2 and CO_2 while there the retentate consists of nearly pure CO and CH_4.

Oxidizer:Fuel ratio control

An important aspect of an autonomous ISPP system is that the oxidizer to fuel ratio can be tightly controlled. Precise control of the oxidizer to fuel ratio was obtained by changing the feed H_2:CO_2 ratio as shown in Figure 3.

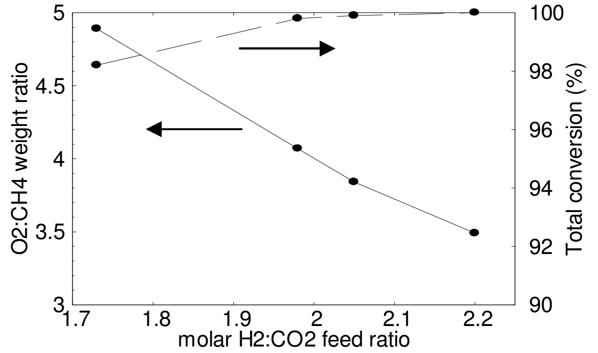

Figure 3: Oxidizer to fuel ratio vs. feed ratio

Energy usage. Through the use of regenerative heat exchangers, the energy consumption of the ISPP system was kept at a minimum. The chemical conversion process discussed above requires about 70 W to heat the reactor and about 10 W of cooling to cool the gas before the gas/ liquid separator. The net conversion in the reactor according to reaction (3) is exothermic and produces about 13 W, but this is not sufficient to account for the heat losses to the surroundings. Note that just preheating the gas going into the reactor requires 160 W, but most of this duty is provided by a regenerative heat exchanger.

The electrolysis of the water requires about 300 W and the recycle pump consumes 100 W of electrical power. This brings the total power consumption to 470 W for the chemical conversion process to produce 1 kg of propellant per day.

Conclusions: At this point we have demonstrated the feasibility of converting CO_2 and H_2 into CH_4 and O_2 with nearly 100% conversion in a single reactor. The chemical conversion process requires about 470 W of power to produce 1 kg of propellant per day.

During the remainder of this phase II SBIR project we will integrate a CO_2 acquisition system and a cryogenic distillation column. When a successful experimental system is developed the entire apparatus will be rebuilt into a complete end-to-end flight-like ISPP system.

Acknowledgement: This work was conducted under NASA Small Business Innovation Research (SBIR) Funding. Janine Captain is the NASA KSC Contracting Officer's Technical Representative (COTR).

BUILDING PRIVATE AND PUBLIC SECTOR SUPPORT FOR SPACE RESOURCE USE

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Introduction: This presentation will discuss ways in which the public perception of space resource use may be improved, with the objective of co-opting the existing network of successful lobbying and public interest groups to support the development of technologies for commercial In-Situ Resource Utilization (ISRU). The absence of vocal public support for the development of space resources has hindered that work in both the funding of national space programs and the generation of interest among potential private sector investors. Through building a base of favourable public awareness, the perceived risks and benefits of the technologies involved in space resource use may be improved; serving to both attract the interest of private sector investors and advance the perception held by public sector decision-makers[1].

Until space resource utilization becomes commercially viable, with space-based companies able to support themselves through retained earnings, significant public funding will be required from Government to develop the technologies required for ISRU. As all nations will face conflicting budgetary demands over the decades required to fully develop ISRU technologies, it may be expected that space resource programs will be threatened with reduced funding and possible cancellation many times before they are capable of generating a self-sustaining private sector profit.

When faced with the task of drafting a national budget during recessionary periods, Governments prioritize programs for funding based upon their importance to security, benefit to the economy, maintenance of infrastructure and other factors related to the improvement of a nation in time of distress; criteria which ISRU research would find it difficult to meet. However, in addition to concerns of practical need, Governments also consider the opinion of the voting public when choosing targets of spending reduction or cancellation: Rather than face organized protest from disgruntled voters who support a program targeted for spending reduction, decision-makers are inclined to instead select a project unlikely to generate a significant amount of vocal objection if cancelled. Strong affinity with the general public thus serves to protect otherwise vulnerable Government-funded programs during periods of economic decline. While it would be unthinkable for a budget drafting committee to eliminate programs for agricultural subsidy, environmental monitoring or romanticized traditions such as the Amtrak passenger railway system[2], it would be relatively easy for decision-makers to balance a national budget by targeting expensive programs which have a limited impact and are not closely followed by the general public.

The research of ISRU technologies, being both expensive and relatively unknown to the public, is vulnerable to cancellation. However, if favourable public perception can be developed for space resource utilization, programs engaged in that objective will face a greater chance of successfully weathering future periods of economic distress. As business opportunities emerge for space resources, that familiarity may then translate into a receptive private sector investment environment, making ISRU projects an emerging industry whose risks and opportunities are well understood by all.

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A ROBOTIC MISSION STRATEGY FOR CHOOSING AN ISRU PROSPECT AND PROCESS. J. B. Plescia, P. Spudis, B. Bussey. Applied Physics Laboratory, Johns Hopkins University, Laurel MD 20723-6099.

Introduction: The utilization of in situ resources (ISRU) is critical to establishing a permanent human presence on the Moon, cutting the ties to Earth, and making exploration of other parts of the solar system more economical. Many ideas have been offered about different types of resources and their potential benefit [1] ranging from the use of the regolith as shielding material, the use of metals in the regolith for structures and the use of solar power. We believe the resources that will have the most immediate impact are those that reduce the mass of the material launched from the Earth. One of the largest mass elements is fuel for travel to and from the Moon and from its surface to orbit, thus in situ fuel production is provide significant launch mass reduction. A second near-term objective is the use of resources to replenish of life support gases and liquids, which although minor in terms of mass, provides for risk reduction.

Key Resources: Hydrogen and oxygen are the two key elements for fuel and life support. Oxygen occurs across the entire surface and is bound in silicate and oxide minerals. Hydrogen also occurs globally but at much lower concentrations; locally, its concentration can be significantly elevated above the global average. Thus, it is the hydrogen distribution that has the most leverage in terms of the selection of the site for ISRU development and the outpost. There are clearly other resources to be exploited, however, we focus here on a strategy to determine the locations with the highest potential to produce hydrogen and oxygen.

In situ production of hydrogen is important for many reasons. Hydrogen brought from the Earth for fuel must be cryogenically stored. Thus, in addition to mass of the hydrogen itself, there are mass and power penalties of the storage system. Hydrogen is also used in various oxygen production processes involving the reduction of Fe and Ti oxides. In the reaction with FeO, H in the amount of 25% of the amount of O to be produced is used in the process.

Oxygen is the most common element on the Moon (~60% of the atoms). But, the oxygen is tightly bound in silicate and oxide minerals. The most common silicate minerals [2] are pyroxene, comprising <10% to >55% of a sample; and plagioclase, making up ~70% in highlands material to ~10% in some basalts. Pyroxene is a complex solid-solution series with Ca, Na, Fe and Mg bound to silica; plagioclase is also solid-solution series ranging from sodic (rare) to calcic (abundant) end-members.

Hydrogen occurs in Apollo and Luna soil samples in amounts of ~50 ppm [3]. The H content of rocks is relatively low (< 10 μg/g), but much higher in the regolith (2-200 μg/g). Lunar Prospector Neutron Spectrometer (LPNS) data show the polar regions have enhanced hydrogen content (about 160 ppm) relative to the lower latitude areas (average 55 ppm).

The resolution of the best LPNS data is of the order 30 km [4] which is larger than many of the individual permanently shadowed areas. [4,5] modeled the H signature as being due to H_2O ice sequestered in permanently shadowed areas and derived a local abundance (in the shadowed area) of as much as 1700±900 ppm (equivalent to 1.5±0.8 wt % H_2O). The assumption that the hydrogen is sequestered in the permanently shadowed areas is only that – an assumption. While it is consistent with models of cold trapping [6,7,8] if the hydrogen is largely from solar wind sources [9], it could equally be true that it is uniformly distributed across the poles at concentration of ~160 ppm.

Lunar pyroclastic material [10] is also a suggested to be a potential source of hydrogen [11]. The black glasses (dark because they have devitrified) are suggested to have higher hydrogen content because of the presence of surface ilmenite crystals which have a larger adsorption capacity for H and are fine-grained size. The black pyroclastic material from the Apollo 17 site had higher concentrations of O, Fe and Ti. Ti is associated with higher retention of H and He because the oxide mineral ilmenite ($FeTiO_3$) is more resistant to radiation damage and better able to retain the solar wind gases.

Exploration Strategy: We must have a better understanding of the distribution of lunar H and its form and concentration. However, exploration of the poles is difficult, requiring significant mass and power to successfully operate and survive. A phased approach of robotic missions may make such exploration and characterization easier and more affordable and allow an informed decision regarding outpost location and ISRU development. Thus, we suggest the following strategy:

1. Polar Remote Sensing Data. Lunar polar orbiters from several nations will soon produce data necessary to assess the nature and extent of the poorly characterized polar deposits. Data sets of particular importance are: topography, illumination and shadow maps, high resolution images of potential landing sites, and maps of putative ice deposits.

2. Polar Lander Mission. This mission would be to an area of near-permanent sun light. The primary objective would be to sample the regolith to depths of 1-2 m and analytically determine the H content. If the

H content in the illuminated areas is of the order 160 ppm, it would suggest that the H is of solar wind origin and uniformly distributed across the polar region. In this case, H sequestration in the permanently shadowed regions would not be an important mechanism and would lower the priority of or eliminate the need to explore those areas. If the H content is of the order 50 ppm (similar to that found elsewhere on the Moon) it would indicate that the "missing" H was sequestered somewhere – logically, the permanently shadowed areas. A neutron spectrometer to provide a high-spatial resolution measurement of the neutron flux at the same site as the analytic measurement and thus calibrate the orbital neutron data would also be carried. The potential for solar power would be assessed by mapping the surface illumination over the course of a year.

3. Pyroclastic Deposit Lander. The objective would be to determine the H content of a dark pyroclastic deposit. As black glass contains ilmenite, a H carrier, it is postulated that mature regolith on a pyroclastic deposit would be an easy-to-mine, high concentration prospect. Sites such as Sulpicius Gallus on edge of Mare Serenitatis or Rima Bode, east of Copernicus, are prime candidates for such deposits. The mineralogy, chemistry, and the H content of the pyroclastics would be determined to depths of 1-2 m. The neutron signature at the surface would also be measured.

As a result of these missions, one could evaluate the relative costs of extraction of H and O from either the polar highlands regolith (illuminated and/or shadowed) or a pyroclastic deposit, theoretically a favorable H prospect. If the H were sequestered in the shadowed areas, its form and distribution would still need be determined, but a decision could be made at this point as to which source would be used.

4. Polar Shadowed Region Exploration. To assess the form, concentration and distribution of polar H, a mission would be sent to the most promising permanently shadowed area identified from remote-sensing data (e.g., Shackleton). A mobility system would be required to ensure that a sufficient number of sites are examined to understand the nature of the H (e.g., for a heterogeneous distribution of 10-20% ice, >20 sites are needed to characterization it at 90% confidence). The payload would include a drill to obtain samples to depths of 1-2 m, volatile analysis instrumentation, neutron spectrometer, and possibly a ground penetrating radar; the latter two being used to trace the H distribution between drill samples.

With the successful completion of this mission, sufficient information would be in hand to make a decision regarding the process that is most advantageous for O and H production. Such a decision involves not only the energy to split the O and H from their parent molecules or extract it from the regolith, but also the infrastructure necessary to process the regolith, extract the volatiles, and store the volatiles. This also feeds directly into the selection of an outpost site on the Moon.

5. ISRU Process Demonstration. The next step would be to demonstrate on the Moon the specific ISRU process that had been selected on the basis of the previous missions. This mission would demonstrate, at the appropriate scale, the collection, extraction and storage of the H and O. Depending upon the feedstock, experiments on different regolith collection and processing schemes could be demonstrated. This could be conducted, on a series of missions, at various scales up to production scale.

6. Regolith Handling and Processing. Prior to the operational phase of ISRU, demonstrations of the regolith handling process are highly desirable. Like the ISRU demonstration, these could be incremental with various excavation and transportation concepts being tested at larger and larger scales.

Summary: This mission series collects scale-appropriate information, in a logical sequence and a timely manner. It will reduce long-term risk, enable early ISRU accomplishment, and ultimately, permit the development of large-scale ISRU on the Moon, an important goal of the Vision for Space Exploration.

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A PROOF OF CONCEPT OF VACUUM PYROLYSIS.

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Introduction: The *in-situ* production of oxygen on the Moon will be a key part of reducing the weight and cost of a spacecraft launched from Earth. Vacuum pyrolysis is one method being researched to produce oxygen from lunar regolith. One advantage of using vacuum pyrolysis is the feedstock can be unbeneficiated regolith [1]. The regolith will dissociate at a low pressure and high temperature. Another distinct advantage of vacuum pyrolysis over other Lunar oxygen production techniques is there is no need for resupply missions from Earth as there are no consumables used in the process. However, work to directly measure the dissociated species has not been completed.

Experiment: In order to be most efficient, the vacuum pyrolysis chamber needs to be held at an optimum temperature and pressure to produce the maximum O_2 yield. If the temperature is too low, the O_2 will not be produced and if it is too high, monatomic oxygen will be produced. Numerical analysis was performed on the average Apollo 15 sample to determine at what pressures and corresponding temperatures would produce the highest oxygen yield. The numerical analysis showed that the sample should produce between 10% and 15% oxygen yield by weight depending on the pressure in the chamber [2].

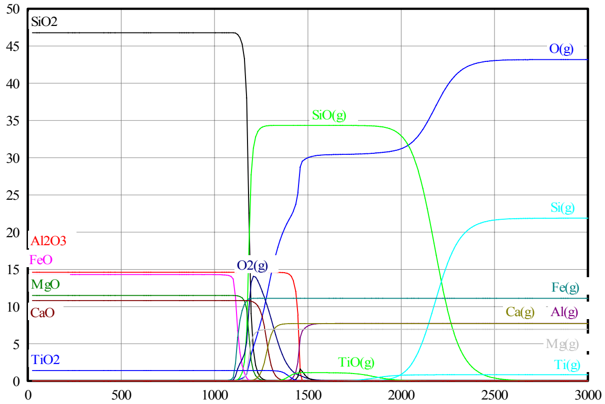

Figure 1. Apollo 15 percent composition dissociation and temperarure at 7.50x10^{-7} Torr [2].

Vacuum furnace tests were conducted using ilmenite, enstatite, and MLS-1A simulant. First, the samples were outgassed for a period of two hours in a vacuum oven at 200°C to remove all water of hydration and volatile gases in the samples. The samples were then massed before being placed into a vacuum furnace. They were exposed to a vacuum while being heated at a rate of no more than 12°C per minute to a temperature of 1400°C and held for 20 minutes. A MKS PPT residual gas analyzer (RGA) monitored the vaporized gases from the samples. After the samples cooled to room temperature, they were again massed to determine the percentage mass loss of non-condensed material.

Results: The MLS-1A sample when heated to 1400°C vaporized completly. The primary mineral in the MLS-1A simulant is SiO_2. The dissociation of the SiO_2 can be seen in Figure 2. As the vacuum furnace heated to 1400°C the SiO_2 dissociated into SiO and oxygen. The trend of the decrease in SiO and the increase in silicon can be seen in the RGA data in **Figure 2.** The MLS-1. sample from the test shown in Figure 2 exhibited a non-condensed mass loss of 1.17%.

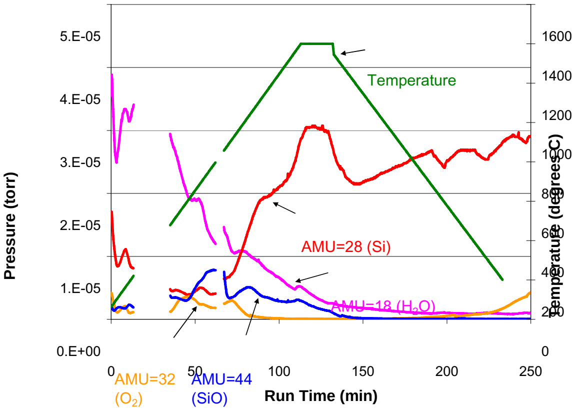

Figure 2. RGA data from MLS-1A vacuum furnace test.

Conclusion: The distinct peak of silicon partial pressure at the peak temperature shows that the SiO_2 in the stimulant was dissociating. In a separate test with no sample in the chamber, no peak was seen for the atomic mass 28. During the test of MLS-1 there was no rise in other atmospheric species, such as water, hence the atomic mass 28 is not believed to be atmospheric nitrogen. The SiO also follows the trend of reducing in partial pressure as the silicon increases in partial pressure. The oxygen is believed to have reacted in the furnace before being measured by the RGA, which is consistent with apparent oxidation observed in the chamber.

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Lunar Physical Simulant: Evolution, Production and Use. Jim Richard[1], Dale S. Boucher[2] and M. M. Battler[3] [1]Electric Vehicle Controllers Ltd. (EVC), 2200 Valleyview Road, Val Caron, Ontario, CANADA P3N 1L1 e-mail:jrichard@norcat.org. [2]Northern Centre for Advanced Technology Inc. (NORCAT), 1400 Barydowne Road, Sudbury, Ontario, CANADA P3A 3V8 e-mail:dboucher@norcat.org. [3]Planetary and Space Science Centre, Department of Geology, University of New Brunswick, Fredericton, NB, E3B 5A3, Canada, melissa.battler@unb.ca,

Introduction: Development of drilling and excavation equipment and the desire for In Situ Resource Utilization (ISRU) Capability Demonstration missions to the Lunar South Pole, has led EVC and NORCAT to recognize the need for access to an anorthositic physical simulant in which to conduct relevant testing. Sufficient quantities of such a simulant were not readily available. Since successful equipment design is dependent on testing in relevant material, it became apparent that the timely development of an appropriate simulant was necessary.

Evolution: Early in 2005, EVC/NORCAT, along with the University of New Brunswick began defining the desireable characteristics of the simulant as well as looking for suitable terestrial source material. Several different anorthosites were investigated. Based on previously published data obtained from actual lunar samples, one particular anorthosite was selected for further development. Proprietary crushing techniques were developed with the aim of producing a simulant with correct particle size distribution while minimizing the impact of the crushing process on the desired particle shape.

In recognition of the fact that the lunar surface also contains abrasive glass particles and agglutinates, investigations were done to find a suitable additive to the simulant to approximate these characteristics.

Production: In December of 2005, approximately 180 kg of combined simulant was manufactured. This simulant was produced for in–house testing of drilling equipment. An additional 800 kg of material is currently under production. Approximately 400 kg of this simulant will include the glass. The balance will be anorthosite only. For handling purposes the batches are being produced in 10 kg quantities.

Material Safety Data Sheet information is currently being collected for the anorthositic, glass and combined products.

Use: Before selecting a simulant it is necessary to properly define the parameters under which the material will be utilized. If the objective is to supply an environment in which to obtain relevant data, the production of the simulant is only the first step. Testing must be conducted to ensure the material is properly prepared to mitigate any detrimental effects on the data collected. This includes but is not limited to the techniques used for compaction of the material, moisture content regulation, freezing and the application of a vacuum.

REQUIREMENTS AND TECHNIQUES FOR DEVELOPING AND MEASURING SIMULANT MATERIALS. Doug Rickman[1*], Charles Owens[2], Rick Howard[3], Carole McLemore[4+], [1]Marshall Space Flight Center, National Aeronautics and Space Administration, 320 Sparkman Drive, Huntsville, AL 35805 doug.rickman@nasa.gov, [2]Teledyne Brown Engineering, Huntsville, Al 35805 charles.e.owens@nasa.gov, [3]Teledyne Brown Engineering, Huntsville, Al 35805, rick.howard@tbe.com, [4]NASA, Marshall Space Flight Center, Huntsville, AL 35812 carole.a.mclemore@nasa.gov [*]Corresponding Author, [+]Point of contact for additional information.

Introduction: The 1989 workshop report entitled *Workshop on Production and Uses of Simulated Lunar Materials* [1] and the *Lunar Regolith Simulant Materials: Recommendations for Standardization, Production, and Usage*, NASA Technical Publication [2] both identifed and reinforced a need for a set of standards and requirements for the production and usage of the lunar simulant materials. As NASA prepares to return to the moon, a set of requirements [3] have been developed for simulant materials and methods to produce and measure those simulants have been defined. Addressed in the requirements document are: 1) a method for evaluating the quality of any simulant of a regolith, 2) the minimum characteristics for simulants of lunar regolith, and 3) a method to produce lunar regolith simulants needed for NASA's Exploration mission. A method to evaluate new and current simulants has also been rigorously defined through the mathematics of Figures of Merit (FoM), a concept new to simulant development.

A single FoM is conceptually an algorithm defining a single characteristic of a simulant and provides a clear comparison of that characteristic for both the simulant and a reference material. Included as an intrinsic part of the algorithm is a minimum acceptable performance for the characteristic of interest. The algorithms for the FoM for Standard Lunar Regolith Simulants are also explicitly keyed to a recommended method to make lunar simulants.

Benefits for this approach; 1) permit multiple materials to be used as standards; 2) allow multiple simulants to be compared in a standardized manner; 3) allows simulants to be standardized to a definition based on measurement protocols and not restricted to a physical reference material; 4) new batches of simulants or multiple providers of simulants can be readily compared, and 5) simulant requirements are permitted to evolve as knowledge or needs change.

Intended Users: The scientific and engineering communities are the primary two intended users of lunar regolith simulant materials.

Utilization of the simulant by the science community will be in small quantities (kilograms vs. metric tons in most cases) in a laboratory or specialized pilot facility with the intent of developing or improving a process (e.g. oxygen or metals extraction) and may only require discrete amounts of simulant. Expectations are that the FoMs for these simulants will have higher values and tighter tolerances banding together to require more closely controlled simulant production. This in turn reflects on the additional quality control aspects of how the simulant materials were collected, processed, and blended, with particular attention to minimizing contamination.

Potential vendors may use offsite analytical techniques to verify the simulant to the FoMs applied. "Offsite" implies that statistically relevant samples have been taken from the components individually and the simulant after mixing, and analyzed in a laboratory setting to verify the quality of the product. Tighter production tolerances or secondary processing are expected to drive higher dollar/kg costs to the end user.

Utilization of the simulant by the engineering community will be in larger quantities (metric tons) necessary to develop large-scale processes for lunar production facilities and construction. Examples of engineering uses include developing drills and excavation equipment along with handling and hauling mass quantities of regolith. Processes developed for lunar industrial applications must be robust enough to handle small amounts of contamination inherent in the processing of large quantities of rocks and minerals on Earth. Many of these contaminants will be introduced during lunar processing as well. Expectations are that the FoMs for these simulants will have lower values for some characteristics based on their intended end use. Potential vendors may use insite analytical techniques to verify quality of the simulant during production. "Insite" implies that a continuous sampling and analysis is occurring during the production run. Common methods of measurement utilized in continuous industrial processing are laser diffraction and automated vision systems. Automated analytic techniques coupled with large quantity production are expected to reduce the dollar/kg costs to the end user.

Establishing Requirements Through the Figures of Merit: Based on the work published in the *Lunar Regolith Simulant Materials: Recommendations for Standardization, Production, and Usage*, NASA Technical Publication [2], four key characteristics of the lunar regolith have been initially selected for the Simulant Requirements Document. Those characteristics are; composition, size, shape and density. As needs change new requirements and FoMs may be added, deleted or modified. To demonstrate the link between a Figure of Merit and requirements, the FoM of "composition" is used as an example.

The Figure of Merit termed "composition" defines the geologic constituents of the simulant without reference to textural features, such as particle shape and particle size. Composition includes the following classes of constituents: lithic fragments, mineral grains, glasses and agglutinates. Conceptually, composition addresses the chemical makeup of individual particles. The Simulant Requirements Document specifies the rock types, their chemical make up and which materials may or may not be used to establish a simulant requiring this type of Figure of Merit.

Establishing a Reference Material: In normal use a reference material would be defined as a regolith core sample returned by an Apollo mission. However, any material real or predicted may be used, including another simulant. The reference material is measured and assigned values of 1 for all properties to be described by the Figures of Merit. The simulant is measured for the same properties as the referenced material and the differences are evaluated according to the algorithms of the FoMs selected for comparison.

The usefulness of allowing a predicted material to be a reference is that as mission planners evaluate and select potential lunar sites for exploration, existing and new simulants may be evaluated for potential analogs for those sites through the Figures of Merit. If simulants must be produced, manufacturers of such materials now have a way to measure their product and select the "best fit" of raw materials and processing techniques.

Contamination of Simulant Materials: Contaminants can be introduced into simulant materials at any point during their manufacturing and storage, rendering the material useless for some applications. Vapors from nearby solvents or fine particles from nearby construction sites have been known to contaminate and disrupt the manufacture of new simulants. Thus, the Simulant Requirements Document addresses this problem and defines the maximum allowable contaminants in a simulant material.

Conclusions: Requirements and techniques have been developed that allow the simulant provider to compare their product to a standard reference material through Figures of Merit. Standard reference material may be physical material such as the Apollo core samples or a predicted material such as a polar landing site. The simulant provider is not restricted to providing a single "high fidelity" simulant, which may be costly to produce. The provider can now develop "lower fidelity" simulants for engineering applications such as drilling and mobility applications.

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Acknowledgements: The following individuals contributed to the development of the Lunar Regolith Simulant Requirements Document; Susan Batiste, University of Colorado, Boulder; Paul Carpenter, BAE Systems Analytical and Ordnance Solutions; Raymond French, Marshall Space Flight Center /NASA; Hans Hoelzer, Teledyne Brown Engineering; Rick Howard, Teledyne Brown Engineering; John Lindsay, Lunar and Planetary Institute; Carole McLemore, Marshall Space Flight Center/NASA; Sarah Noble, Johnson Space Center/NASA; Chuck Owens, Teledyne Brown Engineering; Doug Rickman, Marshall Space Flight Center /NASA; Ian Ridley, United States Geological Survey ; Laurent Sibille, ASRC Aerospace Corp; Doug Stoeser, United States Geological Survey; Susan Wentworth, ERC Inc., Engineering and Science Contract Group; Steve Wilson, United States Geological Survey. The MSFC and USGS team wish to acknowledge the contributions of the Stillwater Mining Company, who generously provided their time and information. They also wish to acknowledge the contribution of Michael L. Zientek, USGS, for his time and patience.

AN INTEGRATED LUNAR MANUFACTURING PLANT.

Building the Fleet in Support of Continuous Presence on Mars

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Abstract: *A first generation design of an integrated* front-to-back *ISRU solution is presented as industrial process. Most of the technology required has industrial legacy while a fraction of the proposed plant is still emerging from the laboratory. All of the technology will require rational integration, translation into space-qualified componentry and partitioning into* 'flyable' *industrial pallets.*

A number of placeholders are employed while technologies appropriate to the integration are sought. Several iterations of design are inevitable as we 'drill down' into the details of chemistry, process, conversion processes and value-added mechanisms. The top-level functional partitioning as presented is certainly subject to change and currently includes the Preprocessing of Regolith Soils, Metals Extraction from Regolith Ore, Glass Manufacturing from Regolith Ore, CVD Deposition, Assembly, Production QA and Applications.

One of the very unique methods employed is to split the ore into two distinct flows, one for metals extraction and another for fabricating glass fiber. The glass fiber is bifurcated into at least two streams where one fiber type is CVD plated with Iron and another with Aluminum. These dissimilar fibers are woven into complex shapes by programmable 3D weaving machines and by taping fiberglass fabrics onto rotating drums. The molds and forms thus created are subjected to combustion synthesis which fuse the fibers together. Further plate-up by CVD Iron and Nickel augmented by doping of carbon, chromium, manganese and the like, allow for extremely precise synthesis of high-quality steels, devoid of processing flaws. The resulting structures have imbedded fiber reinforcement.

All of this work is accomplished with relatively low demands for energy, especially when compared to the 'hot' conventional processes employed for steel production on Earth. Through the use of fiberglass it will not be necessary to haul Lead and Tin to the Moon for use in molds. The production facilities are entirely automated for unattended operation 24/7. One of the many program objectives is to manufacture parts for repair, replacement and reproduction in the form of second generation manufacturing plants. Another is to keep the import of feedstocks from Earth to a minimum. The ultimate goal is to fabricate major components on the Lunar surface for assembly at a shipyard in Lunar Orbit or nearby Lagrangian Point.

METAL-CO$_2$ PROPULSION FOR MARS MISSIONS: CURRENT STATUS AND OPPORTUNITIES.

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Introduction: Mars ISRU plans usually involve production of liquid propellant components (e.g. O_2, CO, CH_4) on the planet surface. The common problem in these scenarios is the significant power required to produce, liquefy, and store cryogenic propellants. An alternative approach in the Mars ISRU, reviewed in this presentation, suggests using the Martian CO_2 directly as an oxidizer in a jet [1-4] or rocket [5-13] engine. This approach is based on the unique ability of some metals to burn with CO_2, briefly discussed below.

Combustion of Metals in CO_2: Reactions of metals with CO_2 have been present in propulsion and pyrotechnics for many years. For example, in solid rocket engines, Al particles burn in gaseous products of ammonium perchlorate/hydrocarbon binder combustion, where CO_2 and H_2O are the main oxidizers. The solid rocket applications and the idea of metal/CO_2 propulsion on Mars and Venus inspired researchers to study combustion of Al and Mg in CO_2, experimentally [14-41] and theoretically [25, 37, 42-45]. The fundamental studies show that both Mg and Al particles rapidly burn in CO_2 environment producing metal oxide, CO and relatively small amount of carbon. There is, however, a significant difference in ignition of Mg and Al, important for applications. Magnesium ignites in CO_2 at temperatures slightly above its melting point (933 K) whereas aluminum must be heated to near the melting point of Al_2O_3 (2327 K). Ignition of Al particles can be improved by additives and coatings. For example, Ni coating decreases the ignition temperature of Al particles by ~1000 K [46-48]. Analysis of the above-referred literature shows that significant knowledge and a high level of understanding have been reached for combustion of single Mg and Al particles in CO_2.

Types of Metal-CO$_2$ Propulsion: Performance characteristics of jet engines in CO_2 atmosphere of Mars were calculated for Al, AlH_3, H_2 [1], and Mg [2, 4] as fuel. Unfortunately, low atmospheric pressure on Mars leads to either low thrust [1], or large specific fuel consumption and extremely large inlet and exhaust nozzle [2]. In addition, stable operation of the metal-CO_2 turbojet is doubtful due to deposition of solid combustion products on the turbine blades [3] while ramjets require supersonic speeds of vehicle and hence cannot be used for takeoff from the Martian surface.

In [5], a rocket engine using liquefied CO_2 as an oxidizer and metals as fuel was proposed for Mars ascent vehicles. Thermodynamic calculations of the engine performance characteristics were made for various candidate metals, their hydrides and mixtures with hydrogen-containing compounds [5, 8]. The results indicate that the highest theoretical specific impulse (I_{sp}) could be reached with Be or BeH_2, while Mg and Al show the best results among other, nontoxic metals. Boranes proposed in [7] were excluded from further consideration due to high condensed phase fractions in the combustion products and expected boron oxide deposition in nozzles [8]. On the contrary, Mg and Al show relatively low fractions of condensed phase in combustion products, and their oxides have high melting points (3100 and 2327 K, respectively), which is a favorable fact to avoid agglomeration and deposition. Replacement of pure Mg or Al by a hydride of the metal increases the maximum I_{sp} but does not effect (for Al) or decreases (for Mg) I_{sp} at oxidizer/fuel ratios higher than stoichiometric. The thermodynamic calculations, analysis of properties and available ignition/combustion characteristics of metals support the conclusion that Mg is the main candidate fuel for rocket engine using CO_2. Aluminum can also be used provided its ignition is improved.

Production of Liquid CO$_2$ and Metal Fuel on Mars: Temperature and pressure on Mars surface create favorable conditions for liquefaction of CO_2 from the atmosphere. For example, Lockheed Martin's method collects pure CO_2 as a solid mass on a chilled surface and then produces high pressure liquid CO_2 by allowing the frozen mass to thaw [49]. For the metal fuel, two options are possible. The easier option is to transport the metal fuel from Earth to Mars. In this case, the in-situ propellant production system (ISPPS) is reduced to the CO_2 acquisition system, decreasing both power consumption and mass of ISPPS by about 80% [7]. The second option is to produce the metal fuel on Mars. One possibility is to recycle metal parts of lander or other materials that are no longer needed. Note that transforming structural aluminum to powdered fuel for $H_2/O_2/Al$ rocket engines was discussed for recycling the Space Shuttle external tank on the orbit [50]. Another possibility is to recover the metal fuel from the Martian ores or soils. The content of Mg in Martian regolith is estimated to be 3.6%, against 0.5% in terrestrial soil [51]. There exists voluminous literature on methods for extraction of metals from lunar and Martian soils. Dissolving the regolith in supercritical CO_2 [52] is particularly attractive as it involves liquid CO_2, obtained in large amounts anyway during production of the engine oxidizer.

Design of Metal-CO_2 Rocket Engine: Among different design options for the metal/CO_2 rocket propulsion system [5, 9, 10], direct feeding of the metal powder and the use of gelled CO_2/metal propellant are of particular interest. The direct powder feeding option involves a combination of a piston-cylinder assembly and a carrier gas, developed for engines and reactors using powdered metal fuel [4, 12, 53-55]. Vaporized CO_2 or an additional gaseous component, such as H_2 or N_2, can be used as the carrier gas. Note that to use CO_2 as carrier seems preferable because the use of additional component reduces the in-situ fraction of propellant. Additional liquid CO_2 can be fed as a conventional liquid propellant. In the case of gelled CO_2/metal propellant design, the feed system becomes even simpler, while still retaining the possibility to easily throttle and restart the engine. Although additional propellant processing operations on Mars are required, this design deserves further investigation. Experience in studies of metallized gelled propellants containing Al, kerosene, liquid O_2 and H_2 [56, 57] can be used for development of gelled CO_2/metal propellants.

Potential Missions Using Metal-CO_2 Propulsion: The reduction of propellant mass transported from Earth makes the metal/CO_2 rocket engine advantageous even despite the relatively low I_{sp} (~200 s for Mg or Al as fuel). It should be noted that I_{sp} can be increased by addition of hydrogen [3] but the H_2 storage is a significant problem. The term used sometimes in ISRU "effective I_{sp}", which is the thrust per pound of propellant transported from Earth, is higher by several times than the "normal" I_{sp} in missions with Martian CO_2 and Earth-born metal fuel, and tends to infinity when all propellant is produced on Mars. More careful analyses for "Martian CO_2 - Earth-born metal fuel" demonstrated that the proposed rocket propulsion system could be used as the first stage of the ascent vehicle in a mission with a single takeoff to Earth or to low Mars orbit [6, 12]. Significant advantages of metal/CO_2 propulsion are expected in missions with several ballistic flights (hops) on Mars, when the oxidizer (liquid CO_2) is taken from the atmosphere prior to each hop [5, 6, 10]. The most applicable analysis was made recently for a small (200 kg) hopper mission where CO_2 acquisition and required power were taken into account [13]. The obtained results show that the proposed hopper is competitive with a rover, while offering the benefit of terrain independence.

Thus, the rocket propulsion system using liquefied Martian CO_2 and Earth-born metal fuel could be advantageous in forthcoming robotic missions while the production of both CO_2 and metal fuel on Mars could play a significant role in more advanced, including human, missions.

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Journal Abbreviations: *CESW: Combustion, Explosion, Shock Waves; CF: Combustion and Flame; CST: Combustion Science and Technology; JBIS: Journal of the British Interplanetary Society; JPP: Journal of Propulsion and Power; PCI: Proceeding of the Combustion Institute.*

Layered Architectures for Mitigation and Processing of Planetary Dust for Manned and Robotic Space Exploration

Frederick A. Slane and Gary ‘ROD’ Rodriguez

Abstract: *This paper is a fully elaborated version of the paper submitted to ASCE 2005 which was constrained in length and content. Multiple methods, technologies and protocols are proposed to address the many disparate aspects of dust mitigation. Effective integration of this emerging patchwork of solutions will require consistent metrics across disciplines. We posit a multi-layered mitigation architecture with attainable criteria for each layer. With astronaut(s) at the 'center' of the protection layers, environmental standards would set the criteria for the innermost level. Construction of the architecture will establish specific definitions, specifications, standards, implementation contexts and exceptions. Key to the success of the methodology proposed are successive layers of application, providing a robust redundancy. The baseline environmental definitions deliberately set the design points to reasonable and adequate standards. Provisional working standards are set as placeholders. The architecture will serve to align the many mitigation opportunities into a manageable set of engineering guidelines.*[1]

In May of 2005, NASA’s Johnson SpaceFlight Center co-sponsored with NASA/Colorado School of Mines’ Project Dust, the first Dust Focus Conference. This conference explored mitigation dust opportunities on the Moon and Mars for both human and robotic exploration. Dr. Harrison Schmitt’s presentation crystalized our thinking about establishing a layered architecture for human and robotics exploration and development. Our early notions had been context-driven and focussed on the hardware and mitigations, whether a rover, an EVA suit, a lander or an habitat. Dr. Schmitt’s description of his ‘layers-of-an-onion’ approach would neatly adapt our layered plies to a more generalized series of protective cocoons through implementation of successive mitigation measures.

From anecdotes of the Apollo astronauts to video observations of Mars rovers *Spirit* and *Opportunity* it is clear that dust is a significant component of local planetary environments. This paper is constructed to communicate an emerging approach which can provide guidance for dust mitigation and ISRU research teams. Methods of vetting information and communicating to dependent layers are a key component. The over-arching objective of this architectural pursuit is translating basic science information to effective systems performance on the Moon and Mars.

Many technologies and protocols have been proposed to address the disparate aspects of dust mitigation. Effective integration of this emerging

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[1] This research was supported under NASA BAA Contract NNM05AA88C.

patchwork of problems and solutions will require consistent metrics across many and diverse disciplines. Similar to many other technical endeavors, the perceived utility of a guiding protocol or standards architecture will include the basic research, the solution engineering and field operations. We first enumerate the global processes which take the dust efforts from concept through research and on to application. These processes loosely correspond to the Technology Readiness Levels (TRL) used by NASA to characterize the distance covered by a technology between concept and *flight-ready* hardware.

The processes which constitute the core of a Dust Research and Development Plan are the Architectural Framework, Basic Science, Applied Science, System Design, System Fabrication, System Integration, System Operations and System Disposal.

The fragmented landscape of dust hazards mitigation was unified and clarified through yet another application of layered definitions. Industrial and Human-Physiological requirements were found to be compatibly defined on this new ‘scale.’

Conversations about mitigation applications and facility designs will probably benefit significantly through the diagramming techniques suggested by Scallion. This tool will bring rigor and standardization to now numerous manned and unmanned exploration structures and architectures.

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A One-Piece Lunar Regolith-Bag Garage Prototype

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Abstract

Shelter structures on the moon, even in early phases of exploration, should incorporate lunar materials as much as possible. We designed and constructed a prototype for a one-piece regolith-bag unpressurized garage concept, and, in parallel, we conducted a materials testing program to investigate six candidate fabrics to learn how they might perform in the lunar environment. In our concept, a lightweight fabric form is launched from Earth to be landed on the lunar surface and robotically filled with raw lunar regolith.

In the materials testing program, regolith-bag fabric candidates included: Vectran™, Nextel™, Gore PTFE Fabric™, Zylon™, Twaron™, and Nomex™. Tensile (including post radiation exposure), fold, abrasion, and hypervelocity impact testing were performed under ambient conditions, and, within our current means, we also performed these tests under cold and elevated temperatures. In some cases, lunar simulant (JSC-1) was used in conjunction with testing. Our ambition is to continuously refine our testing to reach lunar environmental conditions to the extent possible.

A series of preliminary structures were constructed during design of the final prototype. Design is based on the principles of the classic masonry arch. The prototype was constructed of Kevlar™ and filled with vermiculite (fairly close to the weight of lunar regolith on the moon). The structure is free-standing, but has not yet been load tested. Our plan for the future would be to construct higher fidelity mockups with each iteration, and to conduct appropriate tests of the structure.

LUNAR REGOLITH, SOIL, AND DUST MOVER ON THE MOON

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Returning humans to the Moon in the near-future will involve many considerations, designs, and engineering projects for exploration and ISRU activities. One factor common to all activities on the Moon is the ever-present, sharp, abrasive, glassy dust – the <20 µm portion of the lunar soil consisting of ~20 wt% of the soil. Various ISRU activities will entail movement of the lunar regolith, but conventional means will launch a large portion of dust that will numerous problems as it falls back covering such installations as solar cells, for example. The finest portions remain suspended in electrostatic levitation around the Moon – making for lots of consternation by any astronomers. But, can this dust portion of the soil be kept from having such deleterious effects? This is the subject of our study.

The lunar regolith contains many of the answers to reestablishing us on the Moon. Because of the presence of nanophase metallic Fe (as in a Fe nail) in the impact-produced glass, this "well-graded" soil can be sintered and melted into building blocks, antenna dishes, roads, etc. with the application of microwaves [1]. The surfaces of the dust contain solar-wind particles, providing a potential source of hydrogen for water and fuel. However, there is a down-side to the fine portion of the soil, the DUST. It is prone to being 'kicked up' by most activities on the surface of the Moon, thereby creating a plethora of problems, many experienced during the Apollo Missions, as discussed by Taylor et al. [2]. Therefore, it is imperative to develop a method of handling and collecting lunar regolith that mitigates against the possibility of stirring too much dust into the lunar "atmosphere."

We have devised a potential scheme to mitigate the dust problem utilizing its ferromagnetic pro-perties, due to the presence of nanophase metallic Fe in the ~40-50% impact glass of the lunar soil. The presence of 80-90% glass in the dust makes this portion of the soil totally capable of being attracted by a simple magnet [2]. The presence of this np-Fe bearing glass in larger agglutinates also renders a magnetic susceptibility to the larger grain-sized soil particles. It should be possible to effectively "suck-up" the regolith using magnetic fields. This can be done in a similar fashion to the way maglev trains and coil guns (or gauss weapons) work. These two developing technologies *use consecutive electro-magnets to pull an object along*. The largest advantage of these technologies is that there are no moving parts in the device. Most importantly, such an attracting systems applied to the Moon would not only pull the soil along, but effectively capture the dust as well.

The operation of this 'coil vacuum' is conceptually simple (Fig. 1). This device consists of a series of wound coils individually powered to generate magnetic fields. Soil is picked up by a 'nose coil' and pulled into the center of the coil. As this moving soil approaches this first coil, the coil is powered down, and the next coil in the sequence is powered up and attracts the particles of soil further into the tube. As the soil approaches this second coil, it too is powered down, and the next coil in the sequence is powered up to tractor the soil further down the line. This process of turning coils on and off continues in a "caterpillar / millipede effect" moving the soil particles along this electronic-conveyor belt.

Conceptually a lunar surface-mining operation might use this device to gather and transport soil (+dust) across great distances to processing plants. One possibility is to have a 'Trunk Line' that is capable of large magnetic fields and moving large amounts of material with several feeder lines into it (Figure 2). The feeder lines would branch off of the Trunk Line pulling in material from the surrounding area. This allows for several areas to be excavated simultaneously, and as the regolith is exhausted in one large area, the Trunk Line can be extended to new areas.

To make the "Lunar Magnetic-Soil Vacuum Cleaner" (LMSVC) and the 'coil vacuum' scheme a reality requires several issues to be overcome. First, the magnetic fields must be sufficiently strong as to attract the soil from a reasonable distance and accelerate it to a speed sufficient to carry it to the next coil through momentum. In the case of the Moon, this is eased somewhat by both the absence of atmosphere and the $1/6^{th}$ G gravity on the Moon (lighter to pick up vertically, and less drop in horizontal transport). Second, it will be necessary to determine the on-off timing needed to energize and relax consecutive rings, in order to keep a continuous flow of soil through the tube. The feedback-loop timing will maintain efficiency.

The dust of the Moon is one of the major environmental challenges that we face in returning to the lunar surface. However, this dust can be of great use in making life on the Moon possible. It is a matter of perspective and attitude that can change this pest and curse into an invaluable tool and resource. By using properties that are inherent in the lunar soil, it is possible to eliminate the potential hazard of having this dust suspended above the surface.

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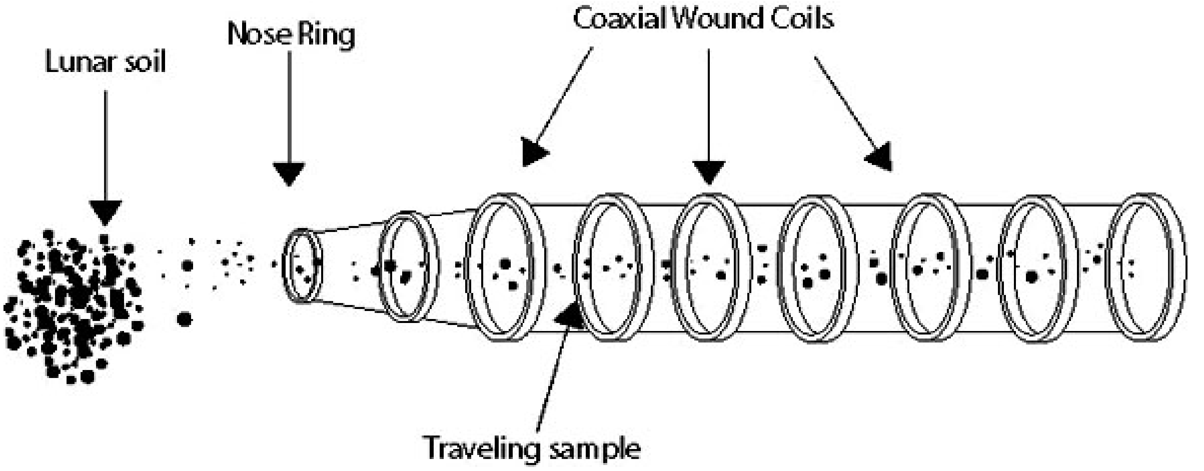

Figure 1. Diagram of our "Lunar Magnetic-Soil Vacuum Cleaner" illustrating a 'coil vacuum'. Coaxial rings are sequentially powered up and down in a rippling effect to move ferromagnetic lunar soil to the right.

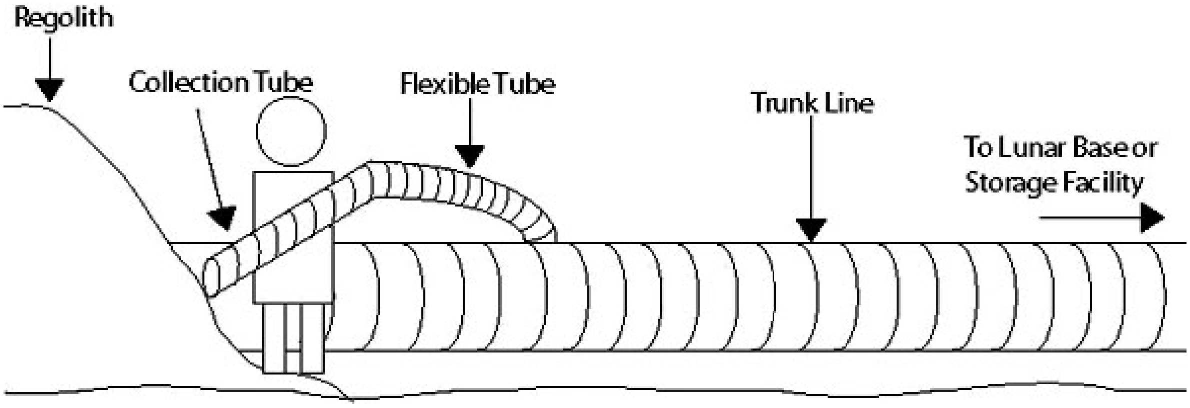

Figure 2. Conceptual drawing of possible method of collecting lunar soil using the "Magnetic-Soil Vacuum Cleaner" (LMSVC) with the concept of a 'coil vacuum'. The astronaut/robot uses a slightly flexible coil 'sucker tube' to collect soil, which is in turn fed into a hard mounted "Trunk Line" that is capable of higher flow rates and is transported to be used at a relatively stationary facility. Multiple collection branches would feed into one trunk line.

POTENTIAL TOXICOLOGY OF LUNAR DUST.

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Introduction: As NASA plans returning humans to the Moon, then on to Mars and the great Beyond, it is imperative that we recall experiences from the Apollo Era. As reviewed by Taylor et al. [1], one problem that was not well anticipated was the ubiquitous, adherent, abrasive, and floating dust – generally the <20 µm portion, which is ~20 wt% of the lunar soil. All "Rock Boxes" on all six Missions leaked from the lunar atmosphere of 10^{-12} torr, in spite of the knife-edge In-metal seals. Habitats will need to be over-pressurized to account for inevitable leaks, especially around entrances. The most critical effect of lunar dust, however, may be on the astronaut's health. With each Apollo Mission to the Moon, astronauts remarked about the "gun powder" smell when they took off their helmets in the LM, upon returning from an EVA. Several astronauts reported respiratory or eye irritations; Jack Schmitt was affected the most with coughing and transient congestion. It was obvious that there was something unusual about the lunar dust.

Flash back to the Viking Missions to Mars, with the fizzing of the "chicken soup" placed on the Martian soil – not life, just UV-induced, highly reactive, oxidizing soil. Take the red planet and move it to 1 AU, take away any vestige of an atmosphere, and that is the Moon. The intense UV radiation, solar wind, plus the extreme micro-meteorite induced comminution of the soil should make the lunar soil and dust extremely chemically reactive, and therefore potentially toxic. But exiting Apollo samples are no doubt passivated by exposure to terrestrial air and moisture, and by exposure to the traces of oxygen present in the nitrogen atmosphere used to preserve them. One of the most important experiments to be performed with the first lunar lander is "the chemical reactivity" of pristine lunar dust in the respirable size range.

Lunar Dust is a unique portion of the regolith on the Moon, consisting predominantly of impact-produced glass containing myriads of nano-sized metallic Fe particles (3-33 nm; Fe like that in a Fe nail; Taylor et al., 2001). It is this nanophase Fe that gives the lunar dust its property of being attracted to a magnet [1] and as discovered by Taylor & Meek [2], its tremendous response to microwave energy. However, the particle-size distribution (PSD) and morphologies are unusual as well and are the subjects of this paper.

Particle-Size Distribution: From the selected number of lunar dust samples that have been processed to date, it is obvious that the dust has a mode of maximum particles at 100-200 nm (Fig.1), exceptionally small. These small particles are capable of moving from human lungs directly into the blood stream. It should be emphasized that these fine particles consist almost entirely of glass containly myriads of nanophase metallic Fe. This highly reduced form of Fe may interact with hemoglobin for oxygen depravation effects. Finding a proper lunar dust simulant to replicate these particle sizes will be difficult. The freshly produced JSC-1Af dust simulant has a particle maximum of 500-700 µm [3-4].

Particle Morphology: Broken pieces of agglutinitic glass make up the majority of the dust particles. Some of the first-cycled agglutinitic glasscontains minute vesicles rendering extreme reaction-surface areas to these particles (Fig. 2). Many of the grains have splash surfaces from melt; others are essentially rounded beads of impact melt. In almost all cases the surfaces of the dust particles are not smooth. Although the aspect ratios are near 1, the effective surface areas of each particle are not well-represented by a sphere. Also, the greatly increased reactive-surface areas of the dust can add significantly to the toxic nature of the dust as this aids surface reactions and dissolution of chemical constituents into the blood stream [5-6].

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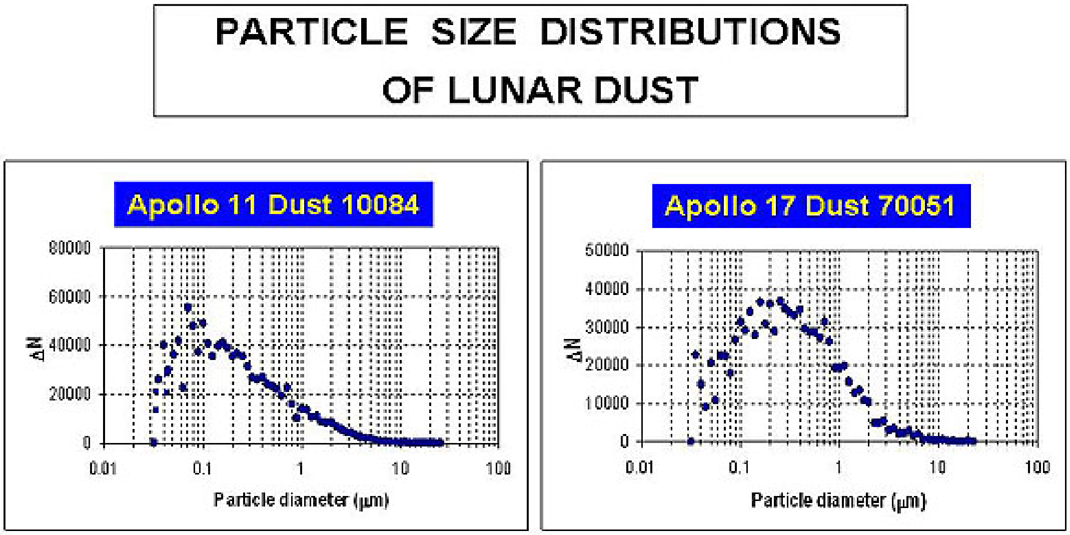
Figure 1. Particle Size Distributions of Apollo 11 and Apollo 17 dust. Note the particle modes at only 100-200 nm, where grains can move directly into an astronaut's blood stream from their lungs. Taken from Park et al. [3-4].



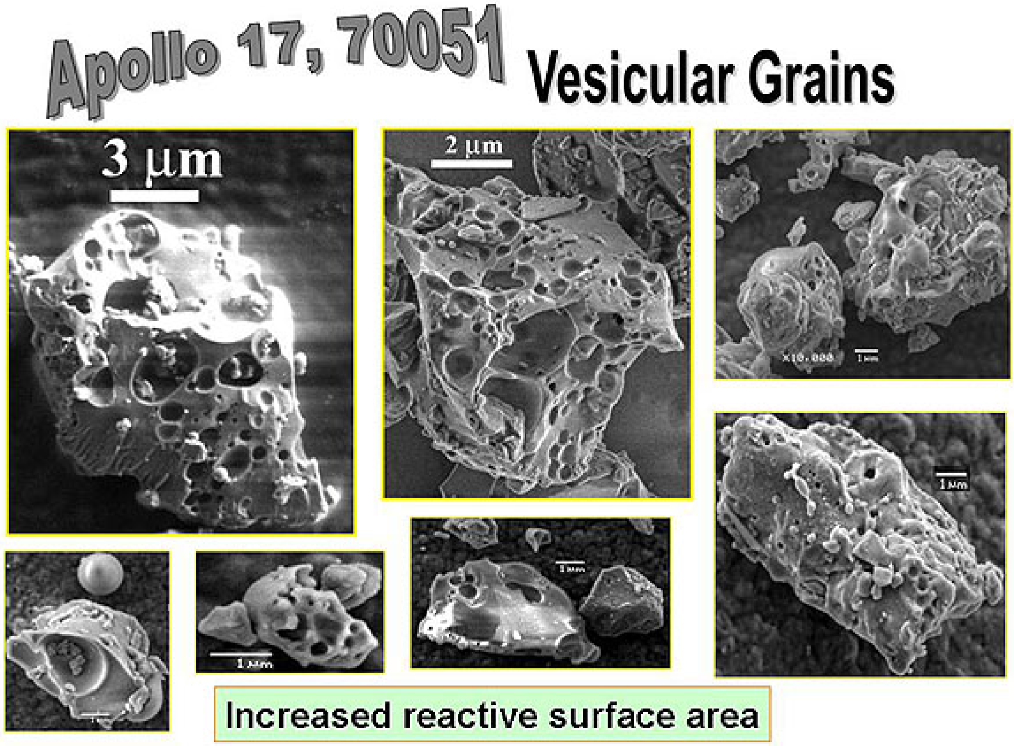


Figure 2. Different morphologies for dust particles in Apollo 17 soil 70051, taken from Liu et al. [5-6]. These morphologies are relatively continuous with decreasing grain size. Note the "Swiss-cheese" texture formed by the escape of solar-wind volatiles during the melting process. Also, note the greatly increased reactive-surface areas because of such textures, in addition to the splash glass see in the lower right.

Future In-Space Operations Support of ISRU.

Future In-Space Operations Working Group members Harley A. Thronson[1], Surendra Sharma[2], and Andrea E. Schweitzer[3].
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Introduction: Future in-space operations (FISO) has the potential to play a vital role in achieving the goals of the *Vision for Space Exploration* and in situ resource utilization (ISRU) on the Moon and Mars. Building upon elements of the evolving Exploration Architecture, the FISO capabilities could support ISRU in ways such as:

- Support advanced lunar surface operations, to coordinate, assist, and communicate over large regions, by, for example, placing a capable permanent utility, relay, storage and support structure at an Earth-Moon libration point.
- Provide support capabilities for human and robotic lunar surface contingencies and emergencies.
- Serve as precursors and demonstrations of new capabilities and advanced technology.

Throughout this abstract “in-space” refers to low-gravity free-space, such as in lunar orbit or at a libration point, to be distinguished from surface-based infrastructure, such as planetary and lunar surface outposts, planetary ISRU units, and planetary lander and access vehicles.

Lunar Surface Operations Support: Future in-space architecture and capabilities will be essential to support major missions as their complexity and the extent of human and robotic presence on the Moon increases over the next few decades. In particular:

Technological Enhancement. Suitable in-space infrastructure at lunar libration points enables advantageous communications and navigation capabilities, such as constant line-of-sight communications to lunar surface for telerobotics/robotics operations with little latency.

Assembly, Service, Repair and Logistics. As human and robotic lunar surface operations become more extensive beyond the early “sortie” missions, a suitable nearby support facility becomes more useful and enables safer operation. For example, contingency supplies and back-up systems, sub-systems and equipment can be stored at an Earth-Moon libration point: fuel and life-support consumables, spare components and additional scientific instruments, and contingency-use vehicles. If fuel, water, oxygen, metals, and other products become advantageous to produce on the lunar surface, a near-lunar depot becomes even more useful and valuable to store products outside the lunar gravity well for availability to in-space users.

Surface Contingencies and Crew Medical Emergencies. Return from the lunar surface, for example in the event of a medical emergency, could take days and subject the crew to potentially dangerous acceleration/deceleration. Furthermore, medical or surgical treatment in zero gravity may not be advisable. Alternatively, a support facility equipped with necessary equipment and supplies at a libration point will be far closer in time, either for supporting the crew to remain on the surface for medical care or as a treatment center to stabilize an emergency in advance of returning the crew to Earth.

Shared Supporting Systems. In-situ resource utilization (ISRU) may share supporting systems and products with other programs. A shared investment will have a strong effect on the cost of long-term space architecture and operational capabilities for ISRU, including storage of fluids and gases derived from ISRU, and their efficient and safe in-space transfer.

Conclusion: The initial phase in the development of FISO will be to build upon, extend, and apply elements of the Exploration Architecture with simultaneous development in areas that might include robotics and telerobotics, advanced EVA and in-space propulsion. In the future, as lunar surface operations become more extensive and with FISO infrastructure in place, we will have more experience and infrastructure to begin advanced human missions to Mars.

THE USE OF TRIBOCHARGING IN THE ELECTROSTATIC BENEFICIATION OF LUNAR SIMULANT.

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Introduction: Any future lunar base and habitat must be constructed from strong dense materials in order to provide for thermal and radiation protection. Lunar soil may meet this need. Lunar regolith has high concentrations of aluminum, silicon, calcium, iron, sodium, and titanium oxides. Refinement or enrichment of specific minerals in the soil before it is chemically processed may be more desirable as it would reduce the size and energy requirements required to produce the virgin material and it may significantly reduce the process' complexity. Also, investigations into the potential production of breathable oxygen from oxidized mineral components are a major research initiative by NASA. The feasibility of extracting oxygen from the FeO component by hydrogen reduction in terrestrial soils has been demonstrated [1].

NASA JSC-1 was used in this study. It is principally basalts, containing phases of plagioclase, pyroxene, olivine, and ilmenite [2,3]. The objective was to investigate the use of tribocharging to charge the lunar stimulant and a parallel plate separator to enrich different lunar soil fractions. This technique takes advantage of the high Lunar vacuum in which much higher voltages can be used on the separation plates than in air. Additionally, the Lunar gravity, only being 1/6 that of Earth, allows the particles more separation time between the plates and therefore enhances separation.

Four different materials were investigated for the triboelectrification process; aluminum, copper, stainless steel, and PTFE. These materials were selected because they offer a wide variation in work functions (aluminum 4.28 eV, copper 4.65 eV, stainless steel 5.04 eV, and PTFE 5.75 eV) [4]. The difference between the work function of each material and the simulant influences the charge obtained by the grains.

Experimental: The JSC-1 was sieved to different grain size fractions (> 100 μm, 75-100 μm, 50-75 μm, 50-25 μm, and < 25 μm) and each fraction was analyzed using X-ray Photoelectron Spectroscopy (XPS) and Secondary Electron Microscopy (SEM) to determine mineral surface composition, speciation, and size distribution as a function of particle size. The objective was to determine if there was a compositional correlation between different particle sizes.

Charge-to-mass (Q/M) measurements in air were performed in air by fluidizing the powder in a bed and passing the simulant through a static mixer of a particular material for 30 seconds and collecting it in a Faraday pail grounded through an electrometer. To measure the Q/M in vacuum, the simulant was placed into a cup with a hole in the bottom supported on a fine mesh screen (325 mesh). The cup could be resistively heated to remove moisture and shaken to allow the dry stimulant to pass through a solid block of material (either PTFE, copper, or aluminum) in which a channel composed of a "zig-zag" series of inclines greater than 50 degrees has been cut (Fig. 1). The voltage to the vibrating motor can be varied to control the amount of simulant passing through the channel.

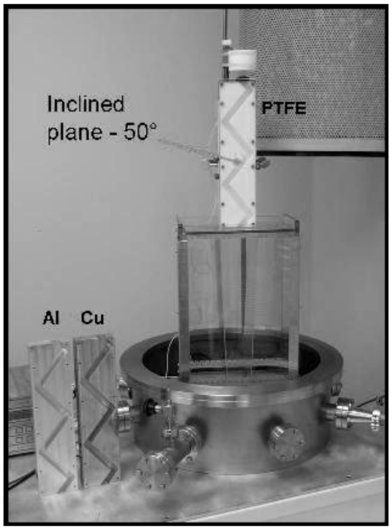

Figure 1. Inclined plane chargers and charge separator experimental setup. The front plates on the chargers have been removed for clarity.

For the separation experiments, the Faraday pail was replaced with the charge separator. The dust accumulated on each plate and on the filter paper in the collection box at the bottom of the plates was weighed to determine the mass-fraction separated. Samples of the simulant collected on each plate were then analyzed by XPS and Raman spectroscopy.

Results and Discussion: The mean relative atomic concentrations of the five sieved size fractions as determined by XPS when converted to weight % were very close to that reported for the bulk composition (within +/- 5%) [2,3], and little compositional variation between the fractions was observed. Therefore the 50-

75 μm size fraction was only used for the tribocharging experiments as this is near the center of the lunar regolith range of 45-100 μm [5]. Figure 2 shows the Q/M measurements of the tribocharging using the static mixers and the incline plane chargers in air, and the incline plane chargers in vacuum. For all chargers, the simulant charged positively against PTFE, while for the three metals, it charged negatively; in direct correlation between the acquired charge on the dust and the work function of the charging material. For the incline plane tribochargers, the Q/M measured in vacuum was larger than that in air for the tested materials. The absence of moisture allowed for better charging. From the plot, the work function of the JSC-1 simulant was estimated to be ~ 5.0-5.3 eV in vacuum. This is lower than found by Sternovsky et al. [6] who determined an effective work function of 5.8 eV for JSC-1 lunar simulant in the 125-150 μm range, but similar to that of 5.25 eV and 5.5 eV determined for Al_2O_3 and SiO_2, respectively [6]. The large variation in acquired charge for each material is most likely due to irregular particle shapes, which allowed charging to occur only on localized spots. Variation in the acquired charge also may be caused by the number of contacts the larger particles have with the charging material.

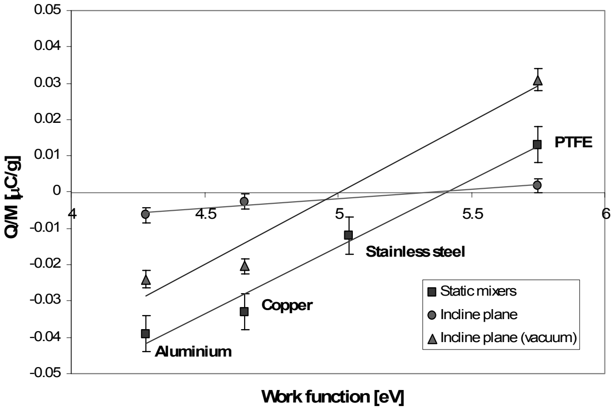

Figure 2. Acquired charge-to-mass (Q/M) as a function of the work function of the charging material; Al (4.28 eV), Cu (4.65 eV), SS (5.04 eV), and PTFE (5.75 eV).

XPS data of the 50 - 75 μm size fraction of JSC-1 after beneficiation with the aluminum inclined plane charger in vacuum, showed a change in the chemical composition of a number of elements in each separation fraction compared to a control sample (Table 4). An increase in the Fe concentration on the negative plate suggests the Fe bearing minerals such as ilmenite ($FeTiO_3$) and olivine ($(Mg, Fe)_2SiO_4$) were charged positively, while the Na-rich plagioclase albite ($NaAl_2Si_2O_8$) charged negatively. The Raman data of the control and separated fractions showed ilmenite ($FeTiO_3$), anatase (TiO_2), magnetite (Fe_3O_4), hematite (α-Fe_2O_3), ferrite ($M^{2+}Fe_2O_4$), olivine ($(Mg,Fe)_2SiO_4$), plagioclase ($NaAlSi_3O_8$/$CaAl_2Si_2O_8$), and pseudobrookite (Fe_2TiO_5). However, in the separated fraction on the negative plate an increased concentration of magnetite and pseudobrookite was observed, whereas on the positive plate predominantly ferrite was observed. However, this is preliminary data and further work is being undertaken.

Table 1. Relative % change on surface composition of elements of interest of JSC-1 simulant from a control sample after one pass through the separator (Carbon and oxygen were not included).

Plate	Na	Fe	Ca	Si	Al
-15kV	-31%	+8.6%	+13%	+28%	+3%
+15kV	+5.7%	-18%	+4%	+8.9%	-11%

Further separation experiments, including using the copper and stainless steel tribochargers, on all sieved size fractions are planned as well as multiple passes of the separated fractions through the separator to improve yield as well as experimenting with NASA's new lunar stimulant JSC-1A.

Conclusions: Lunar stimulant JSC-1 was successfully and consistently tribocharged in air using static, spiral mixers and in vacuum using incline plane gravity chargers of various materials. The incline plane charger was more effective in vacuum.

A direct correlation between the work function of the simulant and that of the charging material was established.

The twin plate separator proved successful in separating simulant by charge with full recovery of the material.

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The Electrochemical Production of Oxygen and Metal via the FFC-Cambridge Process.

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Introduction: The most significant component in any bi-propellant rocket is the oxygen required for fuel combustion. This may account for up to 85%wt of the rocket propulsion reactants. Therefore, it is vital that locally produced oxygen is available from off-world sources to enable more economically viable space exploration to more distant regions of solar systems, and beyond.

Our Moon in particular is a desirable location for the refuelling of rockets. Its relative close proximity to the Earth (~380,000km), and it being the only off-world site so far successfully visited by man, makes it the obvious first candidate when considering the location of a spacecraft refuelling station. Furthermore, elemental analysis of lunar material from Apollo and Luna landings, has yielded that the composition of the lunar surface material is approximately 44%wt oxygen, locked in the form of metal oxides (Figure 1)[1]. Through the novel FFC-Cambridge Process, it may be possible to extract the oxygen component from the lunar regolith to ultimately fuel spacecraft, and produce a potentially useful metallic side-product.

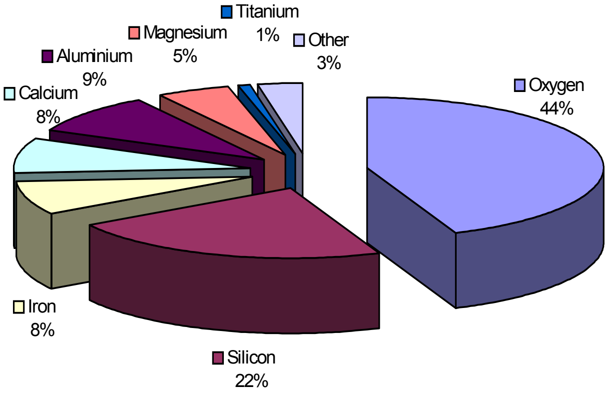

Figure 1. [Elemental weight composition of the Moon's lunar surface material.]

The FFC-Cambridge Process: The novel FFC (Fray-Farthing-Chen)-Cambridge Process was discovered in 1997, by three scientists, Derek J. Fray, Tom W. Farthing and George Z. Chen, at the Materials Science and Metallurgy Department, University of Cambridge, UK. They found that metal could be directly produced from its oxide by negatively charging it in a molten salt electrolytic cell[2].

A significant amount of work has since been concentrated on the electrolytic synthesis of numerous metals and alloys directly from their cathodic metal-oxides. This has involved the reduction of primary lunar regolith constituent metal-oxides, such as: silicon oxide (SiO_2); aluminum oxide (Al_2O_3); and iron oxide (Fe_2O_3).

The FFC-Cambridge Process is a relatively simple process, with low labour and energy requirements. It operates by placing a metal-oxide (MO) into a molten calcium chloride salt bath ($CaCl_2$), and making it a cathode. Consequently, the oxygen from the metal-oxide becomes ionised through the half reaction presented in [1], and leaves the negatively polsarised electrode.

$$MO \rightarrow M + O^{2-} \qquad [1]$$

The inventors of the FFC-Cambridge Process have termed the ionisation of oxygen at the metal-oxide, as *electrodeoxidation.* Over a period of time, a low-oxygen containing metal (M) is produced at the cathode. The oxygen ion (O^{2-}) moves through the molten salt bath through migration, diffusion, and convection processes to arrive at the positively charged anode. Conventionally-used graphite materials react with these oxygen ions to form carbon monoxide or carbon dioxide gas at the anode.

Graphite Anode:
$$nO^{2-} + nC \rightarrow nCO + 2ne^-$$
$$nO^{2-} + n/2\ C \rightarrow n/2\ CO_2 + 2ne^- \qquad [2]$$

However, by replacing an inert anode for a graphite anode it is possible to liberate and generate the desired oxygen gas.

Inert Anode:
$$nO^{2-} \rightarrow n/2\ O_2 + 2ne^- \qquad [3]$$

The basis of this work is therefore essentially to find a suitable non-reactive anode material that is capable of generating oxygen gas from the metal-oxide cathode, and consequently producing a metallic by-product.

Thermodynamic Considerations: The standard reduction potentials for the anodic reactions [2], and [3] have been calculated from a thermodynamic database, at 1173K, using a Ca^{2+}/Ca reference point of zero, and by assuming that all reacting or produced species were at unit activity or unit partial pressure. It was determined that an anodic potential greater than 1.116V and 1.025V would be required to synthesise oxygen on an inert anode, with reference to CO and

CO_2 synthesis on a consumable graphite anode. This energetical demand cannot be avoided as oxygen and not carbon oxides are the desired product. However, it should be noted that oxygen liberation is thermodynamically more favourable than undesired chlorine synthesis (from the decomposition of the calcium chloride salt) by 0.557V. This may ensure that high purity oxygen gas is ultimately obtained.

Experimental Work: Candidate anode materials were selected for testing using the a two-electrode set-up presented in Figure 2. A 4.0g titanium-oxide pellet was made the cathode, with a constant 3.0V potential applied between the electrodes, when immersed into a molten $CaCl_2$ / CaO salt mixture, at 900°C. The oxygen composition of the exhaust gas stream was measured using a stablised zirconia analyzer.

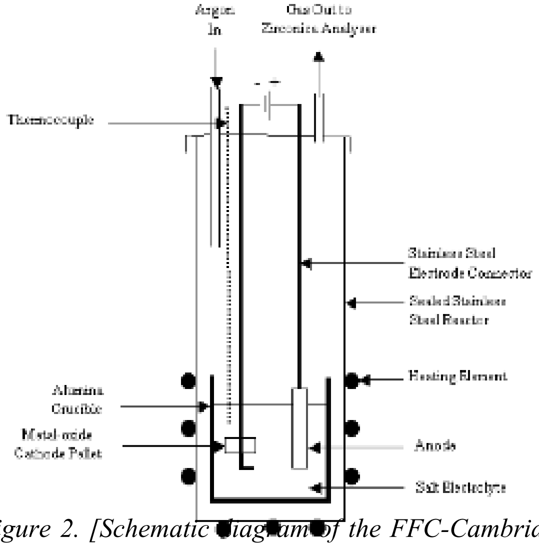

Figure 2. [Schematic diagram of the FFC-Cambridge Process electrolytic cell.]

Once the most suitable candidate anode material had been established, further experimental work was conducted in which JSC-1 (a lunar regolith simulant material obtained from NASA) was made the cathode to establish whether it could be metallised.

Anode Results: It was found that a tin-oxide based material was the most suitable anode for the FFC-Cambridge Process after testing of numerous metal, cermet (metal dispersed within a ceramic matrix), ceramic, and also carbon-based anodes. This is since it remained relatively inert during electrolysis (Figure 3).

Figure 3. [Tin-oxide anode before (left) and after 24hour electrolysis (right).]

Furthermore, it was found that the oxygen detected during electrolysis in the exhaust gas stream using the tin-oxide anode was significantly above its background level. This result indicates that oxygen may indeed be produced from metal-oxides, such as those constituting the lunar surface, using the FFC-Cambridge Process.

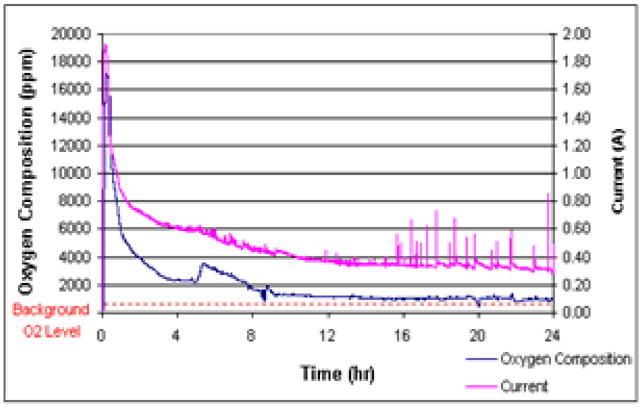

Figure 4. [Oxygen composition and current-to-time profile for the tested tin-oxide anode .]

Cathode Results: JSC-1 pellets of similar composition to lunar regolith were reduced using a tin- oxide anode. It was found that the material became metallised through the application of the FFC-Cambridge Process. Loose, as-received JSC-1 material was also found to be succefully reduced.

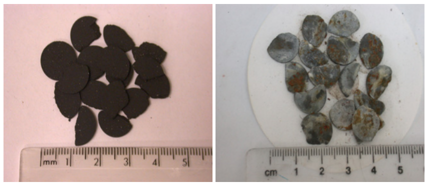

Figure 5. [JSC-1 pellets sintered in argon (left), and metallic pellets obtained after electrolysis (right) .]

Conclusion: The FFC-Cambridge Process was found to be suitable for the production of oxygen from metal-oxides through initial bench-scale testing using a tin-oxide anode. A metallic product was also directly produced from JSC-1 (a lunar regolith simulant material) using the FFC-Cambridge process. This work may be beneficial with regard to producing oxygen and metal on the lunar surface. The oxygen may ultimately be used to fuel spacecraft, and enable more economically viable space-exploration.

References: [1] McKay D. S. (1994), *JSC-1: A New Lunar Soil Simulant* Engineering, Construction and Operation in Space IV; American Society for Civil Engineers p. 857-886. [2] Chen G. Z., and Fray D. J., and Farthing T. W. (2000) *Nature* **407** p.361-364.

KINETIC INVESTIGATION OF WATER PRODUCTION FROM LUNAR SOIL SIMULANT BY HYDROGEN REDUCTION.

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Introduction: In-situ resource utilization (ISRU) technologies will be much more important for the engineering purposes, as future missions for the Moon and Mars exploration and development are advancing to a more active phase. Manned lunar missions will require the use of locally derived materials since transportation from the earth requires much time, cost, and labor. For life support and spacecraft propulsion, oxygen that can be produced from water is the most essential substance. Therefore, water-production from the lunar soil is a primary concern for ISRU.

Over 20 processes of oxygen production on the moon have been proposed [1]. Among these processes, oxygen production employing hydrogen reduction is the most feasible process [2]. In this process, ilmenite contained in the lunar soil is reduced with hydrogen.

$$FeTiO_3(s) + H_2(g) \rightarrow Fe(s) + TiO_2(s) + H_2O(g) \qquad (1)$$

Ilmenite can be easily reduced since the free energy formation in this reaction is relatively low.

Oxygen is subsequently produced by electrolysis of water. Hydrogen produced in reaction (2) can be recycled in reaction (1).

$$H_2O \rightarrow H_2 + 1/2O_2 \qquad (2)$$

Understanding of the hydrogen reduction mechanism of ilmenite is important for the mission of utilizing the lunar soil.

The authors' research group in Japan has been conducting a ground-engineering work on experimental missions for lunar resource utilization. The goal of the research program is to conceptually design an ISRU experiment system for unmanned water-production on the moon, and to define essential technological breakthroughs. As part of the research program, an experimental study on hydrogen reduction of the lunar soil has been performed to design a chemical reactor of the water-production. Some requirements for the reactor design were also determined from our research achievements.

Experimental Apparatus: A fixed-bed reduction reactor and lunar soil simulants were prepared for our water-production experiments. Change in chemical composition of the lunar soil simulant caused by the reduction, the temperature dependence of the reaction rate, and the characteristics of the rate-controlling process were quantitatively evaluated. The schematic diagram of the experimental apparatus is shown in Fig. 1. The measurement system for water-production rate was improved on the previous apparatus reported in 2000 [3]. The apparatus consists of a reactor, a furnace, and a measurement system including a moisture meter, gas flow meters, pressure gauges, and thermocouples, with connecting the A/D converter and a personal computer for data acquisition. Water-production rate were monitored every 0.5 s.

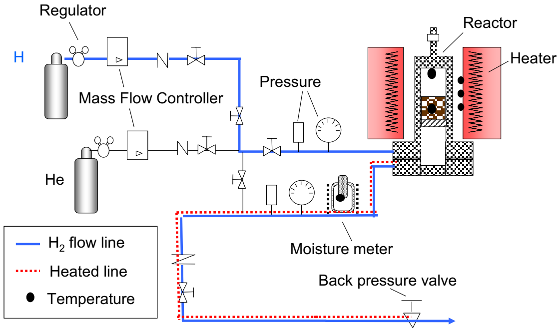

Fig. 1 Lunar soil reduction system by H_2.

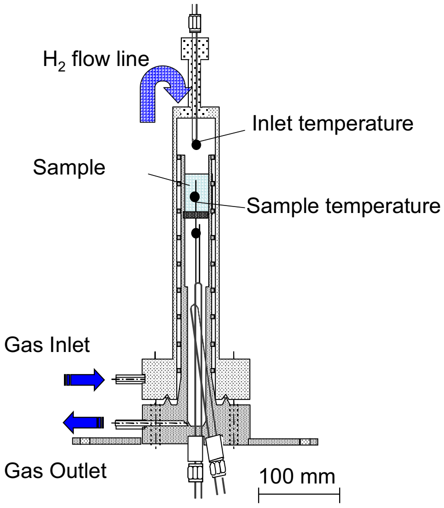

Fig. 2 Reactor of lunar soil reduction by H_2.

The schematic diagram of the reactor is shown in Fig. 2. A reactor is made of Inconel-600, and consists of an inner tube (30 mm i.d., 275 mm long) and an outer tube. The lunar soil simulant is held in the upper part of the inner tube by placing ceramic screen filters with 10 μm-openings and glass wool on the top and bottom ends of the lunar soil simulant. Hydrogen flows up through a preheating gap between the inner and the outer tubes, and reacts with the lunar soil simulant. Hydrogen with produced water is sent to the moisture meter after the outlet. Experiments were conducted with varying of the reaction temperature (1073-1323 K), the hydrogen flow rate (2-6 SL/min), the sample weight (5-15 g), and the particle size of the stimulant (20, 70, 120 μm).

The sample used in the experiments is the lunar soil simulant (Shimizu Corp., Japan) with similar chemical and mechanical properties of the lunar soil. The chemical composition of the sample is shown in Table 2. The lunar soil simulant has the mean particle size of 70 μm, bulk density of 1.55×10^3 kg/m^3, specific gravity of 2.94.

Results and discussion: Effect of temperature on the water-production rate is shown in Fig. 3. Higher temperature leads to higher water-production rate up to 1273 K. Effect of temperatures on the cumulative produced water is shown in Fig. 4. Larger amount of water was produced at higher temperature up to 1273 K. Water-production rate and the cumulative water-production at 1323 K is smaller than those at 1273 K. Partial sintering or melting of glassy contents occurred at higher reaction temperature, resulting in the unreacted FeO and Fe_2O_3 at the inner part of the particle of the lunar soil simulant.

The analysis of chemical composition of the lunar soil simulant before and after reduction was carried out. Ferric oxide (Fe_2O_3) is completely reduced and ferrous oxide (FeO) is slightly reduced by hydrogen. Other components contained in the lunar soil simulant were not influenced by the hydrogen reduction.

Mission Conception: The proposed experiment mission system is mounted on a lunar lander, and transported from the earth to the lunar surface. The system is composed of a solar furnace, a reactor with hydrogen storage, some devices for moisture measurement, chemical analysis, and sample handling. After its landing on the moon, a small amount of lunar soil is sampled and carried to a reactor vessel with a robotistic machine, and then solar heat is supplied to a heating furnace integrated with the reactor. The oxygen-production system after the water-production is proposed in Fig. 5 with indication of the operation temperature and the energy transfer of the process.

Conclusion: Hydrogen reduction process is optimum for oxygen-production on the moon. FeO and Fe_2O_3 contained in the lunar soil simulant are the major reduced components. The reduction temperature at 1273 K and smaller particle are recommended for the water-production form the lunar soil.

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[3] Yoshida H., Watanabe T., Kanamori H., Yoshida T., Ogiwara S., and Eguchi K. (2000) *SRR II*, p.75.

Table 1 Composition of lunar soil simulant.

Component	Lunar Soil Apollo14 [wt%]	Lunar Soil Simulant [wt%]
SiO_2	48.1	50.3
Al_2O_3	17.4	16.3
CaO	10.7	9.4
MgO	9.4	4.4
FeO	10.4	8.7
Fe_2O_3	-	4.4
Others	3.8	6.5
Total	99.8	100.0

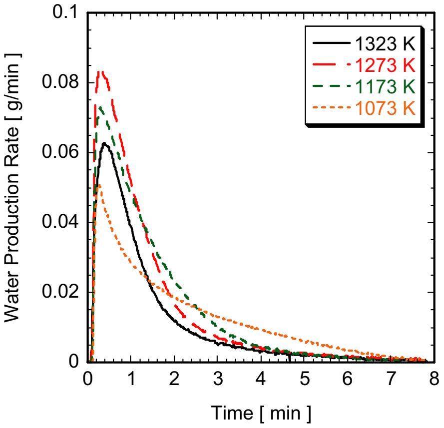

Fig. 3 Effect of temperature on water-production rate.

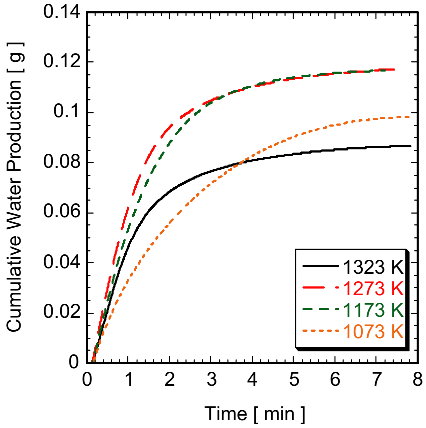

Fig. 4 Effect of temperature on cumulative water-production.

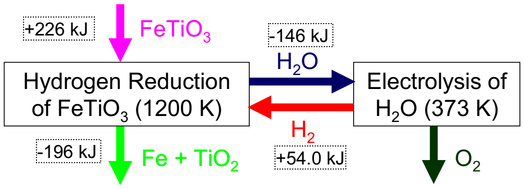

Fig. 5 Process diagram for oxygen-production by H_2 reduction of ilmenite at process temperature.

Galactic Mining Industries, Inc. – Business Plan Development – Market Definition and Revenue Streams

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richwestfall@comcast.net http://www.space-mining.com

Galactic Mining Industries, Inc. is involved in the research and development of Industrial Manufacturing Technologies which will form the basis for Manned Colonization of Earth Orbit, Manned Colonization of the Moon, Earth – Mars Transportation Infrastructure and Martian Colonies.

The investigation of Steel Manufacturing Technologies using In-Situ Resources in Earth Orbit on the Moon on Mars and Beyond forms the foundation for the companies business plans.

This Years Presentation at the Space Resources Roundtable will provide a view of the companies efforts to develop a Workable Business Plan and to provide a glimpse of Market Investigation and Revenue Stream Development Mechanisms envisioned for the near term and important to long term business development.

Entrepreneurial zeal must be mated with developing a cash flow on Earth. Earthly financial solvency established by sales of exacting steel products and venture capital investment will allow the company to grow and fulfill the objective of establishing a space colonization movement.

Galactic Mining Industries, Inc. also possesses proprietary Radiation Shielding Technologies which can be applied to Nuclear Industry Operations on Earth and as Shielding for Spacecraft. These technologies will be briefly presented to define additional very important market presence.

Telepossession Spacecraft Probe missions must be undertaken to provide leverage in venture capital and financing of the company's business plan. Galactic Mining Industries, Inc. proposes the use of Telepossession as a central feature of our Investment Raising Work Plan.

REVENUE GENERATING ACTIVITIES –

1. Provide Contract Services involving the manufacture of Steel Products such as Highly Complex Items such as Dies, Machine Parts, Mechanism Components, etc. on Earth, in Earth Orbit, on the Moon and Beyond utilizing Carbonyl Metallurgical Technologies..
2. Provide Oxygen Fueling Services in Earth Orbit, on the Moon and Beyond as a byproduct of the Carbonyl Metallurgical Manufacturing Technologies of the company..
3. Establishment of Telepossession of Near Earth Resources such as Near Earth Asteroids in the Leveraging of Financial Investment and Capital.
4. Manufacture of Platinum Group Metal – Earth Return Aerodynamic Lifting Body Vehicles to Return Platinum Group Metals to Earth for use in Hydrogen Vehicle and Hydrogen Fuel Infrastructure development. Platinum Group Metals are a major byproduct derived from processing the metal fraction of Asteroids.
5. Establishment of Lagrange Point Operations including Shipyards, Fueling Operations, Space Station Habitat Operations, Food Production, Platinum Group Metals Repositories, Communications Relay and Broadcast Stations, Remote Sensing Detection and Hazards Management Infrastructure.
6. Manufacture of Buzz Aldrin inspired Cycler Earth – Mars Orbiter Shuttle Vehicles to Organizations Transiting from Earth to Mars and back to Earth.
7. Provision of Radiation Shielding Technologies for use on Earth in the Nuclear Power Industry and in Space in Earth Orbit, on the Moon, in transit to Mars and on Mars, and Beyond.
8. In Space Manufacture of Food Production Greenhouse Space Stations for Provision of Missions in Earth Orbit, on the Moon, in Transit to Mars and on Mars, and Beyond.
9. Provide in Space Industrial Park Infrastructure for Support of Organizations involved in the manufacture of Space Colonization Goods and Services.
10. Provide Space Tourism Facilities to Organizations interested in Space Hotel Operations, Space Entertainment and Space Dining Operations.
11. Manufacture of Common Habitation Facilities for Commercial, Governmental, Health Care, Educational, Sports and Athletic Gymnasiums and Stadiums, Correctional Facilities and other Activities and Requirements involving the operation of Earth Orbital Colonies, Lunar Colonies and Martian Colonies.
12. In Space Manufacturing of Spacecraft such as Orbital Maneuvering Tugs, Crew Escape and Rescue Vehicles, Aldrin Earth – Mars Cycler vehicles, Asteroid Retrieval and Processing Vehicles, Telepossession Probes and Landers and more.

SOIL MECHANICS OF LUNAR REGOLITH SIMULANTS FOR PROBE LANDING AND ROVER LOCOMOTION

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Introduction: There are increasing interests in lunar exploration programs. Typical mission targets include scientific quest for the origin and formation process of Earth and Moon, and technological development for future in-situ resource utilization. For both types of missions, technologies for landing and surface locomotion are the key to establish safe and frequent access to specific locations of the lunar surface.

Lunar surface is covered with fine granular or powdery soil called lunar regolith. When a lunar probe makes a touch down on the surface of regolith, we need to make sure that the probe should not slip or bounce in an unexpected way, or tip over. We then need substantial understanding on the motion behavior of the landing probe yielded by the physical interaction between the soils and the legs of the probe.

Surface locomotion is also necessary technology to expand exploration areas and deliver the in-situ devices to specific locations. Wheeled mobile robots (rovers) are efficient designs for this purpose, but on the lunar regolith, we need special attention to wheel slippage that will cause the loss of traction forces, then in the worst case, the rovers will get stuck in the soil. Here we need another substantial understanding on the lunar soil from the viewpoint of traction mechanics.

The authors have been investigating the mechanics of lunar soils using *lunar regolith stimulant.* Our special interests lie in the following two topics; 1) analysis of landing dynamics of lunar probes based on scale model experiments, and 2) analysis of motion behavior of rovers based on a wheel-and-vehicle model.

The former issue provides a basic discussion on how we conduct earth-based experiments of lunar probe landing with scale models. A theory for scale models, or scaling law, will be useful to deduce the real landing behavior that will occur on Moon from the experiments carried out on Earth.

In the latter issue, we have developed a mathematical model for the analysis of traction mechanics of wheels and dynamic motion behavior of a rover. Particularly, the wheel slippages on loose soils have been clarified from the terramechanics-based approach.

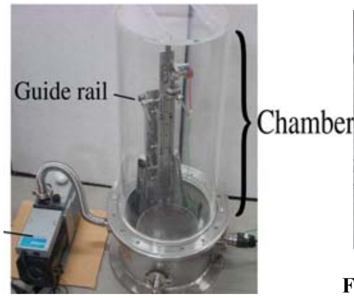

Fig.1 Vacuum chamber

Fig.2 Appearances after the landing (in vacuum)

Scale Modeling for Landing Behavior of a Lunar Probe: We need substantial understanding of the landing behavior of a lunar probe which is caused by physical interactions between the terrain and legs of the probe. In our approach, the law of similarity, or scaling law is applied. The scaling law suggests that if the non-dimensional ratios among equations of motion or related physics between a scale model and reality have a consistent number, the physical phenomena of a real model can be properly deduced from the experimental results. We examine all the related physics equations and derive non-dimensional relationships. The possibility of the relaxation of the similarity law is also investigated so as to mitigate over-constrained relationships and then find a dominat physical phenomenon in a given problem.

In order to evaluate relaxed scaling laws, landing experiments were conducted in a vacuum chamber using simulated lunar soil as shown in Fig.1. The results suggest that the dominant physics for the landing dynamics are inertia forces, friction forces and cohesion forces, but not gravity forces.

As shown in Fig.2, the landing behavior in the 1-atm air and vacuum environments were experimentally compared by observing behaviors with a high-speed camera. As a result, we found the fact that the soil be-

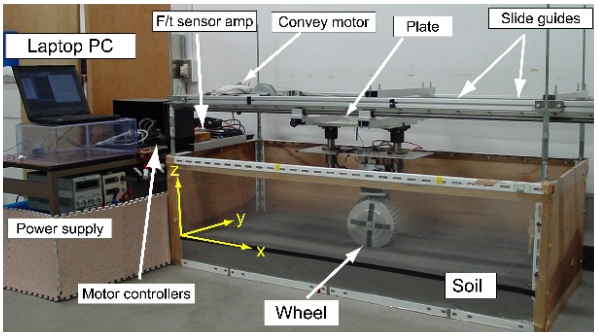

Fig.3 Single wheel test bed

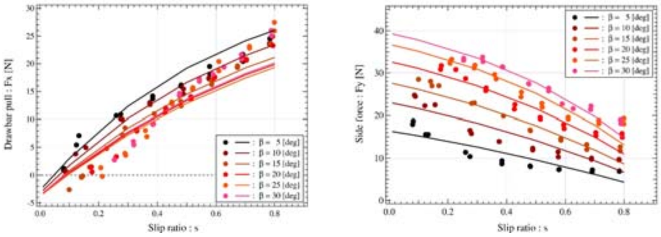

Fig.4 Experimental and simulation results (left: drawbar pull, right : side force)

haves like an elastic lump in the 1-atm air, but in the vacuum, the soil behaves like isolated particulates and an impact crater was formed. From this result, the experiments of the lunar landing should be strongly carried out in the vacuum environment.

Analysis of Motion Behavior of a Rover: To deal with motion behavior of a rover on loose soil, wheel slips should not be neglected. When a wheel is traveling on a loose soil, the wheel can slip both in the longitudinal and lateral directions. The slip in the longitudinal direction is measured by slip ratio, while the slip in the lateral direction is measured by slip angle.

We first investigated the interaction between wheel and loose soil based on the terramechanics approach. In the terramechanics filed, a principle mechanism of the wheel-soil interaction and empirical models of stress distributions underneath a wheel have been investigated in [2]-[4]. According to those conventional models, we have developed the wheel-soil contact model, which can calculate 3-axis wheel forces (drawbar pull, side force, and vertical force) as a function of wheel slips.

The wheel-soil contact model was validated with a single-wheel test bed using lunar regolith simulant (Fig.3.) Experimental measurements of the drawbar pulls and the side forces are respectively plotted in Fig.4, for each slip angle from 5 [deg] to 30 [deg]. Theoretical curves calculated by the wheel-soil contact model are also drawn in the corresponding figures.

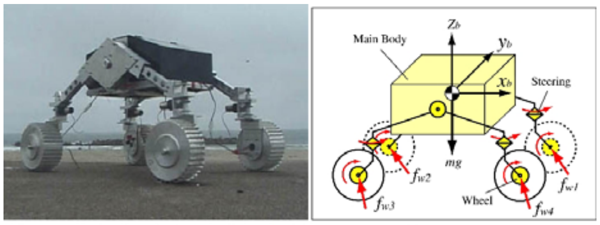
(Rover test bed) (Vehicle dynamics model)

Fig.5 wheel-and-vehicle model

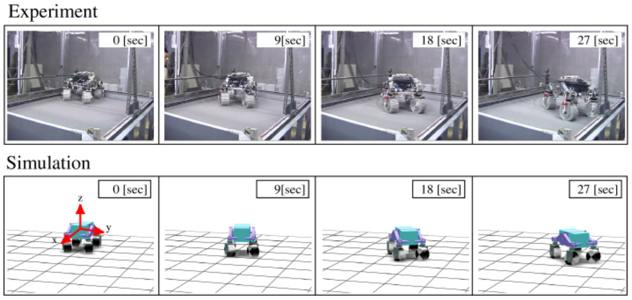

Fig.6 Comparison of simulated and experimental steering motion

The differences between the measured and calculated values are relatively small. These results validate that the wheel-soil contact model is able to represent the wheel's traveling behaviors and the contact forces with an appropriate accuracy.

We have also developed the wheel-and-vehicle model for analysis of the rover's behavior. In this model as described in Fig.5, a dynamics model of a rover is established as an articulated body system, and forces of each wheel are calculated by the use of the wheel-soil contact model. The dynamics simulation using the wheel-and-vehicle model is able to calculate motion behaviors of the rover.

As one of the representative results, a steering trajectory obtained from the simulation was compared to a corresponding experimental trajectory of our rover test bed as shown in Fig.6. From the figure, it can be seen that the wheel-and-vehicle model well agrees with the experimental result with a reasonable accuracy (within 0.08 [m] error.)

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