SPACE RESOURCES ROUNDTABLE VI

COLORADO SCHOOL OF MINES
NOVEMBER 1–3, 2004

PROGRAM AND ABSTRACTS

LPI Contribution No. 1224

SPACE RESOURCES ROUNDTABLE VI

November 1–3, 2004

Colorado School of Mines
Golden, Colorado

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PREFACE

This volume contains abstracts that have been accepted for presentation at the Space Resources Roundtable VI, November 1–3, 2004, Colorado School of Mines, Golden, Colorado.

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DIELECTRIC CONSTANT MEASUREMENTS ON LUNAR SOILS AND TERRESTRIAL MINERALS

R. C. Anderson[1], M. G. Buehler[1], S. Seshardri[1], and M.G. Schaap[2]
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Introduction: The return to the Moon has ignited the need to characterize the lunar regolith using *in situ* methods. An examination of the lunar regolith samples collected by the Apollo astronauts indicates that only a few minerals (silicates and oxides) need be considered for *in situ* resource utilization (ISRU). This simplifies the measurement requirements and allows a detailed analysis using simple methods. Characterizing the physical properties of the rocks and soils is difficult because of many complex parameters such as soil temperature, mineral type, grain size, porosity, and soil conductivity. In this presentation, we will show that the dielectric constant measurement can provide simple detection for oxides such as TiO_2, FeO, and water. Their presence is manifest by an unusually large imaginary permittivity.

Impedance Spectrometer: The dielectric constant, ε, is expresses as the product of the permittivity of free space, ε_0, times the relative permittivity, ε_r. The permittivity is further described as $\varepsilon_r = \varepsilon' - i\varepsilon''$ where ε' is the real permittivity and ε" is the imaginary permittivity [1]. Fig. 1 shows that the real permittivity, ε' can be used to determine the density of lunar soils [2] and terrestrial minerals [3]. The simple relationship shown in the figure holds for silicates and oxides with a few exceptions such as titanates which have high permittivities. The graph in Fig. 2 demonstrates a direct correlation between the amount of $\%TiO_2 + \%FeO$ in the lunar soil. At a measured ε', the amount of $\%TiO_2 + \%FeO$ is determined from ε". Other minerals or water can also cause ε" to be abnormally large. The deviation of the ε" versus ε' above the $\%TiO_2 + \%FeO = 0$ line signals the detection of a mineral in the regolith that needs further identification by, for example, Raman or XRD. The data [2] in Fig. 2 was fitted using a multivariate least squares method; the equation is at the top of the graph.

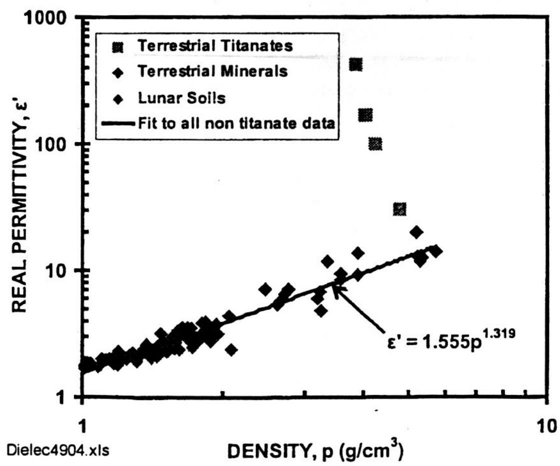

Figure 1. Relationship between real permittivity and density of lunar soils [2] and terrestrial minerals [3].

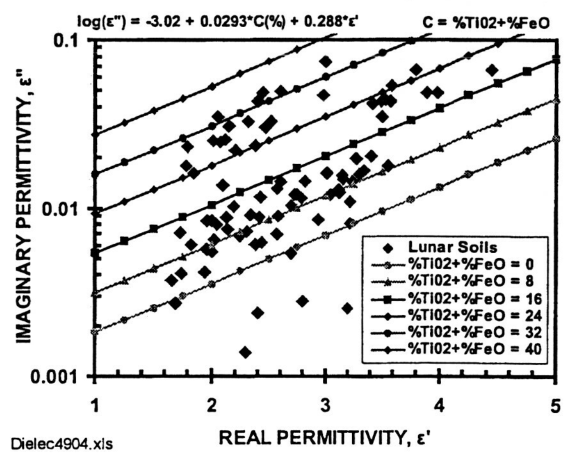

Figure 2. ε" versus ε' for various percentages of TiO_2 and FeO for lunar soils obtained from Apollo missions [2].

Conclusion: Prospecting for minerals on the surface of the Moon calls for developing rapid survey techniques. We propose using impedance spectroscopy that provides dielectric constant measurements, electrostatic measurements that provide data for signature analysis techniques, and magnetic properties measurements. All of these measurements are rapid and the sensors are small and so can be incorporated into the wheel of a roving vehicle allowing real-time *in situ* measurements while the vehicle is in motion.

Acknowledgements: The authors are grateful to Walter Russel, USDA-ARS George E. Brown, Jr. Salinity Laboratory, for extracting the lunar soil data from [2]. File: Dielec4A08Pub.doc

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[3] R. S. Carmichael, *Practical Handbook of Physical Properties of Rocks and Minerals*, CRC Press (Boca Raton, Florida, 1990).

DUST MITIGATION ON ASTRONAUT SPACESUITS

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The particles that make up moon dust and Mars soil can be hazardous to an astronaut's health if not handled properly. Exploration missions require astronauts to establish base habitat on the surface of the Moon and Mars. During these explorations, dust and soil will cling to their space suits and become imbedded in the fabric. The astronauts will track moon dust and mars soil back into their living quarters. This not only will pollute cabin air with millions of tiny air-born particles floating around, but will also be dangerous in the case that the fine particles are breathed in and become trapped in an astronaut's lungs.

In order to mitigate this problem, engineers and scientists at the NASA-Glenn research center and at the Colorado School of Mines are investigating ways to remove these particles from space suits. This problem is very difficult due to the nature of the Lunar regolith: They are extremely small and have jagged edges which can easily latch onto the fibers of the fabric. Important factors in determining a technique include low power and material usage do to the limited supplies in space, making the equipment durable so that it will require little work from astronauts, and the effectiveness, or amount of dust the technique can remove.

The current technique under investigation uses vibrating motors imbedded in the fabric that vibrate and shake the particles free. The particles will be left on the planet's surface or collected in a vacuum to be disposed of later. The motors have an unevenly weighted shaft that, when connected to a power supply, spins unevenly and creates a motion on the fabric similar to what people use at the beach to shake sand off of a beach towel. Because the particles are so small, similar to volcanic ash, caution must be taken to make sure that this technique does not further imbed them into the fabric and make removal more difficult. Only a very precise range of frequency and amplitude of the fabric will produce a suitable vibration. Analysis was done to determine what input factors, such as power, tension in the fabric, and size of motor would produce the desired output.

TOWARD A SUSTAINABLE MARS INFRASTRUCTURE

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Currently, there are four nuclear electric power-generating units operating on Mars (pairs of radioisotope thermal generators, now generating a little of 70 W each, located at the VL-1 and VL-2 landing sites), one small dusty solar array (*Sojourner*) and two somewhat larger solar arrays—one each for the Mars Rovers *Spirit* and *Opportunity*—in use currently. In addition, there are two Viking Landers, three robotic rovers with landers and scientific instruments, numerous aeroshells with associated entry gear, and a variety of crashed landers (Mars 2, Mars 3, Mars 6, Mars Polar Lander, and Beagle) strewn about the Mars landscape. Electric power on the Mars surface is in short supply, but electric power will be the key for developing a robust infrastrucure capable of supporting human explorers.

This talk will utilize the author's more than 25-year involvement with engineering system designs focused on the utilization of extraterrestrial resources, in order to frame the issues related to evolving a sustainable infrastructure on a planetary body that is too far from Earth for teleoperation and too far from the Sun to rely completely on Solar power. The talk will discuss some early work and its legacy, in the context of major increases in distributed computational power, component miniaturization and other advances. In order to build up a capability to return humans from the Martian surface, an unmanned landing and return site with significant levels of on-demand electric power is needed critically, but budgetary constraints and relatively short mission-planning horizons, along with the severe constraints that result from "locking-in" a landing site, will make such a determination and selection extremely difficult to justify. The author is beginning to collaborate with Old Dominion University's National Center for System of Systems Engineering, examining *in situ* resource utilization in the context of *Moon, Mars and Beyond* planning and those implications will be discussed.

GRANULAR MATERIALS AND RISKS IN ISRU

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Working with soil, sand, powders, ores, cement and sintered bricks, excavating, grading construction sites, driving off-road, transporting granules in chutes and pipes, sifting gravel, separating solids from gases, and using hoppers are so routine that it seems straightforward to execute these operations on the Moon and Mars as we do on Earth. We discuss how little these processes are understood and point out the nature of trial-and-error practices that are used in today's massive over-design. Nevertheless, such designs have a high failure rate. Implementation and extensive incremental scaling up of industrial processes are routine because of the inadequate predictive tools for design. We present a number of pragmatic scenarios where granular materials play a role, the risks involved, what some of the basic issues are, and what understanding is needed to greatly reduce the risks. This talk will focus on a particular class of granular flow issues, those that pertain to dense materials, their physics, and the failure problems associated with them. In particular, key issues where basic predictability is lacking include stability of soils for the support of vehicles and facilities, ability to control the flow of dense materials (jamming and flooding/unjamming at the wrong time), the ability to predict stress profiles (hence create reliable designs) for containers such as bunkers or silos. In particular, stress fluctuations, which are not accounted for in standard granular design models, can be very large as granular materials flows, and one result is frequent catastrophic failure of granular devices.

ISRU TECHNOLOGY MODELING AND ANALYSIS

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A preliminary In Situ Resource Utilization (ISRU) technology matrix has been developed that identifies the type of technology, its applications, the rationale for wanting to improve performance, its current status and expected (or desired) future performance. This database can be utilized to determine where the most effective investments can be made in ISRU technologies (as opposed to ISRU systems). Technologies are sorted into demonstration of feasibility vs. performance improvement (optimality) categories through membership in a metric called critical path. Improvements and updates to the technology database will be solicited during SRR6 through a formal survey process.

An approach to modeling the investment value for developing ISRU technology will also be presented, along with quantitative results for specific ISRU subsystems. The basis for the valuation of technology is performance per unit mass (also known as specific mass). The method used to derive value is sensitivity analysis of technical performance parameters within an integrated architectural and economic modeling for ISRU-based human lunar exploration. Changes in technical parameters are mapped directly into economic costs for the exploration scenario. Improvements in overall cost related to enhancing specific technical performance parameters are interpreted as total value of the new technology.

COSTS AND BENEFITS OF ISRU-BASED HUMAN SPACE EXPLORATION

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A three phase 10-year scenario for In Situ Resource Utilization (ISRU)-based human exploration architecture will be introduced as a foundation for an economic cost/benefit model of the value of the use of space resources, including infrastructure and capability growth through time. This architecture is generally consistent with the development of a self-sufficient outpost on the Moon during the period 2020-2030, Cycle 2 of the current NASA exploration vision. A preparatory set of robotic missions has also been assumed to emplace ISRU capabilities as well as infrastructure in preparation for the first human missions. Models for both performance benefits (e.g. the amount of mass that has to be transported from Earth to achieve the desired lunar capability) and relative costs, compared to alternative scenarios that do not utilize ISRU have been developed. Economic differences between the ISRU architecture and the all-expendable baseline will be presented, which provide the basis for quantifying the benefits of ISRU development. Sensitivity analysis of the integrated architectural/economic model will be used to recommend priorities for future research and modeling. Economic conclusions that will be presented include expected product unit costs and rate of return analysis.

REPORT ON THE CONSTRUCTION AND TESTING OF A BUCKET WHEEL EXCAVATOR

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The Northern Centre for Advanced Technologies Inc. (NORCAT), in partnership with Electric Vehicle Controllers Ltd. (EVC), is presently engaged in the development and adaptation of existing mining technologies and methodologies for use extra-terrestrially as precursor and enabling technologies for ISRU and for use as ISSE in support of longer term missions.

More specifically, NORCAT, in collaboration with Colorado School of Mines, has developed, constructed, and tested a bucket wheel excavator. The unit is based upon the design developed by CSM's Mike Duke and Tim Muff.

The design of the test unit was developed with the CSM design as a guide. Considerations were exercised to facilitate construction and testing of key operational parameters. This yielded some changes in design and operating concepts, which were incorporated where appropriate. In addition, some bottle necks and weak points were identified in the original design.

NORCAT engaged Natural Resources Canada (NRCan) to fabricate a lunar regolith simulant from mine tailings that would exhibit some significant similarities to the reported mechanical properties of lunar regolith. The Bucket wheel unit was tested in this simulant in October 2004.

This presentation will report some key results of the Bucket wheel re-design.

THE LUNAR POLAR ILLUMINATION ENVIRONMENT: WHAT WE KNOW & WHAT WE DON'T

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Introduction. The Moon's spin axis is nearly perpendicular to the ecliptic plane which results in unusual lighting conditions at the lunar poles. Areas which have low elevation, such as the floors of impact craters, may never see the Sun, i.e. they are permanently shadowed, whilst regions of high elevation, relative to the local terrain, may be permanently illuminated. The polar illumination conditions represent a key resource with respect to returning to the Moon. Possible ice deposits must be located in areas of permanent shadow, whilst the existence of a region in permanent sunshine has ramifications as a future base site.

Current Knowledge. An analysis of the lunar polar lighting using Clementine image data revealed some interesting illumination conditions. No place in the south polar region appears to be permanently illuminated (Figure 1L). However several regions exist which are illuminated for greater than 70% of a lunar day in winter. Two of these regions, which are only 10 km apart, are collectively illuminated for more than 98% of the time. Near the north pole four areas on the rim of Peary crater were constantly illuminated for an entire lunar day in summer. Both polar regions contain numerous areas of permanent shadow close to each pole.

Modeling of simple impact craters has revealed that there is extensive permanent shadow associated with these features, at least 7500 km^2 and 6500 km^2 at the north and south poles respectively. Additionally permanent shadow can exist in craters more than 10° latitude away from a pole (Figure 1R). These areas represent potential cold traps for volatile deposits.

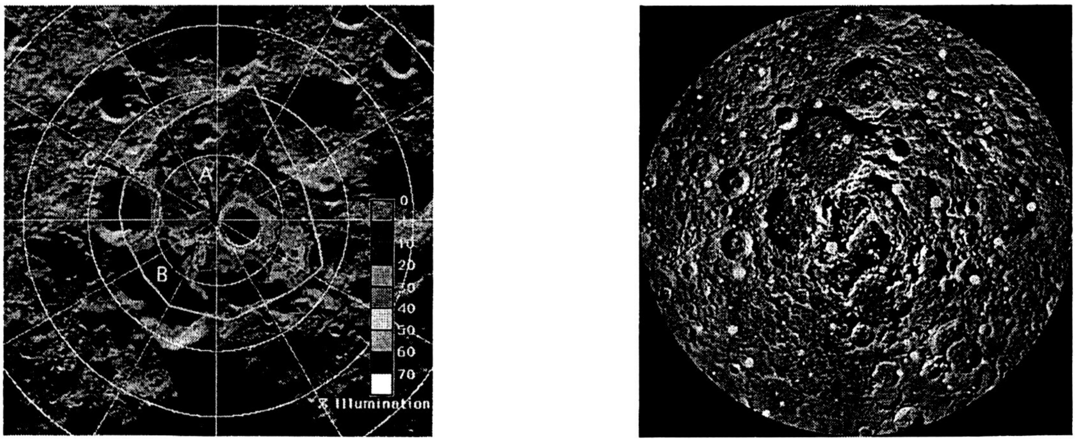

Figure 1. The image on the left is an illumination map of the lunar south pole showing the percentage of a lunar day that a point on the surface is illuminated. The mosaic on the right is a map of the northern lunar polar region showing the location of simple craters that contain permanent shadow.

Future Data. In order to definitively understand the lunar illumination environment, more data is required. Wide area imaging coverage over an entire year is necessary to identify all regions of illumination extremes. Additionally lighting simulations using high resolution topography can produce quantitative illumination maps.

LUNAR SIMULANTS: JSC-1 IS GONE; THE NEED FOR NEW STANDARDIZED ROOT SIMULANTS

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A workshop [1] was held in 1991 to evaluate the status of simulated lunar regolith material and to make recommendations on future requirements and production of such material. As an outgrowth of that workshop, a group centered at Johnson Space Center (JSC) teamed with James Carter of the University of Texas at Dallas and Walter Boles of Texas A&M University to produce and distribute a new standardized lunar regolith simulant termed JSC-1. Carter supervised the field collection, shipping, processing, and initial packaging and transportation of JSC-1. Boles stored and distributed JSC-1. About 25 tons were created and distributed to the lunar science and engineer community; none is left for distribution. JSC-1 served an important role in concepts and designs for lunar base and lunar materials processing. Its chemical and physical properties were described by McKay et al. [2], with its geotechnical properties described by Klosky et al. [3]. While other lunar regolith simulants were produced before JSC-1 [4-6], they were not standardized, and results from tests performed on them were not necessarily equivalent to test results performed on JSC-1. JSC-1 was designed to be chemically, mineralogically, and texturally similar to a mature lunar mare regolith (low titanium). The glass-rich character of JSC-1 (~50%) produced quite different properties compared to other simulants that were made entirely of comminuted crystalline rock, but properties similar to lunar mare near surface regolith.

While it would be difficult to completely duplicate JSC-1, it should be a model for new simulants in which the chemical and physical properties of the lunar regolith are duplicated as closely as possible. We propose that the concept of a standardized simulant be followed by the community, in which large quantities (more than 100 tons) of simulant is produced in a manner that homogenizes it so that all subsamples are equivalent. From this root simulant it would then be possible to produce other more specialized simulants, for example, by implanting solar wind, by adding ice in various proportions, or by adding specific components such as metallic iron, carbon, organics, or halogens to more closely simulate special properties of lunar regolith needed for specific kinds of tests and experiments. In all cases, the specialized simulant branches should begin with the standardized root simulant. While JSC-1 was a mare simulant, an additional root highland simulant would be desirable. Many of the proposed landing sites are in highland terrain, and the properties of lunar highland regolith have some fundamental differences compared to mare regolith. Consequently, we suggest that it is important to design and produce a standardized root highland simulant, as well.

We also propose that the new root lunar simulants be collected at a single locality and characterized by a science and engineering team. New security restrictions make it difficult for JSC to be the collection and distribution site; it will be necessary to perform this service elsewhere. While JSC-1 was distributed at no cost to the customers other than shipping, in this new era of full-cost accounting, the new lunar simulants must be paid for by the customers.

Although preparations are underway for the production of JSC-2, a "clone" of JSC-1, it would appear that a workshop is necessary to bring the community together to form a consensus on requirements for new lunar standardized root simulants and for some of the specialized branch simulants.

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SPACE TRANSPORTATION FOR A LUNAR RESOURCES BASE (LRB)

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This is a report of a work in progress. So far as the author is presently aware, this topic has not been previously addressed. Proprietary work by NASA or others may, however, exist that address similar topics.

This work assumes that a base near the South Pole of our Moon will be established for the purpose of exploiting the resources of the Moon; principally the water ice that many believe was discovered by the *Clementine* and *Lunar Prospector* satellites. The ice is of particular value as, with the aid of the ample solar resource available nearby, it may become an essentially limitless source of oxygen / hydrogen propellants for continued visitation to and expansion of the base and for the support of additional space exploration missions, including human exploration of Mars.

This work placed a total 129 tons initial base for both the in-crater and crater rim installations, as well as a 90 tons "marshalling yard" at the Earth-Moon L-1 libration point. For launch services, the results of an in-house *Shuttle-Derived Heavy Lift Launch Vehicle* study were used. It is called *Aquila*. This vehicle can deliver over 50 tons to low Earth orbit from the Kennedy Space Center, using a combination of *Space Shuttle* and *Delta IV-Heavy* components.

A second stage of the *Delta IV-Heavy* vehicle was used to deliver 15 tons payloads from Earth orbit to docking at L-1. By so doing, no "new start" systems are needed beyond those of the L-1 station and the LRB itself, provided the *Aquila* and *Crew Exploration Vehicle* have been previously developed. At L-1, three of these once-used stages are fitted with landing gear and other elements needed to produce a highly capable *Lunar Vehicle* and it is refueled from propellants delivered from Earth to place the base and to provide a single visit of a six person crew to aid the robotic operations necessary to produce a fully functional base.

If the ground rule is established that "dry" cargo and propellant must be launched separately, 34 launches were required. This will permit over 50% of the launches to launch only propellants.

Later missions, using propellants produced by the *LRB,* show a large net gain in propellants available at L-1. For example, a round trip mission with the *CEV* results in a net gain of over six tons of propellant at L-1; a cargo delivery nets over 69 tons.

Work continues on the "pay-off" phase; that is, further missions making use of the propellants obtained from the shallow "gravity well" of the Moon. Propellants produced on the Moon will only be used from the lunar surface or from L-1; no attempt will be made to deliver them to other locations. That will come, but is "out-of-scope" for the present work.

A Mars mission departing from L-1 with mass of 686 tons can be placed on the trans-Mars trajectory expending lunar-origin propellants and just one of the *Lunar Vehicle*s, requiring an additional 13 *Aquila* launches. This will permit dual Mars spacecraft to be used for each mission with a 28% mass margin over a single, similar mass vehicle departing from low Earth orbit.

AUTONOMOUS IN-SITU RESOURCES PROSPECTOR

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This presentation will describe the concept of an autonomous, intelligent, rover-based rapid surveying system to identify and map several key lunar resources to optimize their ISRU (In Situ Resource Utilization) extraction potential. Prior to an extraction phase for any target resource, ground-based surveys are needed to provide confirmation of remote observation, to quantify and map their 3-D distribution, and to locate optimal extraction sites (e.g. ore bodies) with precision to maximize their economic benefit.

The system will search for and quantify optimal minerals for oxygen production feedstock, water ice, and high glass-content regolith that can be used for building materials. These are targeted because of their utility and because they are, or are likely to be, variable in quantity over spatial scales accessible to a rover (i.e., few km). Oxygen has benefits for life support systems and as an oxidizer for propellants. Water is a key resource for sustainable exploration, with utility for life support, propellants, and other industrial processes. High glass-content regolith has utility as a feedstock for building materials as it readily sinters upon heating into a cohesive matrix more readily than other regolith materials or crystalline basalts. Lunar glasses are also a potential feedstock for oxygen production, as many are rich in iron and titanium oxides that are optimal for oxygen extraction.

To accomplish this task, a system of sensors and decision-making algorithms for an autonomous prospecting rover is described. One set of sensors will be located in the wheel tread of the robotic search vehicle providing contact sensor data on regolith composition. Another set of instruments will be housed on the platform of the rover, including VIS-NIR imagers and spectrometers, both for far-field context and near-field characterization of the regolith in the immediate vicinity of the rover. Also included in the sensor suite are a neutron spectrometer, ground-penetrating radar, and an instrumented cone penetrometer for subsurface assessment. Output from these sensors will be evaluated autonomously in real-time by decision-making software to evaluate if any of the targeted resources has been detected, and if so, to quantify their abundance. Algorithms for optimizing the mapping strategy based on target resource abundance and distribution are also included in the autonomous software.

This approach emphasizes on-the-fly survey measurements to enable efficient and rapid prospecting of large areas, which will improve the economics of ISRU system approaches. The mature technology will enable autonomous rovers to create in-situ resource maps of lunar or other planetary surfaces, which will facilitate human and robotic exploration.

EXTRACTION OF OXYGEN FROM THE MARTIAN ATMOSPHERE

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A mechanical process was designed for direct extraction of molecular oxygen from the martian atmosphere based on liquefaction of the majority component, CO_2, followed by separation of the lower-boiling components. The atmospheric gases are compressed from about 0.007 bar to 13 bar and then cooled to liquefy most of the CO_2. The uncondensed gases are further compressed to 30 bar or more, and then cooled again to recover water as ice and to remove much of the remaining CO_2. The final gaseous products consisting mostly of nitrogen, oxygen, and carbon monoxide are liquefied and purified by cryogenic distillation. The liquefied CO_2 is expanded back to the low-pressure atmosphere with the addition of heat to recover a majority of the compression energy and to produce the needed mechanical work. Energy for the process is needed primarily as heat to drive the CO_2-based expansion power system. When properly configured, the extraction process can be a net producer of electricity.

The conceptual design, termed "MARRS" for *Mars Atmosphere Resource Recovery System*, was based on the NASA/JSC Mars Reference Mission (MRM) requirement for oxygen. This mission requires both liquid oxygen for propellant, and gaseous oxygen as a component of air for the mission crew. With single redundancy both for propellant and crew air, the oxygen requirement for the MRM is estimated at 5.8 kg/hr. The process thermal power needed is about 120 kW, which can be provided at 300-500°C. A lower-cost nuclear reactor made largely of stainless steel could serve as the heat source.

The chief development needed for MARRS is an efficient atmospheric compression technology, all other steps being derived from conventional chemical engineering separations. The conceptual design describes an exceptionally low-mass compression system that can be made from ultra-lightweight and deployable structures. This system adapts to the rapidly changing martian environment to supply the atmospheric resource to MARRS at constant conditions.

The large amounts of liquid CO_2 by-product that are produced enable a comprehensive martian surface architecture using this liquid as an open cycle working fluid. While most of the 1000 kg/kg oxygen is expanded for power recovery, a small fraction is stored and made available for emergency or backup power, transportation, and surface operations such as drilling. The availability of highly redundant backup power and transportation systems makes the MARRS concept particularly attractive for piloted missions to Mars.

The current study outlines an inherently flexible surface architecture for Mars exploration that uses nuclear heat, a compression-dominated process for extraction of atmospheric resources, and provides a mechanism for highly redundant and reliable operations. The amounts of minor components in the atmosphere, however, are uncertain. While the conceptual design for MARRS is based on a 0.13% oxygen concentration, the actual average value is now believed to be about 0.3%. Such a high value would allow even greater flexibility in design, and greatly reduce the energy and mass requirements to produce oxygen for the MRM. A more detailed design is needed to account for the uniquely high variability in composition, pressure and temperature that characterize the martian atmospheric environment.

MINIMIZING LAUNCH MASS FOR ISRU PROCESSES

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The University of Dayton and the Jet Propulsion Laboratory are developing a methodology for estimating the Earth launch mass (ELM) of processes for *In-Situ* Resource Utilization (ISRU) with a focus on lunar resource recovery. ISRU may be enabling for both an extended presence on the Moon,[1,2] and for large sample return missions and for a human presence on Mars.[2] To accomplish these exploration goals, the resources recovered by ISRU must offset the ELM for the recovery process. An appropriate figure of merit is the cost of the exploration mission, which is closely related to ELM. For a given production rate and resource concentration, the lowest ELM – and the best ISRU process – is achieved by minimizing capital equipment for both the ISRU process and energy production.

ISRU processes incur Carnot limitations and second law losses (irreversibilities) that ultimately determine production rate, material utilization and energy efficiencies. Heat transfer, chemical reaction, and mechanical operations affect the ELM in ways that are best understood by examining the process's detailed energetics. Schemes for chemical and thermal processing that do not incorporate an understanding of second law losses will be incompletely understood.

Our team is developing a methodology that will aid design and selection of ISRU processes by identifying the impact of thermodynamic losses on ELM. The methodology includes mechanical, thermal and chemical operations, and, when completed, will provide a procedure and rationale for optimizing their design and minimizing their cost. The technique for optimizing ISRU with respect to ELM draws from work of England and Funk[3] that relates the cost of endothermic processes to their second law efficiencies. Our team joins their approach for recovering resources by chemical processing with analysis of thermal and mechanical operations in space. Commercial firms provide cost inputs for ELM and planetary landing.

Our initial goal is to provide a generally-useful method for analysis of resource recovery in space that is applicable to the Moon (vacuum environment) and Mars (convective environment). We will develop a listing of irreversibility factors for important operations (such as countercurrent heat recovery from solids) that will make the methodology easy to use. Our sample case is an analysis of a hydro-winning process for oxygen from the lunar regolith.

Operations in space that generate irreversibilities are best understood by analyses that locate where in the operation these losses are produced. Without having this information, designers are limited in their understanding of process efficiency, much like 19th century designers of power production equipment prior to development of the second law of thermodynamics. Our methodology not only can remove this guesswork, but can provide a cost-related figure of merit by which ISRU methods and other processes conducted in space can be compared.

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REMOTE SENSING ASSESSMENT OF LUNAR RESOURCES: WE KNOW WHERE TO GO TO FIND WHAT WE NEED

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The utilization of space resources is necessary to not only foster the growth of human activities in space, but is essential to the President's vision of a "sustained and affordable human and robotic program to explore the solar system and beyond." The distribution of resources will shape planning permanent settlements by affecting decisions about where to locate a settlement. Mapping the location of such resources, however, is not the limiting factor in selecting a site for a lunar base. It is indecision about which resources to use that leaves the location uncertain [1]. A wealth of remotely sensed data exists that can be used to identify targets for future detailed exploration. Thus, the future of space resource utilization predominately rests upon developing a strategy for resource exploration and efficient methods of extraction.

The Clementine [2] and Lunar Prospector [3] missions have provided global datasets that already provide the distribution of many potential lunar resources. Clementine acquired multispectral images from ultraviolet through near-infrared wavelengths. These data allow assessments of the abundances of major minerals (plagioclase, pyroxene, ilmenite, and olivine) on the Moon [4]. In addition, the data can be used to determine the FeO and TiO_2 contents of the surface to ~1wt% accuracy and high spatial resolution [5-8]. The distribution of pyroclastic materials with their enrichments of FeO and TiO_2 and possible volatile elements are mapped using Clementine multispectral data and derived optical maturity data [9]. Perhaps even more important, ^3He can be mapped by association with TiO_2 and surface maturity [10]. The abundance of ^3He in the lunar regolith depends on surface maturity, the amount of solar wind flux, and titanium content. Clementine bi-static radar data provided initial evidence that water-ice exists in permanently-shadowed regions near the poles.

Mission	Measurements
Apollo ~100-150 km/pixel	Gamma-ray and X-ray data Th, K, Mg, Si, Al
Clementine (0.415, 0.75, 0.9, 0.95, 1.0, 1.1, 1.25, 1.5, 2.0, 2.6, and 2.7 μm) ~200 m/pixel	Multispectral images: FeO and TiO_2 Mineralogy/Pyroclastics Optical Maturity ^3He
Lunar Prospector 15-150 km/pixel	Gamma-ray and Neutron data Fe, Ti, Th, K, H, Sm, Gd
Earth-based observations 2-5 km/pixel (spectra) 400 m/pixel (radar)	Visible to near infrared spectra Mineralogy/Pyroclastics Radar Backscatter Maturity Opaque abundance Ice

Lunar Prospector gamma-ray and neutron spectrometers determine the concentrations of Fe, Ti, Th, K, H, Sm, and Gd [8, 11, 12]. Fe and Ti data provide an independent check on the concentrations determined by reflectance spectroscopy [6]. Neutron spectrometer data indicate the presence of hydrogen deposits at the lunar poles, which if present as water-ice suggests a H_2O concentration of 1-2 wt% [13].

Earth-base radar observations (70 cm) also have a sensitivity to bulk FeO and TiO_2 abundance. The correlation of abrupt changes in radar return with color boundaries in Clementine color and TiO_2 images indicates that the data are controlled, to a significant degree, by the TiO_2 (ilmenite) composition of the regolith [14]. The greater depth of penetration of radar data compared to the Clementine data (several meters versus microns) will allows the assay of TiO_2 abundance to greater depth. Earth-based radar does not, however, concur with Clementine concerning the existence of ice at the south pole of the Moon [15]. This apparent discrepancy in the presence of ice has not been satisfactory explained, and will require closer study by orbiting and landed missions

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ROBOTIC SUBSURFACE ANALYZER AND SAMPLE HANDLER FOR RESOURCE RECONNAISSANCE AND PRELIMINARY SITE ASSESSMENT FOR ISRU ACTIVITIES AT THE LUNAR COLD TRAPS

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Since the 1960s, claims have been made that water ice deposits should exist in permanently shadowed craters near both lunar poles. Recent interpretations of data from the Lunar Prospector-Neutron Spectrometer (LP-NS) confirm that significant concentrations of hydrogen exist, probably in the form of water ice, in the permanently shadowed polar cold traps. Yet, due to the large spatial resolution (45–60 km) of the LP-NS measurements relative to these shadowed craters (~5–25 km), these data offer little certainty regarding the precise location, form or distribution of these deposits. Even less is known about how such deposits of water ice might effect lunar regolith physical properties relevant to mining, excavation, water extraction and construction. These uncertainties will need to be addressed in order to validate fundamental lunar In Situ Resource Utilization (ISRU) precepts by 2011. Given the importance of the *in situ* utilization of water and other resources to the future of space exploration a need arises for the advanced deployment of a robotic and reconfigurable system for physical properties and resource reconnaissance. Based on a collection of high-TRL designs, the Subsurface Analyzer and Sample Handler (SASH) addresses these needs, particularly determining the location and form of water ice and the physical properties of regolith. SASH would be capable of: (1) subsurface access via drilling, on the order of 3–10 meters into both competent targets (ice, rock) and regolith; (2) down-hole analysis through drill string embedded instrumentation and sensors (Neutron Spectrometer and Microscopic Imager), enabling water ice identification and physical properties measurements; (3) core and unconsolidated sample acquisition from rock and regolith; (4) sample handling and processing, with minimized contamination, sample containerization and delivery to a modular instrument payload. This system would be designed with three mission enabling goals, including: (1) a self-contained, low power, low mass, "black box" configuration for operations from a lander, various classes of rovers or a surface-based platform with human assistance or robotic anchoring mechanisms; (2) reconfigurable and scalable sample handling for delivery to various types of instrumentation, depending on mission requirements; and (3) the use of advanced automation control and diagnostic techniques that will afford local human deployed, remote teleoperation and fully autonomous intelligent operations.

Though a great deal of technology has been advanced toward these objectives, the SASH system faces significant design challenges, including the low gravity environment, various levels of autonomy in operations, radiation exposure, dust contamination, and temperature extremes and deltas. Significant input from the scientific and engineering communities, as well as a significant environmental testing program, will be required to guide the design process.

The impact of this technology would be far-reaching. SASH would reduce cost, time and risk in the pursuit of mission architectures and landing site selections for Lunar Planetary Surface Operations (LPSO), specifically ISRU activities. During crewed missions, SASH would reduce unnecessary Extra-Vehicular Activity risks to human safety. De-coupling SASH from a fixed surface instrumentation suite and delivery platform will require a modular and flexible design. This will enable maximum reconfiguration and reuse over years of field deployments, and multiple missions. The SASH system would significantly contribute to the OExS Technology portfolio and would increase the potential success of ISRU on both the Moon and Mars.

ECONOMIC LAWS AND THE LUNAR IMPERATIVE: OUTLINE OF COMPONENTS FOR A SUSTAINED DEVELOPMENT STRATEGY

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With the renewed attention to **Space Exploration and the role of humans in Space** questions of the uses of the Moon and other bodies of the Solar system have come to the forefront: is human Space flight but a romantic quest of childhood dreams or are there key opportunities to be opened and explored for the benefit of mankind – on Earth or in Space.

Economic laws – which apply in Space as well as on Earth – will limit beneficial uses of Space for Earth to the immediate vicinity of Earth in the solar system, the Moon. These 'constraints' will limit the uses for Earth to essentially observations, communications and energy – all **commodities with 'low mass' and 'speed of light'** transmission.

The revolutionary concept of a **'condominium' of observation facilities** is proposed for observations of the universe, the sun and the Earth - providing a stable, nearly limitless aperture across the electromagnetic spectrum with huge advantages in reliability, costs and assurance of continuity of observations. Similarly, **communications, navigation, command and control of civil and scientific activities** on the Moon and for Cis-.and Translunar space will change fundamentally.

Beyond these uses, the 'tapping' of the vast Solar **energy resources** available on the Moon promises fundamental changes in Space operations, Space transportation and potentially clean energy supplies across all regions of Earth. E.g. with 1 GWe supply on the Moon a new age of **'fuel less' space transportation** across Cis- and Translunar space is enabled, ultimately allowing speeds of up to one third the speed of light for missions to nearby solar systems.

Last and not least, with such assured energy supplies, all the **lunar resources** can be tapped for the establishment of Closed Ecological Life Support Systems (CELSS) leading to the **first settlement independent of Earth** – a most historic step for mankind to assuring its survival and expansion into Space.

Key words:

Space observations, Space communications, Space transportation, energy supplies, lunar resources, fuel less transportation, Space operations, closed ecological life support systems, Space power, Space asset management, Space enterprise, Space exploration, Humans in Space, assurance of survival.

GRANULAR FLOW AND IN-SITU RESOURCE UTILIZATION

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The long-term human or robotic exploration of the Moon and Mars will require the exploitation of indigenous mineral and/or atmospheric resources. Technologies for In-Situ Resource Utilization (ISRU) must be developed for propellant production, habitat, infrastructure, and the extraction of water and breathable gas. Although a few of the required minerals are abundant, others are present only in trace. Consequently, ISRU will require mining, transporting, processing, and separating massive quantities of solid materials.

On Earth, these activities have been carried out on a large scale in the oil, chemical, mining, and construction industries for more than a century. However, because the basic principles governing the transport of granular solids and their interaction with gases are poorly understood, the design of reliable solids processes still involves conception on the lab scale, exhaustive tests in a pilot unit, and operation of a demonstration plant. Because it is difficult to mimic conditions of reduced gravity at the pilot scale, technology development for ISRU must strike a different balance between empirical design and rational predictions. ISRU development must rely on computer simulations and theoretical models to carry out scale-up.

In many computer simulations of granular solids, the particles are followed as discrete entities. The challenge is to model accurately the interactions with the surrounding gas and the collisions between particles. Theoretical models, on the other hand, employ a set of differential equations, usually treating the gas and solid phases as inter-penetrating continua. A limitation of models is that the constitutive laws, drag relations and boundary conditions employed in them are not yet well-established. At this stage of their development, neither the simulations nor the models can be used blindly for design.

Experimental research in granular flow is necessary to test the predictions of the simulations and theory against well-controlled experiments before they can be extended to reliable process design. We will describe experiments that have been undertaken in microgravity to provide such tests for particle segregation in collisional grain flows and for the transport of colliding grains driven by a gas. In these two situations, there are preliminary indications that theory and simulations capture important features of the flow, but additional experiments are required to build confidence in the predictive powers of the simulations and the models.

POWER LANDER FOR SUPPORT OF LONG-TERM LUNAR PRESENCE

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Emerging industrial base and the consequent sustained manned Lunar presence will require consistent high power capacities. This paper proposes a first iteration design of a flyable electric power platform which could serve as an enabler of Lunar Development and Exploration. It is intended to support a small facility solo or an emerging industrial base as part of a grid.

Lunar Missions, Habitats and Facilities stand to benefit from an expected decade of non-stop operation, the economics of scale, Commercial Off-The-Shelf (COTS) availability, standardization of design, and logistical support for Lunar encampments provided by this architecture. The unattended and unmanned vehicle design is to be man- and robotics-serviceable after delivery by current and proposed heavy-lift boosters. Design continuity within a family of systems will improve reliability through "lessons learned" in the field.

Further, various configurations of the proposed scalable architecture will provide reference platforms for the indigenous construction of similar power plant facilities from in-situ Lunar resources (ISRU). The baseline design should be directed towards those materials available on the Moon and expected to be manufacturable on-site within the first decade of operation.

NEAR EARTH OBJECT CHARACTERIZATION, EXPLORATION AND EXPLOITATION

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Introduction – The purpose of this paper is to outline how asteroid exploration can leverage from Project Constellation technologies and the benefits to space exploration that can result from exploiting asteroid resources. There are multiple reasons for exploring these bodies: 1) Little is known about their characteristics to help us with mitigation strategies in the event of an impact threat; 2) Many Near Earth Asteroids (NEAs) contain raw material and ore required for manufacturing, fuel production and a basis for testing in situ resource utilization concepts (consider the case of Iron/Nickel asteroids); 3) Asteroid exploration provides unique opportunities to further expand the human/robotic interaction required for advanced exploration; 4) Some of these objects are relatively close especially when considering human missions to Mars; 5) There is a great deal to be learned about the origin of the solar system and primordial history of the planets through the study of asteroids; 6) Asteroid rendezvous missions are a logical step in a spiral approach to human deep space missions.

Asteroid Resources - Resources expected to be abundant on some asteroids are water, iron, nickel, platinum group metals, and organic compounds. Earth based observation for the characterization and detection of NEAs as well as their resources potential could be amplified by Lunar based observation.

Technology Requirements – The technology required for these types of missions are within the bounds of the Exploration Initiative and Project Constellation. Some of the required technologies would be: 1) A highly maneuverable, reusable, refuelable Crew Exploration Vehicle (CEV); 2) Robotic Landers/Explorers; 3) Equipment to support mining operations (drilling equipment, excavation, and processing equipment); 4) Advanced EVA; 5) Advanced power systems; 6) Technologies that are part of Project Prometheus (nuclear power systems, RTGs, NEP, etc.); 7) ISRU production systems; 8) Close proximity rendezvous, station keeping and operations.

Public Outreach – Human missions to NEAs would provide an excellent opportunity to capture the public attention on deep space missions. The benefits and applications of humans and robots producing fuel and refueling vehicles while in deep space must be clearly explained to the public. Several NEAs should be targeted and evaluated for initial missions. Mission concepts should be proposed and evaluated to drive out mission and system requirements. Early robotic missions to resource rich NEAs could provide sample returns to validate the remotely sensed information.

Summary/Conclusion – NEAs offer an opportunity for short-duration, low delta v missions and are a logical step for human activities beyond low earth orbit (Chapman 1990). NEA resources, like those of the Moon, begin to build an economic base for a sustained human presence in space. Accessible targets such as these provide an opportunity to conduct in situ research as well as provide a test bed for systems necessary for long duration missions.

Resources:

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2. The New Solar System, J.K. Beatty and A. Chaikin, editors, Cambridge University Press, 1990, C. Chapman, pages 231-240.

MISSION DESIGN FOR ECONOMICALLY SELF-SUPPORTING LARGE SCALE LUNAR TELEPRESENCE

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Telepresence provides the ability to sense and interact with a potentially hostile environment without the difficulties of getting there, being there, and then returning. Given the limitations of the speed of light, the Moon, which is approximately two and a half seconds round trip distant, is accessible to near-real time telepresence. In addition to the obvious scientific motivations to further explore the surface of the Moon, there is also substantial mass appeal among the general public to interact. The popular access of "live" pictures over the internet from various Mars Rover missions exemplifies this and demonstrated a level of internet activity that was (and still is) without precedent.

A mission design is presented to provide on-going large scale telepresence opportunities on the lunar surface at various levels of interaction with an access fee structure to provide economic self-support. A baseline study includes 10 rover vehicles, each carrying 50 independently controlled stereoscopic camera heads, collectively supporting 500 simultaneous Earth-bound users. A Lander acts as an Earth relay link, permitting the rovers to be relatively simple, light weight, and low cost. The Lander, which provides terminal transport of the rover fleet to the lunar surface, can be relocated, expanding the exploration area. The entire operation is solar powered and without consumables. Rover steering and camera pan and tilt commands are up linked from Earth-bound users over a relatively low bandwidth RF to the Lander, and relayed to the rover fleet. Stereoscopic camera feeds from the 50 camera heads on each rover are relayed to the Lander, which combines them with those of the other rovers, and down links them to the Earth over a high bandwidth optical data link. A one watt Laser (820 nm) on the Moon, transmitted through a one meter telescope, and received on the Earth by a similar sized telescope, results in a positive link margin.

Levels of telepresence are organized into a hierarchy of interaction, with associated access fees. Remote steering command of a given rover represents the highest level, with the highest associated access fee. Prior "driver's education" and demonstration of proficiency on a simulator are needed. A remote co-pilot monitors actual lunar navigation, and may intervene to prevent potentially disastrous maneuvers. Areas of historic importance on the Moon must be treated with respect, and we must be careful not to run over Neil Armstrong's footprints. The next level of telepresence interaction involves active viewing where an Earth-bound user can direct the pan and tilt of a given stereoscopic camera head on a given rover to visually explore the surrounding lunar landscape. The lowest level of telepresence is the passive user, where the user simply goes along for the ride, looking wherever the active viewer (or driver) has chosen. An essentially unlimited number of users can share a given camera feed, or hop among the 500 channels.

Operational availability, due to the solar powered nature of this mission, occurs for at most 14 Earth days every synodic month, and low sun angle limits this to perhaps 12 working days. 13 synodic months per year yields 156 working Earth days and since a lunar day is in continuous sunlight 24 hours per Earth day, there are 3744 working hours per year. If we partition user access into 15 minute time slices then there are 14,976 15 minute time slices per year per active channel from the Moon. An example of an access fee structure is that drivers are charged $100, active viewers $10, and passive viewers $1 per 15 minute time slice. A 10 vehicle fleet with 500 viewer channels will receive about $15 million from driver revenue, and almost $75 million from active viewers. If there are 10 passive viewers per active viewer, an additional roughly $75 million is added. If there are 100, this number is closer to $750 million. Additional income may derive from cable access television ("The Moon Channel"), theme park sites, and so on.

In conclusion, this proposed mission design provides near-real time telepresence exploration to a large number of simultaneous users, with an access fee structure to make it economically self-supporting. An additional and perhaps greater benefit in personal access to space and the surface of another world is the enhanced desire to significantly expand human presence there. Need a 15 minute break? Why not spend it on the Moon?

TUMBLEWEED: A NEW PARADIGM FOR SURVEYING THE SURFACE OF MARS FOR IN-SITU RESOURCES

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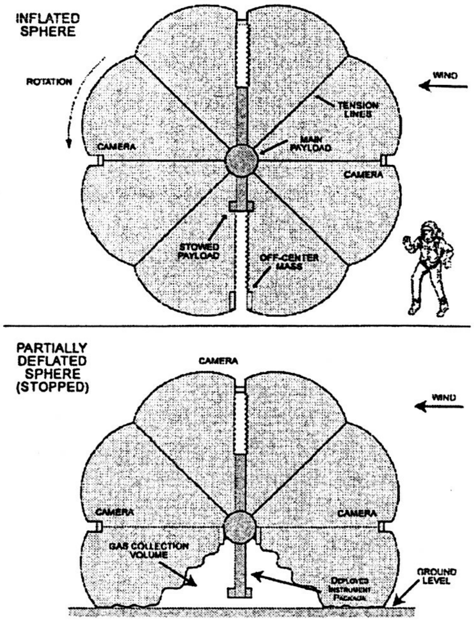
Introduction: Inflatable and rigid Tumbleweeds are wind-propelled long-range vehicles based on well-developed and field tested technology (Figure 1 and Figure 2) [1,2]. Different Tumbleweed configurations can provide the capability to operate in varying terrains and accommodate a wide range of instrument packages making them suitable for autonomous surveys for in-situ natural resources. Tumbleweeds are lightweight and relatively inexpensive, making them very attractive for multiple deployments or piggy-backing on larger missions. Modeling and testing have shown that a 6 meter diameter Tumbleweed is capable of climbing 25° hills, traveling over 1 meter diameter boulders, and ranging over a thousand kilometers. Tumbleweeds have a potential payload capability of about 10 kg with approximately 10-20W of power. Stopping for measurements can be accomplished using partial deflation or other braking mechanisms (Figure 1).

Surveys for In-situ Resources: Tumbleweeds are capable of performing autonomous long-duration surveys over large areas on Mars. The presence of liquid water, for example, can potentially be mapped as a function of depth using simple low mass and low power instruments and an onboard positioning system. During recent field-testing of the inflatable Tumbleweed, data was relayed back to JPL via an Iridium modem. Many of the desired instruments for resource discovery are currently under development for in-situ applications, but have not yet been miniaturized to the point where they can be integrated into Tumbleweed. It is anticipated that within a few years, instruments such as gas chromatograph mass spectrometers (GC-MS) and ground-penetrating radar (GPR) will be deployable on Tumbleweed.

Acknowledgements: This work was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration and at the NASA Langley Research Center.



Figurel. Inflatable Tumbleweeds can be stopped by partially deflating the ball and pulling on one of the central payload tension cords to create a "turtle effect."

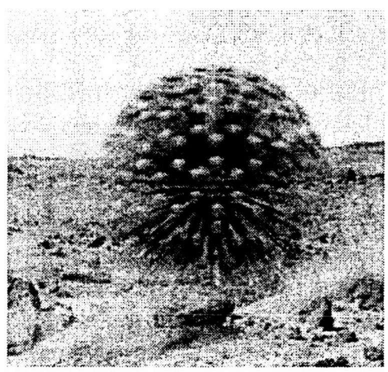


Figure 2. NASA Langley Research Center rigid Tumbleweed concept [2].

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SIMULATION OF HELIUM-3 EXTRACTION FROM LUNAR ILMENITE

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Introduction: Knowledge of the trapping mechanisms and diffusion characteristics of solar-wind implanted isotopes in the minerals of the lunar regolith will enable the optimization of the processes to extract solar wind gases from regolith particles. Extraction parameters include the temperature and duration of extraction, particle size, and gas yield [1]. Diffusion data will increase the efficiency and profitability of future mining ventures. This data will also assist in optimizing the evaluations of various potential mining sites based on remote sensing data. For instance, if magnesian ilmenite ($Mg_xFe_{1-x}TiO_3$) is found to retain He better than stoichiometric ilmenite ($FeTiO_3$), remote sensing data for Mg could be considered in addition to Ti and maturity data.

The context of the currently discussed work is the mining of helium-3 for potential use as a fuel for fusion energy generation [e.g. 2]. However, the potential resources deposited by the solar wind include hydrogen (and derived water), helium-4, nitrogen and carbon. Implantation experiments such as those performed for helium isotopes in ilmenite are important for the optimized extraction of these additional resources. These experiments can easily be reproduced for most elements or isotopes of interest.

Helium-3 Implantations of Ilmenite: Helium isotopes were implanted into terrestrial ilmenite using plasma source ion implantation (PSII), a non-line of sight technique developed for uniformly implanting a variety of atoms orthogonally into materials [3]. It is very conducive to simulation of solar wind implantation because implantation energies of 1 keV/amu are easily achieved. The target -- in this case a silicon wafer with thin polished samples of terrestrial ilmenite lying on top -- is placed in a 1 m^3 chamber which is evacuated to a base pressure of about 10^{-6} torr. Helium-4 and helium-3 gas is allowed to flow through the chamber at a pressure of several millitorr. A plasma is generated using tungsten filaments to ionize the gas by energetic primary electron impact. The evolution of helium isotopes from the implanted samples was performed using isochronal and isothermal annealing similar to the experiments performed on the Apollo samples. The measured release profiles were found to be quite similar to the release profiles measured for regolith samples from the Apollo 11 site [4].

Reconnaissance of Lunar Solar-wind Resources: Since remote sensing of helium-3 has been shown to be impossible without an added source of protons or neutrons [5], helium-3 concentrations are currently associated with titanium concentrations and maturity indices measured by remote sensing. We propose that in-situ mapping of lunar helium-3 concentrations or other species of interest is possible using well-developed borehole neutron or proton sources in concert with gamma-ray detectors. Such instruments should be considered for in-situ discovery of in-situ resources on both the Moon and on Mars.

Acknowledgements: This work was carried out in the Fusion Technology Institute (FTI) at the University of Wisconsin – Madison. Funding was generously provided by the Wisconsin Space Grant Consortium, NASA Johnson Space Center and the Graduate School of the University of Wisconsin. Special thanks to R.O. Pepin, University of Minnesota for performing the measurements of helium release.

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MARS DEEP DRILLING REMAINS A HIGH PRIORITY

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In 1992, The University of Texas Center for Space Research (CSR) submitted a proposal to the NASA Scout Program to drill a "deep" well on Mars. The proposal was unsuccessful. However, the mission remains viable, and can still be accomplished for a very low cost.

The science of this mission remains of utmost interest to the science community, and no deep drilling mission is scheduled currently. Deep drilling is the only way to verify the character of the Martian subsurface, particularly to characterize any water to be found there, and eventually to explore for liquid water.

During the preparation of the Scout proposal, a very strong team was forged, and several of the team members, including NASA Centers, have expressed a strong interest in pursuing this mission in the near future.

In its existing programs (GRACE, ICESAT, others), CSR has developed strong international ties, particularly with Germany. The GRACE partnership resulted in a sharing of mission expenses between the two countries. This type of partnership remains very viable for a Mars Deep Drilling Mission.

Baker Hughes, Inc., and the NASA Johnson Space Center have built and tested a prototype Mars deep drill, so the technology risk has been greatly reduced.

All of these factors come together to suggest that a very low cost, low risk mission can be proposed to NASA, either in response to a future Scout mission call, or as an independent international mission.

SELENE SCIENTIFIC DATA PRODUCTS AND THEIR APPLICATION TO CHARACTERIZATION OF LUNAR POTENTIAL RESOURCES

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SELenogical ENgineering Explorer (SELENE) is a Japanese mission to investigate the origin and evolution of the moon. The 14 scientific instruments will provide massive datasets of great importance not only for science but also for future utilization of the moon. For example, we can completely map the permanently shadowed/illuminated areas around the poles. The terrain camera (TC) can monitor the seasonal variation of the illumination conditions during the SELENE mission period of one year, while Clementine/UVVIS covered only two months. With the high energy resolution, the gamma-ray spectrometer (GRS) will identify the hydrogen emission line if water ice exists in the permanently shadowed areas. TC and the Laser ALTimeter (LALT) will measure the surface topography with the high spatial resolution and accuracy. The global element distribution can be determined by the GRS and X-ray fluorescence spectrometer (XRS). Spectral Profiler (SP) and Multi-band Imager (MI) reveal the mineralogy of lunar surface in detail. In this presentation, we describe the SELENE datasets and discuss their vital role in characterizing the potential resources on the moon.

THE IDENTIFICATION OF GAS HYDRATE RESOURCES ON MARS: IMPLICATIONS FOR HUMAN EXPLORATION AND LONG-TERM HABITATION

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Terrestrial experience, and the recent discovery of trace amounts of methane in the Martian atmosphere that is almost certainly leaking from subsurface Mars, suggests that Mars may be rich in a primary natural resource that could aid future human exploration and long-term habitation. This resource would be methane hydrate. Deposits similar to those found on Earth may provide potable water for drinking, agriculture and oxygen, fuel for return trips and outward exploration as well as local power, and industrial feedstock for manufacturing plastic products such as building, vehicle, and utility components.

In Earth's permafrost regions, methane hydrate and water ice form a compound cryogenic zone whose extent is determined by the local surface temperature, geothermal gradient, and increasing pressure that occurs with depth. The region of the crust that satisfies these criteria is called the Hydrate Stability Zone (HSZ). Water ice is stable from the surface down to about zero degrees C whereas methane hydrate on Mars may be found at depths ranging from several tens of meters to as much as a km below the base of the local Martian cryosphere. Hydrate can be formed anywhere in the HSZ and high methane (or other hydrocarbon gas) fluxes can cause water-ice to recrystallize to hydrate. Relatively near-surface hydrate accumulations could also have been caused as downward propagation of the freezing-front at the base of the prograding cryosphere during the original freeze-up of Mars had the potential to have incorporated subsurface methane as hydrate -- in concentrations that may range from a dispersed, low grade diagenetic mineralization, to high grade deposits formed by focused flow of methane. The extent to which the HSZ is occupied by hydrate is unclear but on Earth, shallow permafrost hydrate in commercial concentrations has been tested, and may have been extracted for some years from Russian (West Siberian) deposits.

Because the lifetime of atmospheric methane is so short, its recent detection on Mars is generally attributed to leakage from a subsurface methanogenic biosphere although volcanic emissions from igneous fractionation could also be a source. Regardless of the source, if significant methane is being produced at depth on Mars, it is almost inescapable that much of it would be sequestered in the form of hydrate deposits in the cryosphere in a manner similar to that which occurs in permafrost regions on Earth

Identification of methane hydrate resources is vital. Exploration for subsurface hydrate on Mars can be accomplished by adapting remote sensing techniques such as seismic analysis that are currently employed on Earth. For the final phase of resource evaluation, development of remote, autonomous drilling capability will be necessary (autonomous Earth seafloor drilling capability already exists). In addition, lightweight, rapid prototyping, plastics fabrication apparatus that could be sent to Mars with early human explorers will allow a variety of life and expedition-sustaining items to be fabricated on Mars. Gas to liquid fuel fabrication apparatus will allow the natural gas to be converted to higher energy density liquid fuels for use in chemical rockets, vehicles or other local uses. In other words, a wide variety of portable industrial capability will have to be developed that can be brought to Mars to support human exploration and colonization that will utilize the subsurface methane hydrate (and CO_2) resources.

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MICRO-STRUCTURED HEAT EXCHANGERS AND REACTORS FOR ISRU AND ENERGY CONVERSION

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A large fraction of technologies for in-situ resource utilization on the Moon and Mars involves high temperature processes and catalytic reactions. Conversion of energy from a chemical source is also an important element in both space travel as well as establishment of human habitat in space. Heat exchangers and catalytic reactors with micro-scaled features can provide significant weight and volume reductions compared to currently available systems. We report on development of micro-machined thermal and chemical devices that have surface features of the order of 100's of microns, over areas of the order of 10's to 100's of cm. These devices are fabricated by the LIGA technique, which utilizes x-ray lithography and electroplating to form micro-structures with aspect ratios in the range of 1:10. These micro-structured surfaces provide significant enhancement to heat and mass transfer, and thus allow for miniaturization of thermo-chemical devices.

A number of thermo-chemical devices suitable for ISRU and energy conversion will be introduced. We will report on the performance of micro-machined cross-flow heat exchangers with a performance to volume ratio which is 10 times higher than the best heat exchanger currently available. We will also report on the development and performance of a novel cooling device based on micro jet cooling arrays (MJCA). MJCA consists of arrays of 200-400 micron jets created in three dimensional structures that allows localized removal of coolant immediately after contact with the target surface. These devices provide extremely high heat transfer coefficients over large areas.

Progress in development of micro-machined ceramic devices suitable for high temperature heat exchangers and catalytic combustors will be discussed. Micro-machined ceramic substrates which can be sealed to form leakage-free fluid conduits are currently under construction. These structures will open the door to miniaturization of a large number of high temperature applications, ranging from integrated catalytic combustor and heat exchanger to intimately coupled endo- and exo-thermic reactive gas streams. We will report on prototype devices under fabrication, and demonstrate a number of key enabling technologies in this area.

ROCKS TO ROBOTS: A BIOLOGICAL GROWTH APPROACH TO RAPID LUNAR INDUSTRIALIZATION *OR* HOW TO REALIZE VON NEUMANN'S VISION

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We propose a strategy for rapidly attaining and maximizing lunar industrial capability.

Consider a series of 1000 kg EELV (Evolved Expendable Launch Vehicle) lunar payloads. These payloads bring the following technologies: Telepresence robotics for mining and material manipulation, ISRU (In Situ Resource Utilization) production of solar electric power, solar furnaces for fusion of regolith ceramics, and electrolytic reduction of metals from regolith.

Using telepresence, regolith is mined on a kilogram scale for ISRU. Telepresence-operated ISRU apparatus immediately produces metals and ceramics, also on kilogram scales. Metals, particularly iron, are shaped using casting, powder metallurgy, and light machining methods. This produces a versatile kit of assorted stock mechanical components. These lunar kits, together with required earth-based components, are assembled by telepresence to generate additional mining and fabrication equipment, as well as more telepresence robots.

Re-supply missions provide critical earth-based ingredients, such as miniature cameras, computer controllers, reagents for thin-film solar cell production, electrodes, forming dies, and tool bits. However, the overall proportion of earth-based content is reduced as rapidly as possible by several strategies. Designs maximize use of lunar iron, the first metal that will be produced. Simple mechanical devices, built with lunar materials using methods at hand, are favored over more sophisticated earth-based technologies. As mining operations are scaled up, more elements and minerals become available, which provides more options to eliminate earth-based content. Accumulating know-how also yields new methods of substituting lunar for earth-based content.

The key element of this approach is the geometric, or biological, growth rates that are possible. Consider this illustration: If the initial 1000 kg ISRU package produces an average of 0.1-0.2 kg of apparatus per hour, the mass doubles in one year. At this point, the production rate has also doubled since more production apparatus has been built. At the end of ten years, the cumulative apparatus is a million kilograms, capable of producing 100 kilograms of apparatus per hour. This is the power of the force Einstein called the most powerful in the Universe – compound interest.

We view extensive telepresence as essential. Abundant, tool-wielding robotic telepresence permits the flexibility to rapidly realize the pragmatic solutions needed for this pioneering enterprise, and to assemble, operate and maintain all the required apparatus.

The advantage of beginning ISRU immediately on a kilogram scale is that spacecraft required to deliver 1000 kg are available now, and are affordable. Using "biological" growth, we can start small and "grow" the millions of kilograms of industrial capability we need in situ. This capability will otherwise wait decades or longer for the required heavy lift to materialize.

SOLAR ENERGY UTILIZATION FOR IN-SITU RESOURCE UTILIZATION

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Physical Sciences Inc. (PSI) has been developing the Optical Waveguide (OW) system for solar energy utilization. In this system, solar radiation is collected by the concentrator which transfers the concentrated solar radiation to the OW transmission line. The OW transmission line transports the solar radiation to the location of solar energy utilization. Applications of this system include: material processing, plant lighting and power generation in space.

Since 1988, the author and his colleague have been working on development of the Optical Waveguide (OW) Solar Power System with funding from Air Force Astronautics Laboratory. The work undertaken in this program includes theoretical and experimental investigation of key components of the OW system, and conceptual design, performance analysis and survivability evaluation of the OW Solar Power. Subsequently, Physical Sciences Inc. (PSI) has been developing the OW System for utilization of solar energy in space as well as on the ground.

The first embodiment of the OW system discussed above was implemented for lunar material processing with funding from NASA/JSC (SBIR Phase I and II). In this program, we developed an engineering prototype of the solar energy system for thermochemical reduction of lunar oxide. The product oxygen is to be used as a propellant for space transportation. Figure 1 shows a photo of the ground test model of the OW solar energy system developed in this program. The system consists of three major components: the concentrator, the solar power transmission line, and the thermal reactor.

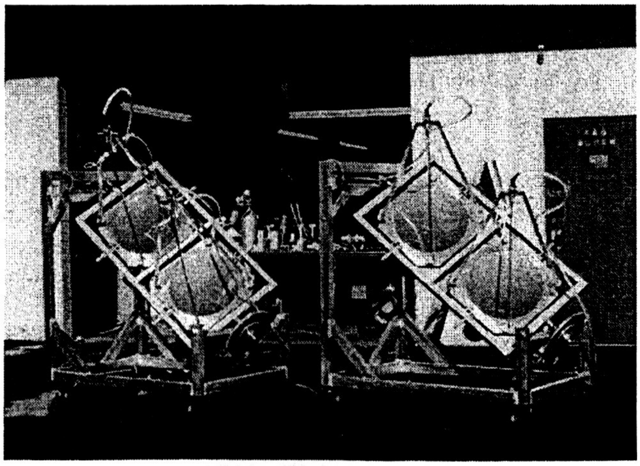

FIGURE 1. The Ground Test Model of the OW Solar Energy System.

In this presentation, a review of our work conducted during the last 10 years for in-situ resource utilization, plant growing and power generation in space is presented.

LESSONS FROM EARTH: EXPERIENCES WHICH CAN GUIDE LUNAR AND ASTEROIDAL DEVELOPMENT

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Although space-based projects face unique technical challenges, they will encounter many of the same regulatory, logistical and financial issues which other large-scale enterprises have been presented with in the past. Given this commonality, it is possible many of the same solutions engineered for issues confronted on Earth may be applied to the challenges faced in space as well.

This paper will examine the successes of a few key technologies, social policies and business frameworks of the past century and consider what lessons may be learned from those examples to assist public and private sector projects involving the Moon, Mars and Near Earth Asteroids.

These examples will include:

- the development of global infrastructure for the Liquid Natural Gas industry;
- the increased effectiveness of asset use due to land title reform;
- the objective of resource claims for assets extracted from public land;
- asset distribution to citizens through the Alaska Permanent Fund Dividend Program; and
- the regulatory environment behind the rapid emergence of 802.11b / Wi-Fi technology.

By looking to these past projects and social frameworks for examples of success in their respective fields of endeavour, the Space Resources Roundtable may assist national space agencies and emerging private sector enterprises by proposing policies and frameworks which draw upon the best of this industrial experience. Actions which may be taken within the scope of the SRR's activities over the next year to assist this goal will be proposed as part of this paper's conclusions.

SILVER: SURFACE IMAGING FOR LUNAR VOLATILES, RESOURCES, AND EXPLORATION

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The Surface Imaging for Lunar Volatiles, Exploration, and Resources (SILVER) instrument is a proposed imaging investigation for the 2008 Lunar Reconnaissance Orbiter (LRO) mission. SILVER and its experienced Measurement Team will prepare for and support future lunar human exploration activities, especially landing site identification and certification on the basis of potential resources.

SILVER combines a high-resolution pushbroom visible imaging channel (SILVER-HR) and a wide-field-of-view (45°) framing imaging channel (SILVER-WF). SILVER-HR will obtain a single-detector 6 km imaging swath of 12,228 pixels at 0.5 m/pixel to image >100 km^2 target areas from 50 km altitude, imaging >15% the lunar surface during a 1 year nominal mission. SILVER-HR has excellent stray-light rejection and its imaging detector has selectable time delay integration (TDI) with up to 128 stages for extreme low-light sensitivity, permitting direct imaging of permanently shadowed polar regions in scattered sunlight or earthshine. SILVER-WF will obtain geodetic framing images in a 2048 x 2048 format at 20 m/pixel, with 60% along-track overlap stereo for imaging context and for derivation of a global digital elevation model of meter-scale lunar topography.

SILVER addresses 5 of the 8 Measurement Investigations for the Lunar Reconnaissance Orbiter (LRO: (1) Assessment of submeter-scale features to facilitate safety analysis for potential lunar landing sites; (2) Geodetic lunar global topography; (3) Landform-scale imaging of lunar surfaces in permanently shadowed regions; (4) Identification of putative deposits of near-surface water ice in the Moon's polar cold traps; and (5) Characterization of the Moon's polar region illumination environment at relevant temporal scales.

The SILVER investigation combines the experience and heritage of the University of Colorado's Laboratory for Atmospheric and Space Physics (LASP) with that of the Southwest Research Institute (SwRI) to build a superb imaging investigation optimized to the exploration objectives of the Lunar Reconnaissance Orbiter mission and the Lunar Exploration Program. The SILVER Operations Facility, which partners with Applied Coherent Technologies (ACT), will be co-located with the primary instrument builder and the Principal Investigator at LASP. Moreover, SILVER utilizes the experience and heritage of the Exploratory Computing Environments group at Ames Research Center—producers of the landing site selection planning products for the Mars Exploration Rovers—to create and distribute high-level data products that enable planning for future landed missions of the Lunar Exploration Program, addressing the goals of NASA's Exploration Vision.

The SILVER team includes an Apollo-Veteran Advisory Committer, cementing ties to the experience of humanity's previous lunar field expeditions. Its members are: M. Duke (Colorado School of Mines); N. Hinners (LASP and Lockheed Martin, retired); H. Schmidt (Apollo 17 astronaut and University of Wisconsin); G. J. Taylor (University of Hawaii); and D. Wilhelms (U.S. Geological Survey, retired).

SILVER's Education and Public Outreach (E/PO) program will develop a deep understanding of lunar geology and geography in the context of Earth's geology and history with a focus on topography, mapping and remote sensing. The E/PO program will create curricular enhancements, including 3-D visualizations, and will engage Explorer Schools and Colorado MESA after school programs in a year-long set of lessons and activities, culminating in a contest for choosing a lunar landing site. LASP leads these E/PO efforts in conjunction with the SILVER Measurement Team, NASA Explorer Schools, Colorado MESA Program, NASA Ames and RMC Research Corporation.

EXPLORATION OF THE IMPACT OF ISRU ON ARCHITECTURAL SYSTEM MASS AND COST

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This paper addresses a concept-level model that produces technical design parameters and economic feasibility information addressing future Human Exploration platforms. A design methodology and analytical tool is used to create feasible concept design information for these space platforms at the architectural level. The design tool has been validated against a number of actual facility designs, and appropriate modal variables are adjusted to ensure that statistical approximations are valid for subsequent analyses. The tool is then employed in the examination of the impact of various payloads on the power, size (volume), and mass of the platform proposed.

The development of the analytical tool employed an approach that accommodated possible payloads characterized as simplified parameters such as power, weight, volume, crew size, and endurance. In creating the approach, basic principles are employed and combined with parametric estimates as necessary. Key system parameters are identified in conjunction with overall system design. Typical ranges for these key parameters are provided based on empirical data extracted from actual human spaceflight systems.

Using this tool a sample Exploration architecture is formulated with emphasis on cost minimization through variance of key mission requirements. Further, the use of ISRU (In Situ Resource Utilization) is considered to minimize the consumables needed for transport from Earth. A baseline architecture is compared to one that uses ISRU and the impact on system mass and cost is determined.

This paper is based on work Dr. Reynerson completed at George Washington University in fulfillment for the degree of Doctor of Science in Astronautics. Dr. Mike Griffin, former head of NASA's Human Mars Mission, was a member of the dissertation committee.

Summary Biography for Dr. Charles Martin Reynerson

Associate Technical Fellow, The Boeing Company, Boulder, Colorado. Dr. Reynerson received his Doctorate of Science in Astronautics from the George Washington University, Engineers degree (between MS and D.Sc.) in Aeronautics and Astronautics (EEA) from MIT, Engineers (NE) degree in Naval Engineering from MIT, and BS from U.C. Berkley. He has extensive experience in the development of space systems with NASA where he was the Assistant Deputy for Space Shuttle Integration, National Reconnaissance Office (NRO) Liaison for Space Technology Programs, and Project Manager and Contracting Officer's Technical Representative at the National Reconnaissance Office. He is an ex-Naval Engineering Duty Officer also qualified in submarines. Dr. Reynerson is member of AIAA, AAS, and Tau Beta Pi (National Engineering Honor Society). Dr. Reynerson is also a licensed private pilot.

LUNAR AND MARTIAN FIBERGLASS AS A VERSATILE FAMILY OF ISRU VALUE-ADDED PRODUCTS

Gary "ROD" Rodriguez, Systems Architect, sysRAND Corporation

Lunar Regolith consists principally of silicates, in some cases as volcanic or impact glasses. We continue to contend that silicon is more versatile in application than all of the other Lunar-available elements combined and shouldn't end up in Lunar slag-heaps and instead should be the fundamental building block for a wide range of value-added products in a CisLunar economy. Fabrication of silicate glasses are conventional industrial processes and anticipated tensile strength of glass made under hard vacuum is an order of magnitude greater than glass produced in atmosphere containing water vapor.

The logic employed in our reasoning includes the fact that any In Situ Resource Utilization (ISRU) effort is going to yield copious masses of silicon oxides which can be used in bulk as conventional glass products or, after further separation, can be synthesized as Silicon and Silicon-Carbide Fullerenes for more exotic applications. Additionally, mechanical wrapping of Silicon Webbing could prove to be more practical and durable and a lot less brittle than attempting large-scale hot glass molding of structural components.

Identified fuel production ISRU efforts yield partially heated masses of metal oxides as waste byproduct – rich in silicates and metal oxides useful in bulk as conventional glass products. Fiberglass manufacturing increases effectiveness of prior ISRU fuel production by taking advantage of mineral benefaction and elevated process exit temperatures. The resulting structures would be spheres and cylinders with various configurations that could apply to human support systems, along with structures useable as storage tanks for the very Oxygen liberated in ISRU applications.

ISRU can manufacture more than fuels: even spacecraft are feasibly and affordably manufactured on Moon based upon fiberglass "tankage" integrated with fiberglass keels. Second-generation structural components may take advantage of Silicon Nanotubes for additional composite strength. Diverse products for human systems support are manufactureable in-situ using glass fibers and fabrics, and CNC-type programmable manufacturing delivering state-of-the-art flexibility of remote design and parts manufacture. These concepts suggest extensibility and evolutionary capability derived when machining tool parts from fiberglass.

Contemporary Terrestrial industrial composite fiber products range from pressure vessels to lightweight sporting goods. A large number of products related to human systems support can similarly be manufactured in-situ using fiber fabric made from lunar silicate glass. Building structures using spun glass would be similar to those currently employed by Raytheon Aircraft or Scaled Composites to build composite aircraft. Pressure containers, structural components, woven fiberglass fabrics, molded and machined solid objects, glass fiber and filament are each large classes of value-added products.

TELEPOSSESSION TRANSFORMS ASTEROIDS INTO RESOURCES

Gary "ROD" Rodriguez, Systems Architect, *sys*RAND Corporation

A deep-space probe with integral RADAR transponders should be a sufficient improvement to a space rock to qualify as a resource mining claim. Such a legal device would allow Aldrin (Earth-Mars) Cycler Orbiters to develop the asteroids, widely viewed as a menace to Earth, into valued resources. Technologies and Capabilities are outlined to encourage new legal conversations.

POWER LANDER FOR SUPPORT OF LONG-TERM LUNAR PRESENCE

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Emerging industrial base and the consequent sustained manned Lunar presence will require consistent high power capacities. This paper proposes a first iteration design of a flyable electric power platform which could serve as an enabler of Lunar Development and Exploration. It is intended to support a small facility solo or an emerging industrial base as part of a grid.

Lunar Missions, Habitats and Facilities stand to benefit from an expected decade of non-stop operation, the economics of scale, Commercial Off-The-Shelf (COTS) availability, standardization of design, and logistical support for Lunar encampments provided by this architecture. The unattended and unmanned vehicle design is to be man- and robotics-serviceable after delivery by current and proposed heavy-lift boosters. Design continuity within a family of systems will improve reliability through "lessons learned" in the field.

Further, various configurations of the proposed scalable architecture will provide reference platforms for the indigenous construction of similar power plant facilities from in-situ Lunar resources (ISRU). The baseline design should be directed towards those materials available on the Moon and expected to be manufacturable on-site within the first decade of operation.

INTELLIGENT EXCAVATION FOR THE MOON

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Intelligent Excavation (IE) is an emerging technology on earth. This technology is being utilized by Fortune 200 mining companies. IE has application to the intensified NASA objective of space exploration. Mining on the moon will require precise spatial reference of mineralization, as identified by evasive and remote sensing exploration methodologies. During the actual extraction process, mining and haulage machines will also require real-time spatial reference, and remote mineral inventory management. Existing mining information technology in the form of IE offers adaptability to geo-base moon requirements. Researching existing earth-based Intelligent Excavation system capacity and accuracy for alteration for mining on the moon offers promise. Such a program meets NASA's Technology Readiness Levels 1 – 5. These readiness levels have as a benchmark; ground truth earth-based evaluation and synthesis into space environments. IE technology is available to meet this in-process research protocol. The benefit of IE to the extraction process is a reduction in cost per unit mined.

SOLAR WIND HELIUM CONCENTRATIONS IN UNDISTURBED LUNAR REGOLITH

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Considerations of the geology of helium in the lunar regolith strongly indicate that agitation of regolith samples before laboratory analysis has caused the loss of solar wind volatiles. For example, the undisturbed concentration of Apollo 11 helium-3 subject to recovery through mining and processing of titanium-rich areas of Mare Tranquillitatis is significantly higher than the 11.8 wppb average measured for samples of Apollo 11 fines. A similar conclusion appears to hold for solar wind helium-4 and hydrogen.

A review of analyses of samples of Apollo 11and other regolith fines as a function of grain-size fraction offer insights into the concentrations of volatiles in undisturbed regolith. For example, the finest size fraction, <20 μm, of 10084,18 show the helium-3 and helium-4 concentrations 27-35% and 19-39% greater, respectively, than the sample as a whole. (1) In the analysis of 10084,47 grain sizes less than 1.4 μm, the concentrations reach 221 wppm and 71 wppb, respectively.(2) Similarly, analysis of 10087,8 grain sizes less than 5 μm, shows the concentrations are 76.1 wppm and 20.1 wppb, respectively.(3) These results almost certainly reflect the increase in total surface area with decreased grain size fraction. On the other hand, helium-3 and helium-4 concentrations in 10084 reach minimums at about 150 μm that are respectively 78-83% and 77-84% lower than in the <20 μm fraction. Concentrations then increase in the coarser factions suggesting that agitation affects the intermediate size fractions more that the small and large fractions. Data also show a correlated decrease in 4He/3He mass ratios with increased grain size fraction in regolith fines, changing from about 3500 to about 3300 before again increasing in the courser fractions. These concentration vs. grain size relationships may reflect the interplay of implantation energy vs. particle mass vs. surface area during repeated agitation as samples were handled and processed from the undisturbed regolith on the Moon to the analyst's mass spectrometer.

Regolith breccias offer some more specific insights into the undisturbed concentrations of solar wind volatiles. Volatiles sealed into some regolith breccias indicate that the undisturbed concentration of helium-3 may be 20.5 wppb or higher. Data indicate that rapid shock or base surge induced induration of regolith, may seal in at least 57% more helium-3 than is preserved in the analyzed samples of Apollo 11 fines. This difference, as well as consideration of 4He/3He ratios as a function of grain size, indicates that losses of helium-3 from Apollo 11 fines due to agitation may be at least 42% of its concentration in undisturbed regolith.

Systematic variations in 4He/3He ratios between fines and breccias and between various grain size fractions also suggest losses of solar wind volatiles due to sample agitation. There also appears to be secondary enrichment of helium-4 relative to helium-3 in regolith modified by impact processes.

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SYNTHESIS OF SOL-GEL PRECURSORS FOR CERAMICS FROM LUNAR AND MARTIAN SOIL SIMULARS

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Recent NASA mission plans for the human exploration of our Solar System has set new priorities for research and development of technologies necessary to enable a long-term human presence on the Moon and Mars. The recovery and processing of metals and oxides from mineral sources on other planets is under study to enable use of ceramics, glasses and metals by explorer outposts.

We report initial results on the production of sol-gel precursors for ceramic products using mineral resources available in martian or lunar soil. The presence of SiO_2, TiO_2, and Al_2O_3 in both martian (44 wt.% SiO_2, 1 wt.% TiO_2, 7 wt.% Al_2O_3) and lunar (48 wt.% SiO_2, 1.5 wt.% TiO_2, 16 wt.% Al_2O_3) soils and the recent developments in chemical processes to solubilize silicates using organic reagents and relatively little energy indicate that such an endeavor is possible. In order to eliminate the risks involved in the use of hydrofluoric acid to dissolve silicates, two distinct chemical routes are investigated to obtain soluble silicon oxide precursors from lunar and martian soil simulars.

Clear solutions of sol-gel precursors have been obtained by dissolution of silica from lunar soil similar JSC-1 in basic ethylene glycol ($C_2H_4(OH)_2$) solutions to form silicon glycolates. Similarly, sol-gel solutions produced from martian soil simulars reveal higher contents of iron oxides. Characterization of the precursor molecules and efforts to further concentrate and hydrolyze the products to obtain gel materials will be presented for evaluation as ceramic precursors.

DRILLING TO EXTRACT LIQUID WATER ON MARS: FEASIBLE AND WORTH THE INVESTMENT

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A critical application for the success of the Exploration Mission is developing cost effective means to extract resources from the Moon and Mars needed to support human exploration. Water is the most important resource in this regard, providing a critical life support consumable, the starting product of energy rich propellants, energy storage media (e.g. fuel cells), and a reagent used in virtually all manufacturing processes. Water is adsorbed and chemically bound in Mars soils, ice is present near the Martian surface at high latitudes, and water vapor is a minor atmospheric constituent, but extracting meaningful quantities requires large complex mechanical systems, massive feedstock handling, and large energy inputs. Liquid water aquifers are almost certain to be found at a depth of several kilometers on Mars based on our understanding of the average subsurface thermal gradient, and geological evidence from recent Mars missions suggests liquid water may be present much closer to the surface at some locations. The discovery of hundreds of recent water-carved gullies on Mars indicates liquid water can be found at depths of 200-500 meters in many locations. Drilling to obtain liquid water via pumping is therefore feasible and could lower the cost and improve the return of Mars exploration more than any other ISRU technology on the horizon. On the Moon, water ice may be found in quantity in permanently shadowed regions near the poles.

A system of modular, reconfigurable, autonomous and human-tended deep drilling technologies should be developed for use initially on Mars precursor missions and later for subsequent crewed missions that are less mass and power constrained. For the Mars application, the drilling technology will be focused on obtaining liquid water via pumping for resource utilization purposes. Early testing on the Moon could be used to establish viability of this technology so that it can be a cornerstone architecture element of Mars exploration, as well as a tool for resource exploration and science.

The required technologies for the Moon and Mars have much in common but there are important differences. On the Moon, directional drilling is likely to call for the use of a conventional drill string (similar to one under development for robotic Mars application) and a steerable down-hole unit. Hole stability in the lunar regolith will require the use of casing or of microwave sintering. Exploitation of lunar resources identified by drilling will subsequently be a mining and processing operation. On Mars the main task will be deep penetration to gain access to liquid water. Penetration to depths of kilometers would require massive equipment if a drill string is used but could be implemented using a wire-line device (one that anchors itself to the bottom of the hole and exerts force on bit from there rather than from the surface) where additional depth penetration requires only the addition of more cable. Its advantages include lightweight and convenience in automating its control since digital data can be more easily communicated. Mars ISRU goals will involve gaining controlled access to liquid water that can be pumped to the surface. Because of the stabilizing effect of ground ice, much of a Martian drill hole may not need stabilization. Preventing bit freeze up may require controlling bit temperature, and cuttings removal may require use of low temperature drilling fluids, such as liquid CO_2 derived from Mars air. It may also be necessary to line the hole with an insulating material to ensure that water does not freeze on its ascent to the surface.

Drills developed for robotic Mars mission applications have been field tested to 10 m depth. Deeper depths suggest a wire line drill string (downhole motor driving the bit) suspended on a cable and an elevator bailer to remove cuttings. Design issues to be addressed for a deep drill include operational simplicity and low mass, bit development and change-out strategies to respond to bit wear and the need to cut a range of materials, cuttings removal approach, systems for anchoring the drill string in the hole and providing weight on bit, casing for hole stability and capping to prevent destructive effects of pressure differentials.

While NASA Code S has recently invested in technology development for robotic drills for Mars exploration (and useful progress has been made) the investment is not consistent in scope with the new Space Exploration vision.

THE UNCERTAIN NATURE OF POLAR LUNAR REGOLITH

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Lunar polar regions are receiving considerable attention because they might contain sizeable quantities of H_2O, which could be useful for lunar development and space commerce [1]. Plans to use those resources are limited by our ignorance of the nature of polar regions. Major uncertainties are outlined here. All can be addressed by missions to permanently shadowed polar regions on the Moon.

Regoltih characteristics: The typical lunar regolith has a mean grain size of ~100 μm, with ~10% of the material smaller than 10 μm [2]. However, the polar regions are in the most ancient lunar highlands, which have been subjected to the most intense bombardment for more than 4 billion years. Hartmann [3] suggests that the upper hundreds of meters have been reworked so extensively that it resembles the typical lunar regolith. Since the heavy bombardment ceased about 3.8 billion years ago, the upper several meters of the Moon have been modified by micrometeorite impacts. That regolith may be much finer grained than typical regolith as it developed on hundreds of meters of fine-grained material. If so, we cannot predict with confidence the physical properties of the regolith (porosity, thermal conducitivity, shear and bearing strength, angle of repose, tribology). A finer grain size provides a much larger surface area for a given mass of regolith, which could enhance adsorption of H_2O and other volatiles and their reaction with regolith grains.

Characteristics of the H_2O deposits: There is clear evidence for enrichment in H in lunar polar regions [4], but what form is it in? Models depict the observed enrichments in hydrogen as being due to solar wind hydrogen, water ice deposited by H_2O released from soil grains that have been bombarded with solar wind hydrogen, and more complex ices released by impacting comets. These deposits could form thin films around regolith grains (adsorbed chemically or physically [5]), partially- to completely-filled pore spaces, or form layers of ice (in the case of comet impacts). Each of these scenarios leads to potentially different physical and geotechnical properties of the regolith, and different properties of the resource. To show the complexities, consider a cometary source for H_2O. In this case the H_2O would be accompanied by CO, CO_2, CH_4 and other gases. If the H_2O precipitated as one of the many forms of ice, it could be relatively pure because of the low solubility of gases it in, but might be associated with deposits of less stable carbon gases. If the H_2O precipitated as amorphous ice, the amorphous ice might contain dissolved CO and other gases. When heated during exploration or extraction, the amorphous ice would crystallize, releasing the trapped gases and possibly producing jets of dust and gas, as happens as comets are heated [e.g., 6]. Moreover, the crystallization is exothermic, possibly leading to a runaway effect, release of CO_2 from its frozen form, loss of the resource, and possibly damage to extraction equipment. At the very least it prevents us from knowing how to design equipment for surface mobility or to extract volatiles from polar regolith. Finally, whatever its state, we do not know how the H_2O resource is distributed with depth or laterally.

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THE NATURE OF LUNAR SOIL: CONSIDERATIONS FOR SIMULANTS

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Introduction: It is obvious that many factors must be considered in making lunar simulants for various ISRU projects. This subject is of major importance (also, see abstract by Carter et al., this meeting) as we move into the near-future endeavors associated with a return to the Moon. Herein, we address the detailed geologic specifics of lunar soil and list many of the geotechnical properties that should be considered before we produce simulants for definitive study purposes.

Formation of Lunar Soil: The lunar soil formed by space weathering processes, the most important of which is micrometeorite (< 1mm) impact dynamics. Although of small mass, these particles possess large amounts of kinetic energy, impinging on the lunar surface with velocities up to 100,000 km/hr. Much of the impacting energy goes into breaking and crushing of fragments into smaller pieces; however, due to the high energy of many of the impacts, the lunar soil is partially to completely melted on a local scale of millimeters. The melted soil incorporates soil fragments and quenches to glass. These aggregates of minerals, rocklets, and glasses are welded (i.e., cemented) together into "agglutinates" [1]. It is the glass in these fragile agglutinates that further becomes comminuted into smaller pieces making for ever-increasing amounts of glass to the lunar soils. Portions of these silicate melts also vaporize, only to condense upon the surfaces of all soil grains. Other cosmic, galactic, and solar-wind particles also perform minor weathering, largely by sputtering; but many of these particles remain imbedded in the outer portions of all lunar soil grains. As demonstrated by Taylor & McKay [2], as the number of lithic fragments decreases, the amount of liberated free minerals increases to a point, with continuing exposure to impact processes actually decreasing the abundance of these mineral fragments. With these changes in rock and mineral fragments, the major accompanying process is the formation of the glass-welded agglutinates; and the abundances of agglutinitic glass increase significantly with decreasing grain size [3]. Due to complicated interactions of the impact melts with solar-wind, as well as productions of vaporized chemistry, the glass of the lunar soil contains myriads of nano-sized Fe^0 grains (4-33 nm), with the soil containing 10X more Fe^0 than the rocks from which it was derived. As a result of all this space weathering, the resulting lunar soil consist of rocklets, minerals, and agglutinates, with major amounts of glasses, impact-produced but also volcanic in origin.

The abundances of glass in lunar soil increases with decreasing grain size, such that the "dust" (i.e., <50 μm) portion of the lunar soil contains over 50% glass, present as sharp, abrasive, interlocking, fragile glass shards and fragments. It is this same "dust" at <50 μm that constitutes approximately 50% of mature lunar soils, as a rule-of-thumb for size distributions. It is the mainly the presence of these huge quantities of glass that contributes to the unusual engineering properties of lunar soil [4].

Geotechnical Soil Properties for Consideration in Simulants: Particle Size Distribution; Particle Shapes; Specific Gravity; Bulk Density; Soil Porosity; Compressibility; Shear Strength; Permeability; Diffusivity; Bearing Capacity; Ultimate Slope Stability; Trafficability; Electrical Conductivity; Dielectric Permittivity; Magnetic Susceptability; etc.

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STEEL PRODUCTION UTILIZING IRON EXTRACTED FROM LUNAR ORES AND SOILS

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Steel compositions will be developed using iron extracted from lunar ores and soils. Research will focus on the hydrogen reduction of iron contained in the lunar simulants MLS-1 (Minnesota Lunar Simulant) and JSC-1 (Johnson Space Center Simulant). This reduced iron will be extracted using carbonyl (CO – carbon monoxide) chemical processes. Extracted iron is in the form of iron pentacarbonyl ($Fe(CO)_5$). Iron pentacarbonyl is used in the Chemical Vapor Deposition (CVD) of various steel coatings onto and inside of mandrel surfaces such as inflatables and slush mold contours.

Inflatable and slush mold forms are to be used to produce components necessary for the establishment of lunar bases and operations. The first mandrel contours which we will investigate will be in the form of cylindrical shapes. Steel compositions will be deposited on the interior or exterior surfaces of these cylindrical shapes to form steel pressure vessels. These pressure vessels will serve as storage for gases and housings for crews and operational activities on the moon. There are specific steel compositions which include boron which are analogous to nickel compositions which have been deposited using Chemical Vapor Deposition (CVD) by William Jenkin and show substantial tensile strengths.

The research proposal submitted to NASA (Steel Production Utilizing Iron Extracted from Lunar Ores and Soils) will in Phase I look in detail at the extraction of Iron from lunar simulants. We will examine a matrix of processing conditions and hardware configurations that can be scaled up to produce flight hardware that can be tested in space and on the Moon. In Phase I, iron extraction will be examined in detail. In Phase I we will also explore rudimentary deposition hardware and basic deposition conditions to a limited degree. In Phase II, we will manufacture and test apparatus capable of extracting iron from lunar simulants and we will expand our research into the deposition of various steel compositions. The first depositions inside of cylindrical inflatables will be carried on in Phase II of the research program, with a sample pressure vessel as one of the deliverables to NASA at the end of the Phase II work. Phase III will actually involve the manufacture of flight hardware suitable for launch and testing in Earth orbit and on the Moon.

Manuals suitable for the construction of processing plants on the Moon will be provided as deliverables at the end of Phase III of this research program. Questions regarding the suitability and scalability of these processes will be answered and future work will be proposed to provide for the In-Situ Resource Utilization of lunar materials in the construction of manned and unmanned lunar bases and operations.

SPACE LAW UPDATE: REAL PROPERTY RIGHTS AND RESOURCE APPROPRIATION

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During the past year, real property rights has become the most important issue in the field of space law. Gregory Nemitz pursued his claim to Asteroid 433 Eros in Federal District Court, where his case was dismissed. That precedent-setting case, *Nemitz vs. the United States*, is now before the Ninth Circuit Court of Appeals. Also in the past year, the International Institute of Space Law, a member organization of the International Astronautical Federation, issued its first ever position paper, "Statement of the Board of Directors Of the International Institute of Space Law (IISL) on Claims to Property Rights Regarding the Moon and Other Celestial Bodies." Finally, the Report of the President's Commission on Implementation of United States Space Exploration Policy (the "Aldridge Commission Report") said that "it is imperative that [property rights] issues be recognized and addressed at an early stage in the implementation of the vision, otherwise there will be little significant private sector activity associated with the development of space resources, one of our key goals." The author will discuss the implications of these developments, including the prospects for future U.S. legislation regarding property rights and mining law in outer space.

CONCEPT FOR LANDED MEASUREMENTS OF MARS THAT WILL HELP IDENTIFY AND CHARACTERIZE POTENTIAL SURFACE RESOURCES

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We describe the concept for a very shallow seismic subsurface imaging capability (< 10 m, equivalent to ~ 10-20 ms) based on proven concepts and commercial techniques with the scientific goal of studying very near-surface planetary structure. The technical goal is to develop a miniaturized percussion-seismic source and geophone receivers, with a long-term goal of full integration with a Mars rover. The seismic system may be used to image the very shallow subsurface region of Mars to detect specific boundaries such as near-surface permafrost and buried layers that may contain easily accessible mineral resources that could be used for *in situ* fabrication and repair of facilities. These near-surface layers may then be reached for direct *in situ* sampling using a mechanical percussion seismic source as a shallow drill or by a customized piezoelectric shallow drilling tool, such as a small Ultrasonic/Sonic Driller/Corer (USDC).

The challenges for very shallow seismic profiling are:

- to reduce transmit pulse length so that near-surface reflectors are not lost in the transmit pulse or surface wave;
- to ensure sufficient high frequency content in the transmit pulse to resolve narrow layers;
- to ensure sufficient energy is transmitted into the ground so that reflected energy is recorded by the geophones.

A Percussion Seismic Source (PSS) is based upon the concept of a solenoid operating in percussive mode with only one moving part: the free mass. The free mass tip will be designed based on concepts for commercial button bits with venturi holes and retrac shank. Manufacture of the bit will be carried out in a single step casting likely based on a titanium carbide alloy using a combustion synthesis method.

Optimum operation of the PSS relative to the geophones would require it to beat against an exposed bedrock surface. In the event that bedrock is mantled by unconsolidated regolith (e.g. as found by the Opportunity MER in the region between bedrock craters at Planum Meridiani) the PSS would have to operate in and penetrate through unconsolidated material before reaching bedrock. Using a bit based on the commercial retrac concept will allow penetration of loosely consolidated surface soil and fractured bedrock. The ridged shank is designed specifically to allow the bit to reverse drill in the event of hole collapse.

The commercial bits have integral compressed air channels in the bit shaft. Compressed air is forced into the channels and out through venturi holes in the bit face to blow out rock dust and cuttings produced at the drill face.

Additional benefits of the bit design, that were not intended for the commercial application are:

- compressed air flushing will clean out the hole leaving a pristine cross section in bedrock ideal for *in situ* rock analysis and imaging;
- grooves of the retrac bit would allow insertion of a miniature downhole sensor suite such as a LIBS and Raman spectrometer (currently under development by Dr. Chris Dreyer, Colorado School of Mines).

USING SPENT FUEL TANKS AS HABITATS

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The idea of using an expended liquid fuel rockets as a serviceable container for human habitation and technical spaces is a recurring topic. With the advent of Dr. Robert Zubrin's simulated habitats the concept has achieved a certain credibility, even acceptance, as a state-of-the-art practice. This paper outlines some design considerations for habitats and supporting structures in low-gravity, and is intended to encourage architects with other constraints and considerations to join the conversation.

Keywords: In Situ Resource Utilization (ISRU) structures, habitat design, expended fuel tanks.

THE APPLICATION OF SELF-PROPAGATING HIGH TEMPERATURE (COMBUSTION) SYNTHESIS (SHS) FOR IN-SPACE FABRICATION AND REPAIR

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Self-propagating high temperature synthesis (SHS), also called combustion synthesis, is an extremely versatile, rapid and energetically favorable process: the energy needed to sustain the process coming from the chemical energy of the exothermic reaction mix. SHS can be used to synthesize, repair and join a wide range of advanced materials, fully dense or with controlled porosity (20-90%), in low vacuum, low and microgravity environments, and in oxygen–free or oxygenated (including a CO_2) environments. As such, these engineered SHS reaction systems can be designed to take advantage of the ambient environment, rendering an extremely high degree of process versatility and flexibility.

A research team based in Golden, Colorado comprising materials scientists from the center for the Commercial Application of Combustion in Space (CCACS) at Colorado School of Mines, and Guigné Space Systems Inc. (GSSI) has developed SHS technologies that are capable of producing net- and near-net-shaped components, and to join both similar and dissimilar materials such as intermetallics, metals, ceramics and composites.

The paper will discuss the application of SHS to fabricate and repair a wide range of materials with examples that include acoustic damping materials for rocket engines, joining of components, shuttle wing repair, and mineral sterilization. In particular, the application of this technology for in-space fabrication and repair will be highlighted.