3rd Annual Joint SRR/PTMSS

Author: Mr. Jim Keravala (jim.keravala@shackletonenergy.com)
Dr Bill Stone, Mr Dale Tietz

Mining Lunar Resources – The Shackleton Energy Program

Abstract

Access to lunar based resources is a cornerstone requirement for the balance of our terrestrial economy and civilization as well as sustained expansion in space. The establishment of propellant depots at key locations in near Earth space enables reusable transportation in space to become a viable proposition. Establishing the cis-Lunar highway required to access lunar sourced water from the cold traps of the polar craters provides the backbone infrastructure for exponential growth for a space-based economy. With that infrastructure in place, space-based solar power generation systems, debris mitigation capabilities and other necessary infrastructure can be established on a fully commercial basis.

Shackleton Energy was founded from the space, mining, energy and exploration sectors to meet this challenge as a fully private venture. Following successful robotic precursor missions, our industrial astronauts combined with robotic mining capability will make first landing on the South Pole of the Moon by mid-2019 to begin deliveries of propellant to our depots in early 2020. Customers, partners, technologies, and most importantly, the investor classes aligned with the risk profiles involved have been identified and all the components for a viable business are available. Infrastructure investment in space programs has traditionally been the province of governments, but sustainable expansion requires commercial leadership and this is now the responsibility of dynamic new industry. The technologies and know-how are ready to be applied. Launch services to LEO are available and the industrial capability exists in the aerospace, mining and energy sectors to enable Shackleton Energy to build an in-orbit and Lunar infrastructure. What is required right now is bold leadership to integrate these assets into an ongoing program.

This presentation discusses the mining element of Shackleton Energy's architecture and business model. SEC business model is based upon the extraction of valuable Lunar resources from the permanently shadowed craters at the south pole of the Moon. Following this step, these resources are pre-processed and shipped to a location in the Earth-Moon system, which is best suited for the customers' needs (LEO, GEO, HEO, L1, L2, etc.). As mining forms the initial starting point in SEC's value chain it is of key importance, influencing trade-offs of the overall architecture and opening other mining operations on the Moon and elsewhere.

Canada's Exploration Prototypes: A Science and Resource Prospecting Context

*Ryan McCoubrey[1], Laurie Chappell[1], Peter Dietrich[1], Hermann Rufenacht[1], Nadeem Ghafoor[1], Claude Gagnon[2], Nathan Orr[3], Tim Barfoot[3], Jeff Tripp[4], Ryan Sookhoo[5], Gordon Osinski[6], Wayne Pollard[7], Mike Daly[8], Martin Picard[9]

[1]MDA
[2]Bombardier Recreational Products Centre for Advanced Technology
[3]University of Toronto Institute for Aerospace Studies
[4]Optech
[5]Hydrogenics
[6]University of Western Ontario
[7]McGill University
[8]York University
[9]Canadian Space Agency

Contact Author: Ryan McCoubrey
Affiliation: MDA
Address: 9445 Airport Road, Brampton, Ontario, Canada
Email: ryan.mccoubrey@mdacorporation.com
Phone: 1-905-790-2800 x4056

Abstract

In 2010, the Canadian Space Agency (CSA) commenced a large program of exploration prototype developments geared towards rapid technology advancement, community development and international collaboration in preparation for future flight missions to the Moon and Mars. Termed the Exploration Surface Mobility (ESM) initiative, the program funded the development of an architecture with a central focus on surface mobility, including rovers, advanced technology payloads and science instruments. This paper provides a prospecting context for the use of three rovers, three technology payloads and three science instruments developed under ESM.

The Lunar Exploration Light Rover (LELR) is a rugged, medium-class lunar mobility platform designed for science, prospecting, surveying and a range of in situ resource (ISRU) activities with interfaces for advanced vision, corers, large drills and earth moving tools. LELR supports both teleoperation and fully autonomous modes including ground control and telepresence, e.g. from an orbital outpost. The Mars Exploration Science Rover (MESR) is a small-class, highly-terrainable system originally designed for Mars but fully compatible with operations on other bodies. MESR can support mission scenarios requiring a highly autonomous science prospecting and in situ geological analysis vehicle capable of operating under limited communication windows and bandwidth constraints. MESR can interface with a mini-corer, microscope and robotic manipulator as well as other payloads. The SL-Commander Rover (SLC) is an electric side-by-side all-terrain vehicle capable of carrying two onboard passengers. SLC is intended to enable EVA-astronaut analogue missions as well as perform autonomous, tele-operated and convoy-style driving. All vehicles support a wide range of payloads via standardized interface connections.

The Next Generation Communications System (NGCS) establishes the communications infrastructure required to operate a planetary mission including rover to lander relays that could be deployed at crater rims. The Next Generation Vision System (NGVS) combines a high performance lidar with a high resolution camera and multi-spectral imager to provide excellent situational awareness and remote prospecting capabilities. The Next Generation Power System (NGPS) provides a high-capacity fuel cell based range extending capability to facilitate large surveys, high power ISRU subsystems and long distance traverses. The Three-Dimensional Exploration Multi-spectral Microscopic Imager (TEMMI) instrument combines 3D topographic mapping with multispectral high-resolution imaging of samples. The Lunar Ground Penetrating Radar (LGPR) instrument enables survey and prospecting in the shallow subsurface region, supporting future lunar resource characterization. The Raman Sensor for the Identification of Carbon (RSIC) instrument is a stand-off, deck or mast mounted laser-based analytical sensor for remote mineralogy.

An exciting component of the ESM program has been the collaboration between a large number of key Canadian stakeholders from across the space program. Industry examples include Bombardier Recreational

Products Centre for Advanced Technology, Optech and Hydrogenics. Academic examples include the University of Toronto Institute for Aerospace Studies (UTIAS) Space Flight Lab and Autonomous Space Robotics Lab as well as the National Optics Institute (INO) in technology elements, and a variety of academic partners from the Canadian space science community. This community development is essential to Canadian and International preparation for future flight missions.

With some systems already delivered to CSA and many more nearing completion, the ESM fleet of vehicles, technology demonstration payloads and science instruments are now ready for near-term use in analogue environments as part of both Canadian and international deployments. The next step is to leverage the momentum created in science, technology, operations, and partnerships as the focus shifts to preparations for a near-term flight mission.

Affordable, rapid bootstrapping of space industry and solar system civilization

Philip T. Metzger, Ph.D., Anthony Muscatello, Ph.D.[2], Robert P. Mueller [3], and James Mantovani, Ph.D.[4]

[1] Physicist, Granular Mechanics and Regolith Operations Lab, NASA Kennedy Space Center, Philip.T.Metzger@nasa.gov, NE-S-1, Kennedy Space Center, FL 32899

[2] Chemist, Applied Chemistry Lab, NASA Kennedy Space Center, Anthony.C.Muscatello@nasa.gov, NE-S-2, Kennedy Space Center, FL 32899

[3] Aerospace Engineer, Surface Systems Office, NASA Kennedy Space Center, Rob.Mueller@nasa.gov, NE-S, Kennedy Space Center, FL 32899

[4] Physicist, Granular Mechanics and Regolith Operations Lab, NASA Kennedy Space Center, James.G.Mantovani@nasa.gov, NE-S-1, Kennedy Space Center, FL 32899

Abstract:

Advances in robotics and additive manufacturing have become game-changing for the prospects of space industry. It has almost become feasible to bootstrap a self-sustaining, self-expanding industry at reasonably low cost. Simple modeling was developed to identify the main parameters of successful bootstrapping. This indicates that bootstrapping can be achieved with as little as 12 metric tons (MT) landed on the Moon during a period of about 20 years. The equipment will be tele-operated and then transitioned to full autonomy so the industry can spread to the asteroid belt and beyond. The strategy begins with a sub-replicating system and evolves it toward full self-sustainability (full closure) via an in situ technology spiral. The industry grows exponentially due to the free real estate, energy, and material resources of space. The mass of industrial assets at the end of bootstrapping will be 156 MT with 60 humanoid robots, or as high as 40,000 MT with as many as 100,000 humanoid robots if faster manufacturing is supported by launching a total of 41 MT to the Moon. Within another few decades with no further investment, it can have millions of times the industrial capacity of the United States. Modeling over wide parameter ranges indicates this is reasonable, but further analysis is needed. This industry promises to revolutionize the human condition.

LUNAR RESOURCES FROM DEPTHS:A NEW APPROACH. V.V. Shevchenko, Sternberg State Astronomical Institute, Lomonosov Moscow State University, Moscow, 119992, Russia (vladislav_shevch@mail.ru).

Introduction: A study of the observed changes on the lunar surface, some of which can be attributed to contemporary processes, is of exceptional interest. In recent years, when scientists obtained high resolution photographic and spectral data from orbiters, new research opportunities have emerged. Prospects have arisen that enable not only tracing the changes caused by shock events but also systematic processes. The latter include the effects of slope movements of surface material on the inner walls of craters. If the first evidence of such landscape changes, as a rule, were referred to the processes of post impact changes directly related to the crater formation, in some cases the follow up studies can revise these views. The morphological analysis of craer forms from largescale images and especially spectral and spectropolarized estimates of the expositional age (or maturity) of the slope material, lead to the conclusion that we observe structures formed over a considerable period of time after the moment of the impact crater formation. Based on the examples studied, it is highly probable that similar slope movements of surface materials can continue at the present time, regardless of the age of the object. In addition to studies of the observed rocks themselves, new prospects emerge for the analysis of the processes causing the movement of material. New information is available on the contemporary evolution of the lunar environment. Slope movements of the crushed granular material, resulting in a fresh outcrop of subsurface mare or highland landscapes, extend our capabilities of studying the deep material of the Moon. Since the length of the slope changes depends on the sizes of craters, remote analysis of rocks occurring at depths of at least several hundred meters is possible [1, 2].

Spectral analyses of the crater avalanche: Processes of the space weathering on the Moon affect the optical properties of an exposed lunar soil. The main spectral/optical effects of space weathering are a reduction of reflectance, attenuation of the 1-μm ferrous absorption band, and a red-sloped continuum creation. In work [3] it was proposed to estimate the maturity of lunar soils from Clementine UVVIS data using a method which decorrelates the effects of variations in Fe2+ concentration from the effects of soil maturity. The local OMAT estimates points out at the occurrence of slope instability processes. Modeled in this way, values of the spectral reflectance yield a value of the optical maturity index OMAT = 0.73, the value of of the spectropolarization maturity index Isp = 3.74, and, accordingly, the model exposition age of the fresh surface outcrops of T ~ 80 years. Fig. 1 shows two fragments of crater Burg inner wall slope. The left fragment is part of the image number M113778346L/R (http://wms.lroc.asu.edu/lroc), the right fragment is part of image from Chang’e 2 (http://moon.bao.ac.cn). The last image was obtained by China's Chang'e 2 lunar probe on 23 October 2010 (Credit: China Lunar Explo- ration Program). The resolution of the image is near 7 m [4].

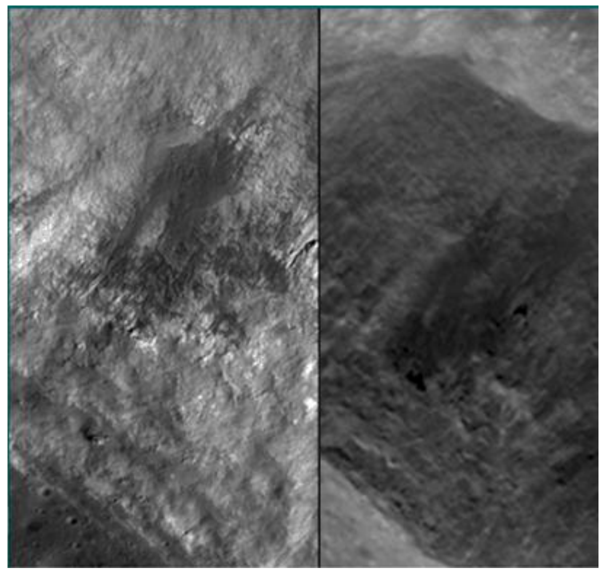


Fig. 1

The presence of very young dark details and immature soils on the inner wall slopes of the crater Burg suggests recent intensive slope processes. The most immature soils covered inner walls of this crater demonstrate that the origin age may be equal to the exposure age of the surface layer on inner wall. Calculated exposure age of the dark feature shows that it be as less as 10 years or less. It’s possible the Lucey’s method [3] is not correct in case of very immature soil however we can propose that observed events are results of current processes.

Iron content in the slope avalanche: In the study of fresh outcrops in number of lunar craters, an important feature is the iron content (or FeO content) in the surface material. From spectral measuring it follows that with decreasing maturity of the cover material the iron content increases to 20% and more. Since we are considering the material of underlying layers, we can conclude that the increase in the iron content is due to the properties of the subsurface material involved in slope processes. In general, the effect of the iron content on the reflectivity, as a major component of the chromophore, is characteristic of the lunar rocks. On the scale of the visible hemisphere a close correlation between the iron content and optical properties of the surface material was studied in detail in many work, for example [5], where landing sites of space probes and manned spacecraft were used as test areas. It was shown with high precision that ironenriched pyroxenes are the most optically active components of the lunar soil. The general conclusion from the comparison of the data is an abnormally high content of iron in the slope features as compared to the back-ground surface. A marked increase in the iron content was found in the cases where shifting of the slope material from deeper subsurface layers took place. The clearest example is dark area in the crater Bürg (Fig. 1). The beginning of the material flow with a low albedo refers to a depth of about 400 m. According to spectral measuring this area is charac terized by an abnormally high content of FeO reaching almost 20 weight %. The dark rocks on the North wall of the crater Bürg are located at approximately the same depth (420m). The content of FeO in the outcrop is approximately 19-20 weight %. Fig. 2 shows subsurface layers of the dark rock with high content of iron on a crater inner wall (image number M124797072, http://wms.lroc.asu.edu/lroc).

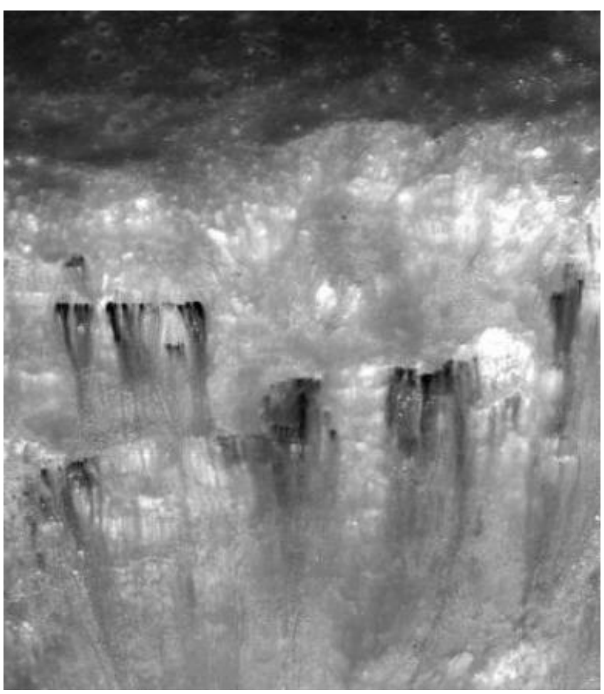


Fig 2

The origin of many of these flows is at a depth of ~ 600 m, where, apparently, lies the material with an average iron content of 17 - 19%, as determined by remote spectral data. The morphological characteristics of the surface, which can be seen in the M113778346L/R high resolution image, are mainly close to a region of the same type, shown in Fig. 1. There are almost no pronounced flows of the flowing soil, and there are impact craters with diameters from 3 to 5 m. Thus, as a result of the analysis, it was found that there is a general trend of increasing Fe content with depth of occurrence of layers of lunar surface material. But individual deviations from this general provision point to a more complex process of formation of the upper layers of the lunar lithosphere and require furher detailed study. The total area of these structures is small, and they seem to have no significant effect on the determination of the average values of the optical parameter of maturity and the iron content in the covering material. However, to fully understand the mechanisms of slope movements of lunar soils and their characteristics, these structures require further investigation with a corresponding resolution of the spectral data.

Conclusions: The scientific use of large scale surveys of the lunar surface, with the assistance of remote methods of planetary astrophysics, has made it possible to to explored processes of contemporary changes on the lunar surface. The analysis of the nature of current slope movements of fine material in lunar craters opens a new area of research that affects several aspects of the phenomena observed in the lunar environment, i.e., from the optical parameters of the covering material to the mechanical properties of soil, iron content and the influence of exogenous processes on them. On the other hand we can get a new possibility of the mining lunar depth material. We can see that slopes of inner crater walls are from 10^o to 20^o in the case. Soil inner friction angle is not more than 20^o for the upper layer material. In this case the bulk density of the surface soil is about 1.5 g/cm^3 along all slopes.

Acknowledgments: Author is grateful to NASA LROC Science Team, M.S.Robinson, PI, and China Lunar Exploration Program for new lunar images.

References: [1] [2] Shevchenko V.V. et al. (2011) *LPS 42*, Abstract #1161. [2] Shevchenko V.V. et al. (2012) *Sol. System Res.*, *46*, 1- 17. [3] Lucey P. G. et al. (2000) *JGR*, *105*, 20.377 – 20.386. [4] Yangxiaoyi Lu, V.V. Shevchenko (2012) *LPS 43*, Abstract #1207. [5] Pieters C.M. et al. (2002) *Icarus*, *155*, 285–298.

EARTH, MOON, VENUS AND MARS WERE DEVELOPED BY THE SAME SCENARIO: EVIDENCE FROM GEOLOGICAL AND PETROLOGICAL DATA. E.V. Sharkov, Institute of Geology of Ore Deposits, Petrography, Mineralogy and Geochemistry RAS, Staromonetny per., 35, Moscow 119017, Russia; sharkov@igem.ru

Introduction: Terrestrial planetary bodies (Earth, Venus, Mars, Mercury and the Moon) have similar structure and consist of essentially iron core and a silicate envelope. Current knowledge about their formation and evolution based on different physical and geochemical speculations and models. The main disadvantage of such hypotheses is their abstract character and ignoring of any data on own tectonomagmatic evolution of those planets. At the same time, just this type of data provide an important information, which is commonly neglected by the most planetologists but necessary for understanding of processes of the planets' internal development and their potential ore resources.

Comparative study of tectonomagmatic evolution of the terrestrial planets showed that their geological development occurred at close scenario and began after solidification of global magma oceans some hundred km deep. Because different values of adiabatic gradient (0.3^{o}C/km) and melting point gradient (3^{o}C/km), it was occurred by way of moving upwards thin crystallization zone and accompanied by powerful crystallizing differentiation of the magmas, which led to accumulation of the most low-temperature components on planets' surfaces. Due to different oceans' deep, the primordial crusts on these bodies were rather different: for example, sialic on the Earth [1 and references herein] and anorthositic on the Moon.

The Earth's tectonomagmatic evolution: The Earth has been much better studied compared to the other planets, therefore we will discuss the main questions of planetary tectonomagmatic evolution using the Earth as a reference body and involve data on the Moon and the other terrestrial planets.

The Earth's geological evolution began ~4 Ga ago from appearance of granite-greenstone terranes (GGT) and divided them granulite belts. Such type of activity (Nuclearic stage) lasted practically all Archean. Magmatism of high-Mg komatiite-basaltic series was located in irregular network of greenstone belts within GGTs, which matrix was composed mainly by tonalite-trondhjemite-granodiorite (TTG) granites (modified primordial crust). GGTs were formed above heads of mantle superplumes of the first generation, composed by depleted (due to directed solidification of the magma ocean) ultramafic material; granulite belts were sedimentary basins, formed above descending mantle flows. The situation could be described in terms of plume-tectonics. This major types of of ore deposits were Au and sulfide Cu-Ni deposits, attributed to greenstone belts.

By the 2.5 Ga the Earth's crust became cratonized (Cratonic stage), and magmas of siliceous high-Mg series (SHMS) began to predominate. Large igneous provinces (LIPs), composed by lava pleaus, dike swarms and large layered mafic-ultramafic intrusions, often with PGE (platinum group elements) mineralization, were typical for early Paleoprterozoic. Origin of the SHMS was linked with large-scale assimilation of lower crustal material by high-temperature mantle-derived magmas.

Cardinal irreversible change of tectonomagmatic activity occurred at 2.35-2.0 Ga from appearance in global scale of geochemical-enriched Fe-Ti picrites and basalts, typical for the Phanerozoic plume-related magmatism [1 and references herein]. This event was followed by emergence of plate tectonics at ~2 Ga, which has existed till now. From this time the Earth enters to Continental-oceanic stage and ancient continental crust began to involved in subduction processes. The crustal material has stored in the "slab cemeteries" [2]. Systematic consumption of the ancient crust in subduction zones obviously started at ca. 2 Ga and led to gradually replacing it by the secondary basaltic (oceanic) crust which arrange about 60% now.

Thus, the composition of mantle melts and geodynamics irretrievably changed over the whole Earth in the range from 2.35 to 2.0 Ga, finally triggered plate tectonics which changed plume tectonics of the early Precambrian [1]. We believe that ascending of the second generation mantle plumes (thermochemical plumes), enriched in Fe, Ti, K, Na, P and other incompatible elements was responsible for all those changes. Such plumes have generated at the core-mantle boundary (CMB) in D" layer and this process is active till now [3].

Tectonomagmatic evolution of the Moon, Venus and Mars: Study of the samples, delivered by American and Soviet space missions, showed that the oldest magmatism of lunar highlands is dated by 4.45-4.25 Ga [4]. It was represented by volcanics of the magnesian suite analogous to the terrestrial early Paleoproterozoic SHMS [6].

Cardinal change of lunar tectono-magmatic processes was begun from appearance of KREEP basalts (4.25-4.02 Ga: [5]) and was complited by formation of large maria depressions with thinned crust and powerful basaltic volcanism occurred 3.9-3.8 Ga. The maria are usually treated as a results of huge meteorite impacts ("Lunar Cataclysm"). However, structure of the maria and geochemistry of their basalts, some of which are close in composition to the terrestrial plume-related magmas (high contents of Fe, Ti, HFSE, etc.) evidence that the maria very likely were a result of mantle plume activity [1].

Like in terrestrial oceans, two types of basalts occurred in the maria: (1) predominated low-Ti, close to terrestrial MORB and (2) high-Ti, close to terrestrial within-plate magmas [6]. Very likely, that the lunar *maria* were specific analogues of Earth's oceans.

Therefore, this stage of the Moon evolution can be correlated with Continental-oceanic stage of the Earth, however, without plate tectonics, typical for the Phanerozoic. Like on the Earth, irreversible transition of tectonomagmatic activity coincided with peak of magnetic field strength (4.2 Ga: [8]).

So, development of the Moon occurred essential quicker and at the same, but shortening scenario.

Data available on Venus and Mars suggest that their tectono-magmatic evolution also occurred at the close scenario [9]. Two major types of morphostructures occur on them: (i) vast lowland plains, composed by young basaltic crust, and (ii) older lightweight uplifted segments with a complicated topography; if we dry the Earth's oceans, we will see the same picture. So, it possible suggest a two-stage evolution of these planets also. During the first stage primordial lithospheres were formed due to directed solidification of global magma oceans. During the second stage the secondary basaltic crust formed due to ascent of thermochemical plumes from the their CMBs. Smaller Mercury is less studied, however, its relief also contains morhostructures resembling lunar *highlands* and *maria*.

Discussion: We believe that irreversible change in development of the terrestrial planetary bodies was attributed to involving of new, geochemically-enriched material in geodynamic processes [1]. This material a long time (for about 2.2 billion years for Earth and about 0.4 billion years for the Moon) could be preserved only in their primordial iron cores.

From this follows that: (i) accretion of the bodies was heterogeneous and (ii) their heating occurred from surface to core, accompanied by cooling of their outer shells, independent from planetary size.

Because the peaks of magnetic field strength of the Earth [7] and the Moon [8] were practically coincided in time with the change of tectonomagmatic activity, we suggest that their primordial iron cores were melted at this time and began to generate previously absent thermochemical mantle plumes which are the main drivers of tectonic processes.

However, the magnetic field on the Earth already existed ~3.45 Ga [7]. Because the new material began to involve in geodynamic processes much later, it is conceivable that the liquid iron, responsible for the magnetic field in Paleoarchean, occurred due to heating of chondrite material of the primordial mantle. This iron in the form of a heavy eutectic Fe + FeS liquid flowed down through the silicate matrix and accumulated on the surface of still cold solid primordial core; it could generate magnetic field, but not participate in the tectonomagmatic processes. Only melting of the primordial iron core, which occurred in Paleoproterozoic, led to drastic change in the development of our planet. Very likely, that other terrestrial planets - Moon, Venus and Mars evolved by the same scenario; the situation on the Mercury is unclear now.

Concluding notes: How it was shown above, the Earth and the Moon, as well as Venus and Mars, developed at the same scenario, with irreversible change of tectonomagmatic processes at the middle stages of their evolution. This change was accompanied by gradually replacing of early "continental" crust by secondary basaltic ("oceanic") one evidence about involving of qualitative-new material in geodynamic processes.

So, prospecting works on these planets can be oriented to the terrestrial situations: for example, it has a meaning to look for precious metals (Au and PGE) in uplifted ancient crust as well as sulfide Cu-Ni ores, whereas VMSD – on basaltic lowlends.

References: [1] Sharkov E.V. and Bogatikov O.A. (2010) *Geotectonics*, *2*: 3-22; [2] Karason H, and van der Hilst R.D. (2000) In: The History and Dynamics of Global Plate Motions. Ed. M. Richards et al. *Geophys. Monogr. 121*: 277-289; [3] Dobretsov N.L. (2008) *Russian Geology and Geophysics, 29*: 587-604; [4] Snyder G.A., Neal C.R., Taylor L.A., Halliday A.N. (1995) *JGR, 100(E5)*: 9365-9388; [5] Snyder G.A., Taylor L.A., Halliday A.N. (1995) *Geochim. Cosmochim.Acta 59*: 1185-1203; [6] Sharkov E.V. & Bogatikov O.A. (2003) *Geochem. Intern., 41*: 519-524; [7] Reddy S.M., Evans D.A.D. (2009) *Geol. Soc., London, Spec. Publ. 323*: 1-26; [8] Rancorn S.K. (1983) *Nature 304* (5927): 589-596; [9] Sharkov E.V., Bogatikov O.A. (2009) *Petrology, 17:* 629-652.

NEW FORMATION PROCESS MODEL OF SPACE RESOURCES WITH VOLATILES AND HEAVY ELEMENTS. Yas. Miura[1, 2, 3]. [1]Yamaguchi University, Yamaguchi, 753-0073, Japan. dfb30@yamaguchi-u.ac.jp. [2]Al.I.C-EUR University and [3]Caltec-JPL.

Introduction: New model of space resources originally triggered by volatile and heavy (including rare-earth-elements, REE) elements is proposed at any brecciated surfaces on the old Moon and primordial planets [1-3] by compared with terrestrial resources formed by magmatic melting process along subduction zones [4], which are general extraterrestrial resources process to be stored at underground interior by melting with gas-fluid states for metallic concentration as space resources [2] as in main purpose of present paper.

Terrestrial resources by magmatic melting: Main process of natural (Earth's) deposits is concentration of any elements (esp. heavy elements) under gas-fluid condition at higher pressure and temperature, which are usually formed along subduction zones among sea-floor rocks, sea-water layers and the re-formed continental hard (well-crystalline) rocks [4]. The main characteristic point of "terrestrial resources" is transported to the *surfaces* by pushing melted magmatic blocks (concentrated melting zones) through sinking subduction zones to deeper places (*i.e.* magmatic convection) [4] (Table 1).

Extraterrestrial resources by interior melting: Space resources of extraterrestrial bodies (*i.e.* the Moon and planets) are located at any concentrated interior, which is transported deeper sites through voids-rich regolith soils by multiple impacts. The main characteristic point of "space resources" is located at shallow to deeper interior by melted zones with rock pressure or shock wave explosion [2, 3] (Table 1). In this sense, space resources should be collected effectively by any drilled methods under surface to deeper interior.

Table 1. Main points of terrestrial and space resources

1) *Terrestrial resources*: On the *surface* by magma melting & floating along plate-subduction zones.
2) *Space resources:* On shallow to deeper *interior* as melted blocks (on the Moon and older planets)

Evidence of voids-rich surface soils for filtering: Transportation of volatiles to deeper interior for space resources is proved by voids-rich and lower density regolith soils collected at the Apollo exploration [5] as shown in Fig.1. The porosity data are changed from the hard rock fragments (2-8%) to breccias (12-22%) of the lunar rocks, though lunar regolith soils reveal higher voids-rich porosity (46-52%) of lunar drilled samples [1-4]. This indicates that voids-rich surface soils are filtering materials for volatiles (and water) during impact reaction on the Moon to form interior melting resources (Fig. 1).

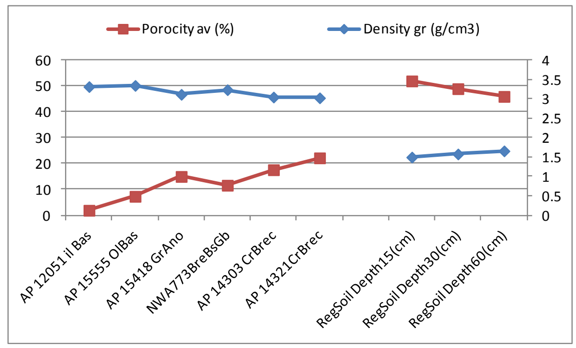


Fig.1. Porosity data of the Apollo lunar rock and voids-rich regolith soils, where surface soils are filtering for volatiles.

Volatiles filtering by the older collision process: Concentrations of volatiles and heavy elements from primordial collision of the Earth-type planets might be found that the largest planet (Earth) with the density highest contains originally considerable volatiles and other elements during collision process relatively than smaller planet (Mars) and the Moon (Fig. 2).

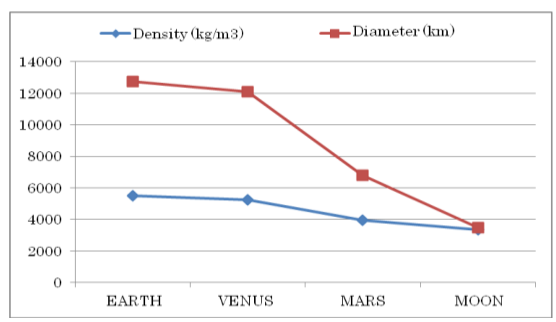


Fig.2. Density and diameter of Earth, Venus, Mars and Moon.

Summary: New formation process of space resources with volatiles and heavy elements for required melting are proposed based on the voids-rich breccias and regolith soils as filtering to deeper interior during impact process.

References: [1] Miura Y. (2012): *LPSC XXXXIII* (LPI), Abstracts #1203, #2920. [2] Miura Y. (2012): *ELS-2012* (DLR), 76-79. [3] Miura Y. (2011): PTMS-2, pp.2. [4] Ernst W.G. (1990): The Dynamic Earth (Col. Univ. Press), 280pp. [5] Heiken G., Vaniman D. and French B., *Lunar source book* (Cambridge Univ. Press) (1991), 27-45.

INTELLIGENT ZIPLINE - GREEN RECONNAISSANCE FOR LAVA TUBE SKYLIGHTS

Samuel W. Ximenes, Exploration Architecture Corporation, sximenes@explorationarchitecture.com

.

Introduction: Robotic reconnaissance to subsurface features on planetary bodies are excellent candidate exploration sites for a next generation of planetary missions for scientific investigations.

It is apparent from recently imaged features such as lava tube skylights and pit openings of both lunar and Mars discoveries observed thus far, that to reach these cavernous voids, traverses down cliffs of great depths of some 45 to 100 meters or more with difficult terrain are required for both robots and eventually human explorers. Negotiation of steep slopes and the climbing in and out of a hole presents technology challenges for accessibility and site characterization technologies.

Accessibility to planetary cave approaches require ingress/egress technology solutions for robots and human explorers.

Equally challenging is the need for planetary protection with first contact of these pristine environments with the reconnaissance technologies employed.

For example, the idea of fusing flyover data with surface data to achieve site characterization of a skylight by means of a lander trajectory directly over the skylight hole during landing approach raises issues of site contamination from fuel plume exhaust being dispersed over the target feature. Subsurface caverns preserve unique geologic environments with access to fresh, dust free outcrops of volcanic rock, and in the case of Mars, potentially may provide astrobiologists with biogeochemical signatures. The risk of site contamination from man-made activity during early exploration stages of a site can be mitigated with a layered approach to intrusive technologies for acceptability of site disturbance. It is clear that basic scientific understanding of these geographic features are needed, as well as knowledge of the engineering constraints to determine viability of potential human habitation and emplacement of associated infrastructure elements. Balancing the ever increasing encroachment of these activities with planetary protection is the premise of the Intelligent Zipline concept for green reconnaissance.

Concept: Intelligent Zipline is a system architecture for robotic deployment of an intelligent cable system that is "shot" across the expanse of a skylight's pit hole opening from a mobile platform, possibly a robotic lander with traverse capability to position itself at an optimum anchoring site. Essentially, a harpoon cannon mounted on a lander shoots a ground penetrator for anchoring a zip line to the cliff walls of the pit. The mobile platform spools the cable feed and acts as primary anchoring point with a deployable mast for securing the cable line. The deployed zip line is then used for offloading science instrument packages from the lander to the center of the pit opening with drop lines for placing the payloads down to the pit floor, or in-situ investigations of the cliff wall as the instrument lowers. Offloading is accomplished either through tele-operation and/or robotically. Intelligence is built into the harpoon projectile for targeting accuracy. Intelligence is built into the trolleys and cable for manipulating payload grappling, loading stress, braking, and tension along the zip line traverse. Power, data, & communications run through the cable.

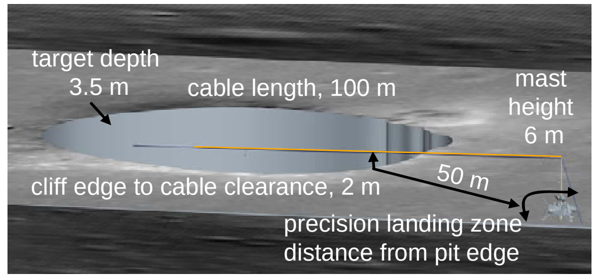
Impact: Intelligent Zipline (IZ) is green technology for minimizing site contamination for investigative science, while being conducive to a concept of operations for site characterization of pit openings and achieving a means of ingress/egress of scientific instruments, robots, and eventually human explorers.

- prevents contamination of the pit from plume and fuel of a lander flyover or other intrusive robotic activity trying to traverse down the cliff walls.
- used to lower down instruments/equipment from center of hole opening (e.g., a LIDAR instrument could be lowered for 360^o field of view laser measurements for a 3D cloud point of the entire pit).
- science investigations, site contamination mitigation, and initial infrastructure buildup of the site are all accomplished with the initial zip line science reconnaissance mission; IZ essentially provides the first infrastructure emplacement at the site for eventual development of an outpost (the zip line could be used as a leader line to build out an eventual gondola line and platform to get larger equipment and crew down; or zip line could be used as a tension line for deployment of other novel ingress/egress concepts).

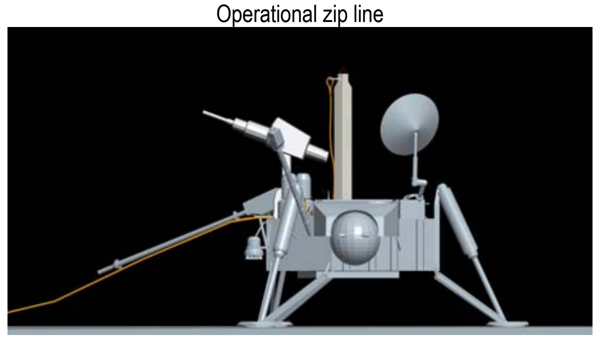
Study: The Marius Hill skylight is used for analysis of a reference mission architecture for the IZ concept. Located in the Marius Hills region on the lunar nearside, this hole is approximately 65 m in diameter and 45 m deep. A preliminary study was conducted using CAD modeling of an initial basic concept of operations (ConOps). Illustrations shown are not intended to be a point design, but a basis for identifying the core mission elements for a quick-look analysis to close the ConOps for concept viability.

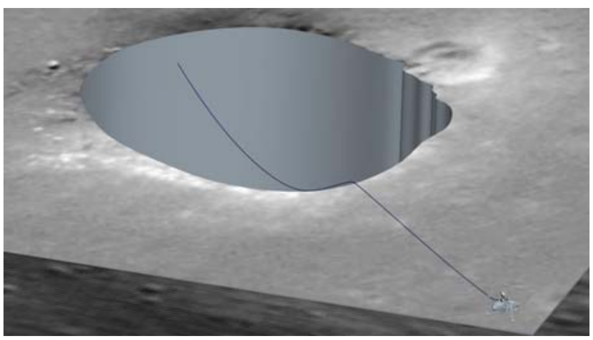
A safety factor of 50 m from the pit edge was used for the platform anchoring point. Precision landing to an anchoring point of 50 m to 100 m from the pit edge was ruled out due to plume and ejecta contamination.

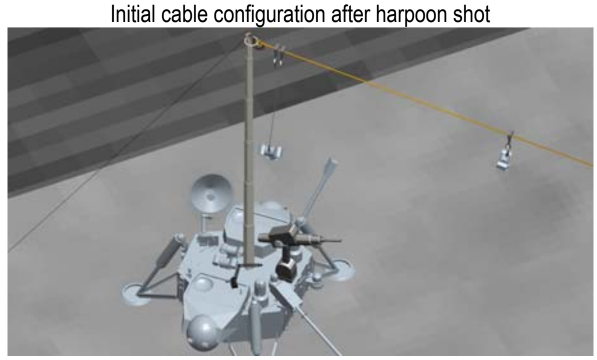
Forward studies will investigate system architecture elements shown in the table below, and a mobility lander (crawler) or lander concept which carries a robotic platform containing the deployable mast and harpoon system, which offloads from lander and robotically traverses from landing site (greater than 200m away from pit edge) to location within 50 m or less for deployment of zipline and payload offloading of science instruments.



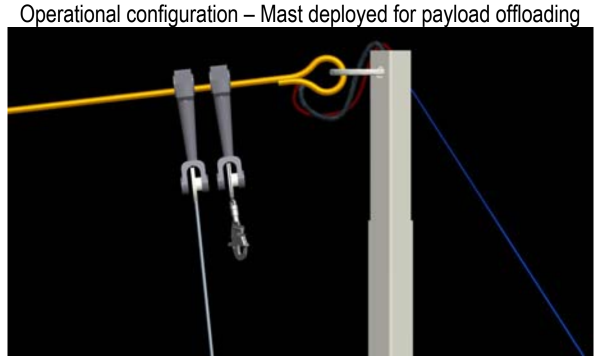
Operational zip line


Initial cable configuration after harpoon shot


Initial cable deployment across the Marius Hills skylight pit


Operational configuration – Mast deployed for payload offloading


Platform configuration with harpoon cannon


Smart trolleys & powered cable for bi-directional robotic traverse

System Architecture Element	Phase I - System Study Investigation
Harpoon cannon	Energy to penetrate optimum depth; sizing explosive charge; leverage GSFC comet harpoon technology
Harpoon	Smart targeting and guided trajectory with trailing cable; imparted energy vs. penetration depth; harpoon mass, tip geometry, cross section; anchoring and stabilization with cable tension
Intelligent cable	Cable type/size; tension/load sensing and auto adjust; comm-power-data interface; trolley/cable interface
Intelligent trolley	Robotic traverse up and down cable length, braking, speed sensing; drop line targeting; zip line & drop line comm-power-data interface; payload spin stabilization; payload grappling
Mast concept and deployment	Telescoping or other means of extension; lightweight carbon fiber materials; inflatable mast; guy cable deployment, anchoring, and horizontal load transfer to compressive load
Cable management	Spooling concepts; length and mass; clearances (spacecraft and pit edge); drape and sag deflection
Scientific instruments	Instrument/sensor types; planetary protection concepts; packaging; drop line interface, connection/release
Landing site proximity	Precision landing; ejecta field safe zone; optimal landing location based on topography and slope advantage
Spacecraft lander	Size, configuration, major element integration; cannon and mast offset geometry; crawl mode mobility for precise positioning; anchoring; comm-power-data requirement and interface to zip line and trolleys

SAMPLING VENUS FROM EARTH ORBIT. G. A. Konesky, K–Plasma, Ltd.
3 Rolling Hill Rd., Hampton Bays, NY 11946, g.konesky@att.net

Introduction: On June 5, 2012 the Sun, Venus, and the Earth will align in an inferior conjunction such that the shadow of Venus will be cast along the surface of the Earth (Venus transit). Lacking any significant magnetic field, the outer atmosphere of Venus is being eroded by the solar wind. The resulting comet-like ion tail has been observed, for example, by the SOHO mission [1] near Earth's L1 Lagrangian point, and by both the Pioneer Venus [2] and Venus Express [3] in the vicinity of Venus. During the Venus transit event, the Earth will also pass through this ion tail, although the Earth's magnetosphere would deflect it. It has been proposed [4], perhaps somewhat controversially, that microorganisms may reside in the habitable upper atmosphere of Venus and these too may be carried away by the erosive solar wind.

A mission is proposed in extended Earth orbit to sample any particulate matter, including potential remnant microorganisms that may be contained in Venus' comet-like tail. An aerogel capture mechanism is employed, followed by subsequent basic analysis using ultraviolet fluorescence as an indicator of potential organic compounds. A low cost CubeSat implementation is discussed.

Venus Habitability: While the surface of Venus is extremely inhospitable, a region exists in the upper atmosphere of Venus, between 45 and 65 km, where the temperature and pressure ranges from -25ºC to 75ºC, and 0.1 to 10 bar, respectively.

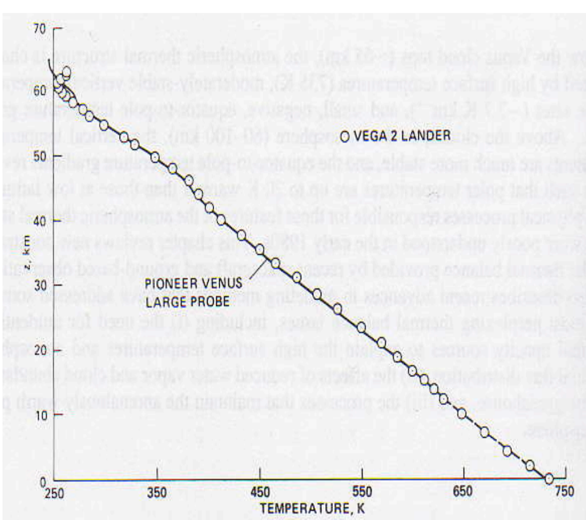


Figure 1. Venus atmospheric temperature profile (NASA/GSFC).

This region of Venus' atmosphere also contains ultraviolet absorbers of an unknown origin whose particle size distribution (primarily from 1 to 4 μm) is compatible with a biological origin [5]. It is difficult to understand the origin of potential cloud-based microorganisms on Venus given its present highly inhospitable surface. However, high a deuterium to hydrogen ratio in Venus' atmosphere [6] suggests that a significant Earth-like ocean once existed and could have been maintained for several billion years by a carbonate-silicate weathering cycle [7].

Figure 2. UV absorbers in Venus' upper atmosphere of an unknown origin (NASA/JPL).

As the Sun gradually brightened, a runaway greenhouse ensued driving the water into the upper atmosphere where solar photodissociation decomposed the water, allowing the lighter hydrogen to escape, and resulted in the present relatively dry conditions [8]. It is interesting to note that during this extended water loss event, the atmosphere of Venus would have been enriched in oxygen from the photodissociating water. In the search for life outside of our solar system, the presence of oxygen in the atmosphere of an exoplanet would generally be considered a positive indication for life. However, the example of Venus provides a potential caution for false-positives [9].

Mission Orbital Design: The transit of Venus would be an ideal time to detect and collect uncharged particles and putative remnant microorganisms from Venus in a Low Earth Orbit (LEO) mission [10]. Unfortunately, there are only two transits of Venus in this century. The first occurred on June 8, 2004 and the next will be on June 5, 2012. They reoccur in 8 year pairs alternately in intervals of 121.5 years and 105.5 years. Given the low frequency of Venus' comet-like tail coming to Earth, we must then consider going to the tail.

The orbits of the Earth and Venus are inclined by approximately 3.39 degrees. At Earth's average distance from the Sun of $149.6x10^6$ km, Venus' comet-like tail will have a maximum displacement from Earth's orbital plane of approximately $8.86x10^6$ km ($5.5x10^6$ miles), as shown in figure 3. However, this maximum distance would occur only as infrequently as transits occur, for similar reasons.

On the other hand, an inferior conjunction, where the Sun, Venus and the Earth are only radially aligned, occurs every about 584.006 days (1 year, 7 months, 6 days, and 18 hours), or 2.59904 Venusian years. During any one of these inferior conjunctions, the orbital plane displacement can vary from zero (a transit) to the maximum value.

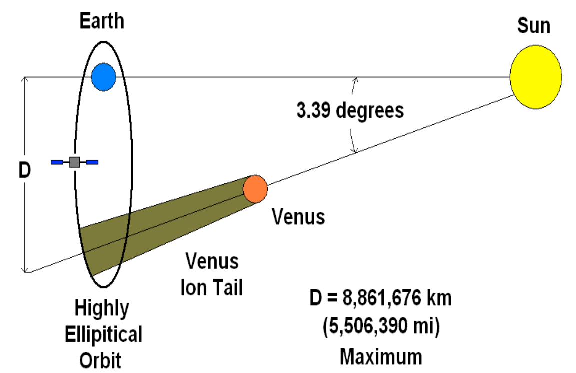


Figure 3. Orbital design for a mission to intercept the ion tail of Venus at maximum plane displacement.

Sample Acquisition and Analysis: The ion component of Venus' comet-like tail is most easily analyzed using a mass spectrometer. The SOHO spacecraft measured an ion flux density [1] of between $2.4x10^3$ and $4.4x10^3$ $cm^{-2}s^{-1}$ at Earth's L1 Lagrangian point 0.01 AU (about $1.5x10^6$ km) sunward of Earth. Wickramasinghe [4] estimates the potential flux of particulates, including putative microorganisms from Venus, to be approximately 1% of the ion flux. He also suggests that the solar wind, moving at about 400 km/s [11] is the primary transport mechanism. However, at a density typically at 10 particles per cm^3, very little thrust would be imparted as compared to the sunlight itself, which is 10^3 to 10^4 times stronger [12].

A mechanism for the collection of particulates coincident with passage through Venus' comet-like tail is suggested by the highly successful use of silica aerogel in the Stardust mission [13]. The very high deceleration forces involved in aerogel capture would necessarily disrupt any structure of putative microorganisms, but identifiable residual organics would survive the impact [14].

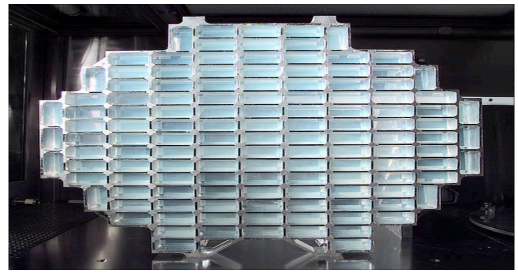


Figure 4. Stardust aerogel collector (NASA/JPL).

Ultraviolet light induced fluorescence is a common method of identifying organic compounds [15] and bioaerosols [16] and is suggested as a mechanism for detecting putative Venusian microorganisms collected by the aerogel.

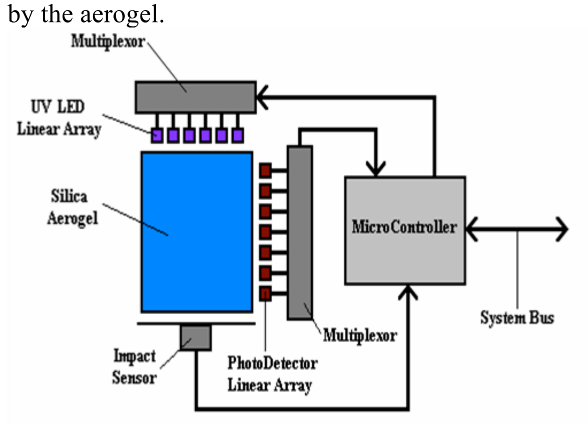


Figure 5. Proposed particle collection and detection.

Possible sources of error include Interplanetary Dust Particles and Carbonaceous Chondrite micrometeorites, and even residual waste water from the International Space Station and other LEO human activities.

References: [1] Grunwaldt H., et al. (1977) *Geophys. Res. Lett., 24,* 1163-1166. [2] Mihalov J. D. and Barnes A. (1982) *JGR, 87,* A11, 9045-9053. [3] Barabash S. et al. (2007) *Nature 450,* 650-653. [4] Wickramasinghe N. and Wickramasinghe J., (2008) *Astrophys. Space Sci., 317,* 133-137. [5] Morowitz H. and Sagan C. (1967) *Nature 215,* 1259-1260. [6] de Bergh C. (1991) *Science 251,* 547-549. [7] Walker J. (1975) *J. Atmos. Sci., 32,* 1248-1255. [8] Kasting J. (1988) *Icarus 74,* 472-494. [9] Konesky G. (2011) *Proc. SPIE 8152,* 815209-1 to -7. [10] Konesky G. (2010) *Proc. SPIE 7819,* 781917-1 to -6. [11] Cravens T. (1997) *Physics of Solar System Plasmas,* Cambridge University Press. [12] Friedman L. (1988) *Star Sailing,* John Wiley and Sons. [13] Bajt S. et al. (2009) *Meteoritics and Planet. Sci., 44,* 471-484. [14] Sandford S. et al. (2006) *Science, 314,* 1720-1725. [15] Bhartia R. et al. (2008) *Appl. Spec., 10,* 1070-1077. [16] Cheng Y. S. (1999) *Aerosol Sci. and Tech. 30,* 186-201.

Evolution of Extra-Terrestrial Mining Robot Concepts

R. P. Mueller[1] and P. J. van Susante[2]

[1]Surface Systems Office, National Aeronautics & Space Administration (NASA). Mail Stop: NE-S, Kennedy Space Center, KSC, FL 32899, USA; PH (321)-867-2557; email: rob.mueller@nasa.gov

[2]Colorado School of Mines, College of Engineering and Computational Sciences, Golden, CO. 80401, USA; PH (720) 272-8892, email: paulvans@mines.edu

ABSTRACT

Space resource mining is an emerging field and industry that has been postulated for over 100 years, especially in science fiction texts. It is widely accepted that space mining must occur to harness the resources in outer space but the specific equipment needed has not been defined or developed beyond terrestrial prototypes.

Outer space contains a vast amount of resources that offer virtually unlimited wealth to the humans that can access and use them for commercial purposes. One of the key technologies for harvesting these resources is robotic mining of regolith, minerals, ices and metals. The harsh environment and vast distances create challenges that are handled best by robotic machines working in collaboration with human explorers. Humans will benefit from the resources that will be mined by robots. They will visit outposts and mining camps as required for exploration, commerce and scientific research, but a continuous presence is most likely to be provided by robotic mining machines that are remotely controlled by humans.

An overview of the evolution of extra-terrestrial mining robot concepts and associated prototypes will be presented to inform and document the current state of this technology. Activities that have been occurring in government, academia and industry will be assessed, and future needs associated with commercial efforts at various space resource mining destinations will also be investigated.

Terrestrial mining applications for lunar regolith excavation robotics. A.M. Neale[1,3] and J. Maré[2,3], [1]Hatch Africa (mneale@hatch.co.za), [2]University of Pretoria (jj.mare@gmail.com), [3]SASRA (www.sasra.co.za)

Introduction: Developing space mining capabilities will have earth benefits[1,2]; technology spin-off being one of them. If such spin-offs and its potential beneficiaries are identified early on, it will be easier to get support for developing the space mining technologies.

This paper looks at lunar excavation robotics as a space mining technology that could have terrestrial spin-off. Possible terrestrial mining applications are identified and ranked to support the identification of potential beneficiaries / investors.

Workshop on applications: A workshop was held with six mining engineers and one mining engineering student (authors included). Background was given on work being done for lunar excavation robotics, and included the examples of: the three musketeers[3], the pneumatic excavator[4], Astrobotics' excavator[5] and the NASA lunabotics competition[6]. For the purpose of the workshop a lunar excavation robot is summarized as:

- Small and lightweight
- Autonomous or tele-operated
- Possibly to swarm
- Reliable

The workshop question was:

"If you had a supply of lunar excavation robots, as per the summary, where would you apply it in the mining industry?"

Results from workshop: The workshop resulted in the following possible applications, each of which is described in the presentation:

1. Mineral sand production
2. Mineral sand top-up
3. Greenfields sampling
4. Crack filling for coal burn dumps
5. Top soil removal
6. Clean up in sensitive areas
7. Scavenging mining losses
8. Scavenging outside mineable limits
9. Pothole mining
10. Narrow stope production
11. Narrow stope vamping
12. Micro mining

Short ranking of options: The workshop was of the opinion that, in order to rank the applications without going into economic detail, it is necessary to look at the scale and flexibility required. Lunar excavation technology would be most competitive in small scale, high flexibility applications.

The 12 options are compared and categorized in Figure 1 acording to scale and flexibility required. Four options fall in the small scale, high flexibility category, and further investigation is recommended for at least these applications.

Scale				
	Large	1		
	Med	2	8,10,12	7
	Small		5,11	3,4,6,9
		Low	Med	High
		Flexibility		

Figure 1: Categorizing of possible terrestrial applications; color scale from maroon to green indicating increased competitiveness of lunar excavation technology

Conclusion: A workshop resulted in 12 possible terrestrial applications for lunar excavation technologies. The applications were categoriszed according to required scale and flexibility. Lunar excavation technology would be more suited to smaller scale, and higher flexibility applications.

The recommended applications for further investigation are: greenfields sampling, crack filling for coal burn dumps, clean up in sensitive areas and pothole mining. Other applications that can be considered for further investigation are: top soil removal, scavenging mining losses, narrow stope vamping.

References:

[1] Schrunk, D., Sharpe, B., Cooper, B., & Thangavelu, M. (2008). *The Moon: Resources , Future Development, and Settlement.* Chichester: Praxis Publishing.

[2] Eckart, P. (2006). The Lunar Base Handbook: An Introduction to Lunar Base Design, Development and Operations. Boston: McGraw-Hill Companies.

[3] Frenzel, F., Fu, T., Gammel, J., Grouchy, P., Law, K., Earon, J., et al. (2010). Robotic Lessons from Mauna Kea. *1st Joint Meeting Between the Space Resources Roundtable and the Planetary and Terrestrial Mining Sciences Symposium.* Golden, Colorado.

[4] Zacny, K.A., Mungas, C., Fisher, D., & Hedlund, M. (2008) *Pneumatic Excavator and Regolith Transport System for Lunar ISRU and Construction*, AIAA SPACE, San Diego, CA

[5] Skonieczny, K. (2011). Advantageous Bucket-Wheel Configuration for Lunar/Planetary Excavators. *2nd Joint Meeting Between the Planetary and Terrestrial Mining Sciences Symposium and the Space Resource Roundtable s.* Ottawa, Ontario.

[6] NASA. (2011). *Lunabotics Mining Competition.* Retrieved September 18 2011, from NASA: http://www.nasa.gov/offices/education/centers/kennedy/technology/lunabotics.html

Investigation traction system development for lunar mobility – Part 2 la suite…

Peter Radziszewski[a], Brad Jones[b]

[a] Department of Mechanical Engineering, McGill University

[b] Neptec Design Group

With the initiation of a planetary mobility program at the Canadian Space Agency, it became important to address the development of some capacity for the development and investigation of vehicle traction systems. Neptec Design Group, through the Canadian Space Agency's Partnership Support Program and the NSERC CRD program, initiated a study on traction system development with the goal to define a methodology for the design of traction systems for lunar mobility. An initial overview of wheel development was presented at the PTMSS/SSR conference in 2010. In this paper, an overview of traction system development will be made followed by a focus on the development and field testing results of the particulate filled chainmail "iRings" traction system.

Real-time modeling of tool and wheel interactions with soil for mining applications

Marek Teichmann, Daniel Holz
CM-Labs Simulations Inc.

Modeling of the interaction between soil cutting tools and planetary soil, including terrain deformations, in the context of a full multibody dynamics simulation is crucial in estimating the efficiency of soil moving during mining operations, which has applications in the design of efficient high-level control algorithms for planetary resource gathering and site shaping, mission planning and scenario analysis, as well as operator training.

We present a set of new algorithms for modeling the interaction between soil cutting tools and planetary soil which allow for modeling of excavation on steep surfaces, as well as latest methods for wheel–soil interaction, all of which are integrated in the same simulation.

In these methods, we combine physics models from terramechanics and soil mechanics to model a rover or other vehicle with a mounted tool, in tasks where soil interaction is an important component, such as excavation tasks. For excavation, we represent the soil using a deformable mesh model based on level sets or height fields.
We consider the impact of both wheel–soil and tool–soil interactions on the vehicle motion by creating a fully coupled simulation of the dynamics of the vehicle and its environment.

We show recent progress on large mining equipment simulation as well as a mission planning tool developed in collaboration with the Canadian Space Agency which employs some of the techniques presented here.

COMBUSTION OF LUNAR REGOLITH/MAGNESIUM MIXTURES. A. Delgado, F. Álvarez, C. White, and E. Shafirovich, Department of Mechanical Engineering, The University of Texas at El Paso, 500 W. University Ave., El Paso, TX 79968, eshafirovich2@utep.edu

Introduction: Self-propagating high-temperature synthesis (SHS) has been used for fabrication of numerous ceramic and other compounds. This technique involves self-sustained propagation of the combustion wave over the mixture due to exothermic reactions between the mixture components. The present paper reports recent results of studies on SHS in mixtures of JSC-1A lunar regolith simulant with magnesium, conducted with the goal to develop a low-energy consuming method for the production of construction materials on the Moon.

Prior Research: Thermodynamic calculations for combustion of Al/JSC-1A and Mg/JSC-1A mixtures have shown that Mg provides the highest adiabatic temperatures [1]. Experiments on the combustion of Mg/JSC-1A mixture pellets confirmed that Mg is a promising metal for the reactions with regolith [1].

Minimization of Magnesium Content: In the thermodynamic calculations, the maximum adiabatic temperature in Mg/JSC-1A mixtures, 1417°C, was achieved at 26 wt% Mg [1]. Experiments with a relatively coarse regolith have shown that steady propagation of a planar combustion front requires Mg concentrations of 24 wt% or more. At 23 wt% Mg, a spinning combustion wave with two hot spots moved along a helical path on the sample surface in opposite directions (Fig. 1) [2]. Note that this is the first experimental observation of the spinning combustion wave with two counter-propagating hot spots in solid-solid mixtures.

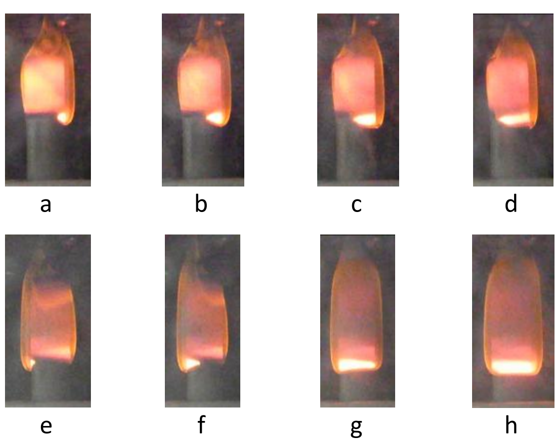


Fig. 1. Images of spin combustion in JSC-1A/Mg pellet (diameter 12.7 mm). Images (a) – (d) show a hot spot that travels from right to left, while images (e) – (h) show a hot spot that travels from left to right.

In lunar missions, it would be desired to decrease the content of Mg that is required for combustion with regolith. To improve the kinetics of reactions between JSC-1A and Mg, the former was subjected to high-energy mechanical milling in a planetary ball mill (Fritsch Pulverisette 7). As a result, the specific surface area of JSC-1A significantly increased and the required concentration of Mg was lowered to 13 wt% [2].

Gravity Effect: To investigate the effect of gravity on the combustion of Mg/JSC-1A mixtures, experiments onboard research aircraft were conducted [3]. The front propagation velocity in the mixtures (26% Mg) was determined during the periods of reduced and increased gravity. Figure 2 indicates a slight trend toward a higher velocity with increasing gravity though the scatter hinders reliable conclusions.

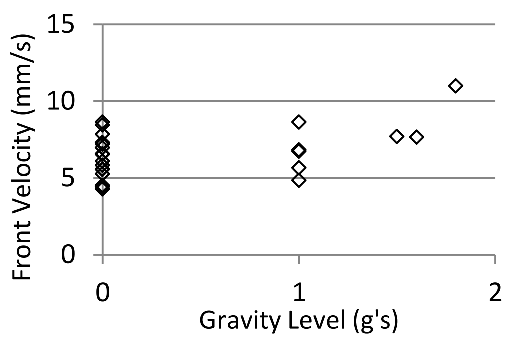


Fig. 2. Combustion front velocity as a function of gravity [3].

Increasing the Strength of Products: In prior experiments with Mg/JSC-1A mixtures, the combustion products were not sufficiently strong for using them as construction materials. The product composition and strength may depend on heat transfer from the pellet to the surroundings during combustion and subsequent cooling. In the present paper, the heat transfer was changed by submerging the pellet in silica and JSC-1A powders.

For these experiments, JSC-1A was milled in the planetary ball mill and mixed with 325-mesh Mg powder. The mixtures (26% Mg) were compacted into pellets (diameter 25.4 mm) using a hydraulic press (19.6 kN). The pellets were wrapped with a 3 mm thick ceramic fiber insulator. A thermocouple in a two-channel ceramic insulator was inserted into each pellet and connected to a data acquisition system. Two types of thermocouples were used: W/Re5% - W/Re26% (type C, Omega) and Chromel-Alumel (type K).

The pellets were submerged in either JSC-1A or silica powder, located in an aluminum can (Fig. 3). The can was placed in a chamber connected to an argon cylinder and a vacuum pump. During the experiment, the pellet was ignited at the top by a Nichrome wire connected to a DC power supply. The experiments were conducted in argon at 90 kPa.

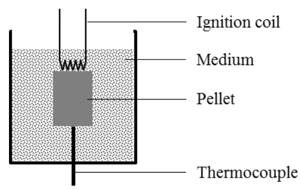


Fig.3. Schematic of the pellet location in the can.

The use of silica as the surrounding medium resulted in the highest strength of the obtained materials. In contrast with the products obtained with no surrounding powder, these materials could not be easily broken (it was possible to only cut them using a saw). Figure 4 shows a photograph of the combustion products obtained in silica environment.

Fig. 4. Cross-section of the product pellet obtained by combustion of Mg/JSC-1A pellet submerged in silica.

Figure 5 shows typical results of temperature measurements. The maximum temperature was 1350-1400°C independently on the environment. It is seen that the use of silica leads to a higher cooling rate immediately after combustion, but the effect becomes the opposite at temperatures lower than 1000°C.

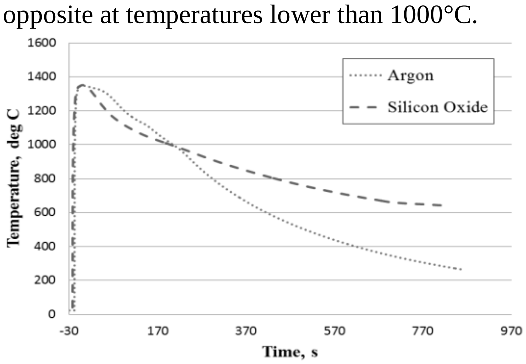


Fig.5. Time variation of temperature during combustion of Mg/JSC-1A pellets in argon (dotted) and silica (dashed) environments. Time “0” corresponds to the maximum temperature.

Figure 6 shows XRD patterns of the products. The highest peaks in both patterns correspond to MgO. The observed differences in other peaks indicate that submerging the sample in silica slightly changes the composition of the combustion products, which include Si and complex oxides of Al, Mg, and Si [1, 3]. Additional studies are required to explain the observed high strength of the products obtained during combustion of Mg/JSC-1A pellets submerged in silica.

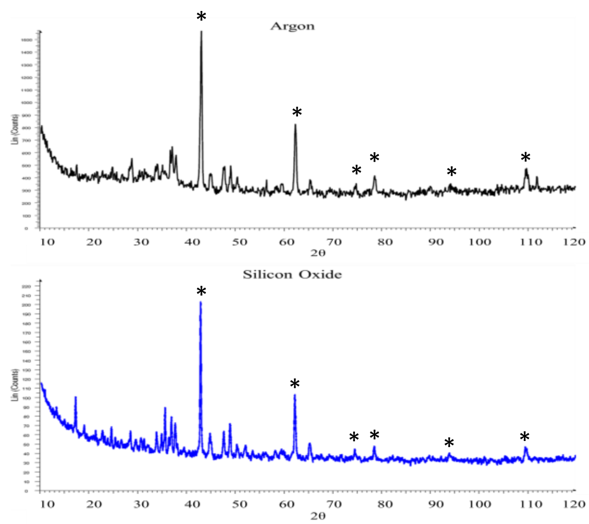


Fig.6. XRD patterns of products obtained in argon (top) and silica (bottom) environments. Asterisks indicate MgO peaks.

Conclusions: Combustion of Mg/JSC-1A mixture pellets has been studied experimentally. At low concentrations of Mg, spin combustion with two counter-propagating hot spots occurs. High-energy ball milling of JSC-1A allows one to obtain combustible mixtures at Mg concentrations as low as 13 wt%. The effect of gravity on the combustion of Mg/JSC-1A pellets is small. Submerging the pellets in silica during combustion significantly increases the strength of the products.

Acknowledgements: This research was supported by the NASA Office of Education. Microgravity experiments were supported by the NASA Reduced Gravity Education Program and by the Center for Space Exploration Technology Research at UTEP.

References: [1] White C., Alvarez F., and Shafirovich E. (2011) *J. Thermophys. Heat Transfer*, 25, 620-625. [2] Álvarez F., White C., Narayana Swamy A.K., and Shafirovich E. (2012), *34th International Symposium on Combustion, July 29 – Aug. 3, 2012, Warsaw, Poland* (accepted). [3] Álvarez F., Delgado A., Frias F., Rubio M., White C., Narayana Swamy A.K., and Shafirovich E. (2012) *50th AIAA Aerospace Sciences Meeting, Nashville, TN, Jan. 9-12, 2012*, AIAA Paper 2012-1119.

ON THE EXTRACTION OF VOLATILES FROM LUNAR REGOLITH USING SOLAR POWER. J. A. Frias[1], Michael VanWoerkom[2], and E. Shafirovich[3], [1]Department of Mechanical Engineering, The University of Texas at El Paso, 500 W. University Ave., El Paso, TX 79968, jafrias@miners.utep.edu, [2]ExoTerra Resource, LLC, 9754 Las Colinas Dr., Lone Tree, CO 80124, m_vanwoerkom@exoterraresource.com, [3]Department of Mechanical Engineering, The University of Texas at El Paso, 500 W. University Ave., El Paso, TX 79968, eshafirovich2@utep.edu.

Introduction: Lunar Crater Observation and Sensing Satellite (LCROSS) and Lunar Reconnaissance Orbiter (LRO) missions have confirmed that in polar regions of the Moon, craters can act as cold storage, capable of accumulating and preserving volatile materials like water ice [1]. The concentration of water in the regolith at the LCROSS impact site is estimated to be 5.6 ± 2.9 wt. % [2]. Other volatiles such as mercury, sodium, sulfur dioxide, carbon dioxide, formaldehyde, ammonia and methanol have been identified [3].

Extraction of water and other useful volatiles from lunar regolith promises great opportunities for the future exploration missions. The present paper investigates methods for the extraction of volatiles from regolith within the shadowed craters of the Moon using solar power.

The concept involves transfer of beamed solar power from concentrators, located either onboard orbiters (Fig. 1) or on the top of the crater walls, to the volatile extraction and processing system, located in the shadowed area. A preliminary design for the extraction system includes an oven heated by solar power that is transferred by the fiber optics from the solar concentrator (Fig. 2). Note that the feasibility of transferring concentrated solar energy by the fiber optics has been demonstrated in successful tests of the optical waveguide solar thermal power system for ISRU applications [4]. The regolith is heated to the temperatures that exceed the boiling points of the contained volatiles at the atmospheric pressure of the Moon. As each volatile reaches its liquefaction point and condenses out of the gas mixture, it is pumped into a separate storage tank.

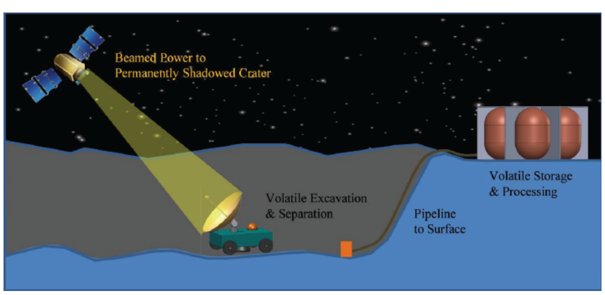


Fig. 1. Lunar volatile extraction architecture.

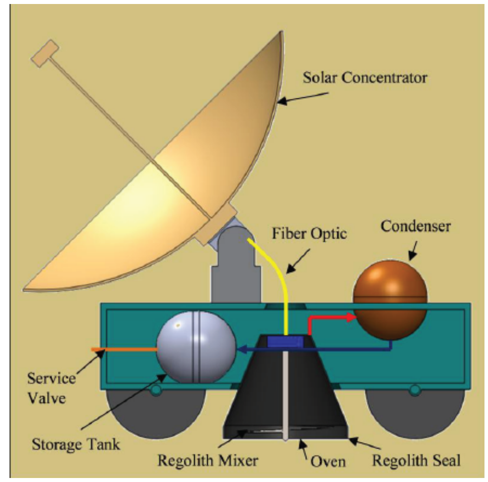


Fig. 2. Volatile extraction and processing system.

To develop the extraction equipment, it is necessary to determine the amount of power that is required for the sublimation of frozen volatiles, located in the lunar regolith. Temperature and atmospheric pressure in the craters of the Moon are 40 K and 10^{-7} Pa, respectively. Note that at 40 K, ice sublimates if pressure is lower than 10^{-54} Pa [5], which explains the existence of ice in lunar craters. To extract volatiles on the Moon, the regolith should be heated to the boiling point at 10^{-7} Pa. For example, the boiling point of water at this pressure is 134 K.

The present paper focuses on the analysis of heat transfer from the top surface of regolith, irradiated by the light beam, down to the underlying layers. This analysis is needed for the determination of required solar power.

Results and Discussion: A two-dimensional steady model for heat transfer in the surface layer of lunar soil irradiated by a vertical light beam was developed using GAMBIT software. The radiation from the regolith surface to the space was neglected. A square of specified size was considered in the vertical plane of the regolith. All four sides of the squares were defined as walls at 40 K and the inside area was defined as the lunar regolith. After the GAMBIT model was created, it was imported into ANSYS FLUENT software, where boundary conditions were assigned to the simulation. The density, specific heat, and thermal conductivity of regolith were taken from [6, 7].

Different values of the heat flux transferred by the light beam were tested.

Figure 3 shows the obtained temperature field in the top part of the selected square area 1 m x 1 m (mesh size 2 mm) at the heat flux of 1000 W/m^2, while Figure 4 shows the calculated temperature along a vertical axis that aligns with the direction of the beam. It is seen that the temperature exceeds the boiling point of water (134 K at 10^{-7} Pa) in a layer as deep as 6 cm.

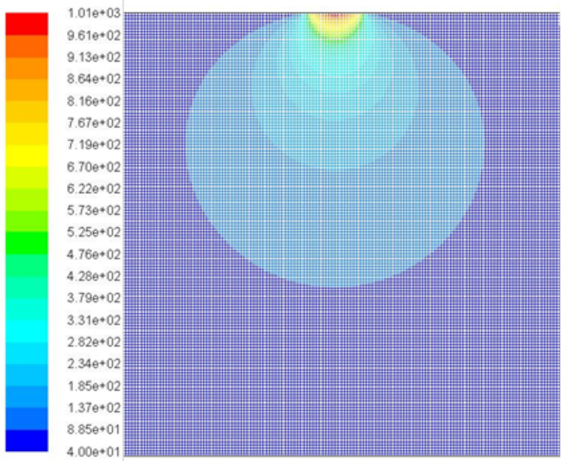


Fig. 3. Temperature field in the surface layer of the Moon heated by the light beam with energy flux of 1000 W/m^2.

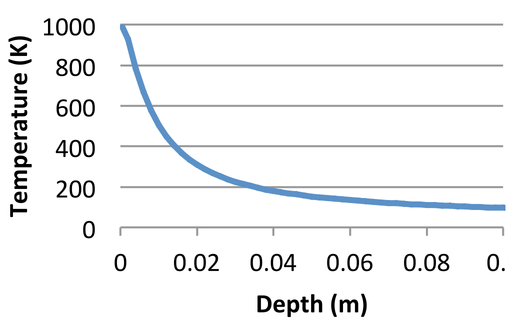


Fig. 4. The regolith temperature as a function of depth calculated for the light beam with energy flux of 1000 W/m^2.

For accurate calculations, the size of the selected area should be sufficiently large, so that the mesh size does not affect the results. Figure 5 shows that at the mesh size 1-5 mm, the "boiling" depth is almost insensitive to the size of the selected area if this size is larger than 0.5 m.

Finally, Figure 6 demonstrates that with increasing the heat flux, the "boiling" depth increases.

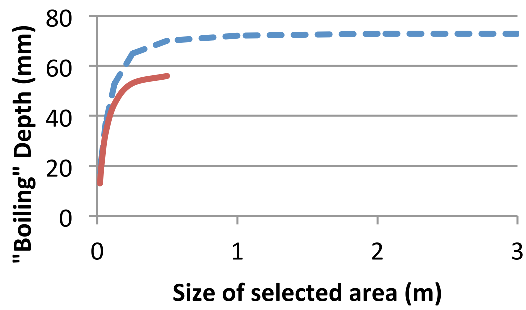


Fig. 5. The "boiling" depth as a function of the size of the selected area; heat flux: 1000 W/m^2; mesh size: 1 mm (solid curve) and 5 mm (dashed curve).

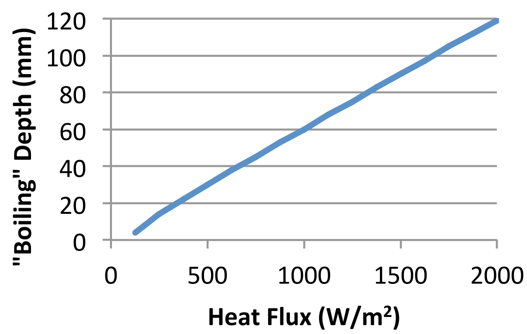


Fig. 6. The "boiling" depth *vs.* the heat flux in the light beam (the area: 1 m x 1 m, mesh size: 2 mm).

Conclusions: A two-dimensional steady model has been developed for heat transfer in lunar regolith irradiated by a beam of concentrated solar power. The model allows one to calculate the depth that can be heated to the boiling point of water or any other volatile at the atmospheric pressure of the Moon.

Acknowledgment: This research is supported by the NASA Office of Education (Group 5 University Research Centers).

References: [1] Gladstone R. et al. (2010) *Science, 330*, 472-476. [2] Colaprete A. et al. (2010) *Science, 330*, 463-468. [3] Paige D. et al. (2010) *Science 330*, 479-482 [4] Nakamura T. and Smith B. (2011) 49th AIAA Aerospace Sciences Meeting, 4-7 Jan. 2011, Orlando, FL, AIAA 2011-433. [5] Feistel R. and Wagner W. (2007) *Geochimica et Cosmochimica Acta, 71*, 36-45. [6] Balasubramaniam R. et al. (2009) 47th AIAA Aerospace Science Meeting, 5-8 Jan. 2009, Orlando, FL, AIAA 2009-1339. [7] Sibille L. et al. (2006) *Lunar Regolith Simulant Materials: Recommendations for Standardization, Production and Usage,* NASA/TP—2006–214605.

EXTRACTING SOLAR-WIND VOLATILES REQUIRES PNEUMATIC SIZE SEPARATION AND TRANSPORT. [1]B. L. Cooper, [2]K. Zacny, and [3]D. S. McKay, [1]ESCG/Jacobs Technology, Houston TX bonnie.l.cooper@nasa.gov, [2]Honeybee Robotics, New York, NY, [3] NASA Lyndon B. Johnson Space Center, Houston TX.

Summary: Pneumatic separation of the finest fraction of lunar soil, and transporting only the material with the highest concentration of volatiles, enhances the (already significant) economic viability of pneumatic conveying in partial gravity. A rough estimate exists for the solar-wind gas content of the "average" regolith [1]; however, we are still working to understand how the amount of each solar-wind gas varies geographically.

Background: Solar wind gases are a source of hydrogen, helium, carbon, nitrogen, and other volatiles that will be valuable commodities on the Moon (e.g. [2]), and these gases can be released at modest temperatures (Figure 2 [3]). Experimental data [4] exist to show that finer grain size soil has increasing hydrogen content (Fig 1), and other solar-wind gases show a similar trend, because the gases are surface-correlated [5].

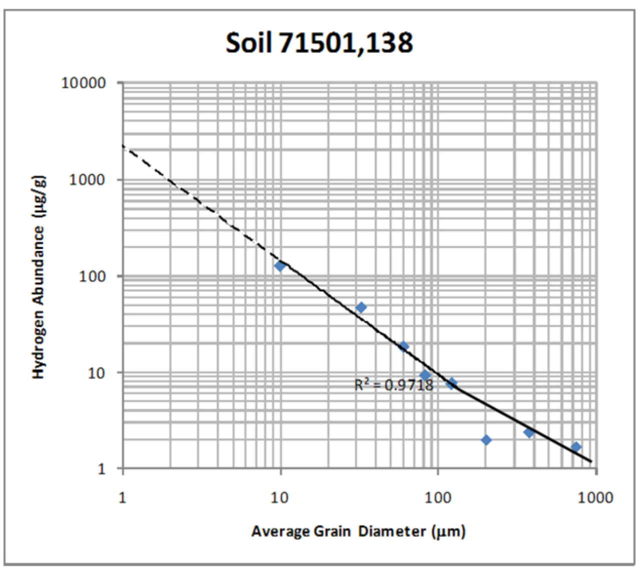


Figure 1. Weight percent of adsorbed hydrogen in lunar soil increases exponentially as grain size decreases.

Concentration of solar-wind gases at finer sizes results from the solar wind volatiles being implanted to depths of a few hundred to a thousand nanometers. At finer grain sizes, these thin surface layers makes up a higher and higher proportion of the bulk material so that the concentration of solar wind volatiles per gram increases significantly.

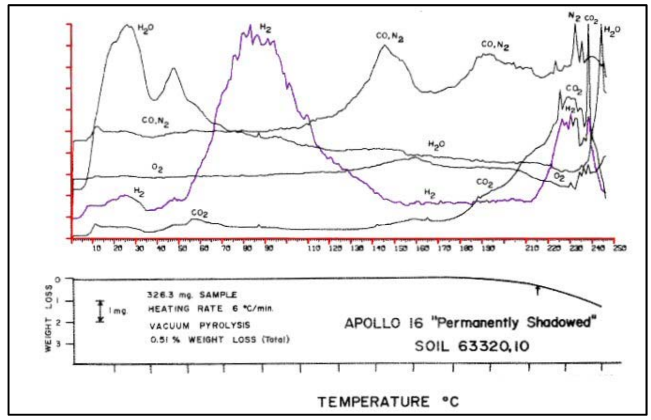


Figure 2. Thermal gas release data for Apollo 16 sample 63320. Note hydrogen release peak at 500°C (from [3]).

While the data of [4] only go down to 10 micrometers mean grain size, extrapolation of this well-behaved correlation curve to 1 micrometer size shows a potential concentration of more than 2000 µg/g, a factor of about 60 increase compared to the bulk soil. A concentration of 2000 µg/g hydrogen is the equivalent of 1.6 % water. This is similar to the amount of water that has been proposed for many sites in the permanently shadowed polar regions.

Figure 3. Pneumatic particle size separation down to 1.7 micrometers has been achieved in the laboratory.

The most mature soils generally have a larger amount of adsorbed solar-wind volatiles (because of their longer exposure time), and ilmenite-rich soils also tend to be enriched in solar-wind hydrogen [6, 7]. Moreover, there is some evidence that soils from shadowed areas (and areas buried under a few cm of regolith) may contain more volatiles than do regolith samples from fully sunlit areas [8].

Pneumatic Separation Benefits: Separation of regolith according to size strongly enhances the efficiency of many proposed ISRU processes [9-13]. Here, we expand upon the approach of [14, 15] to beneficiate lunar soil while simultaneously recovering solar wind gases.

We have developed a method to pneumatically separate particles of 1.7 micrometers size and smaller from lunar soil [16]. This method, coupled with the pneumatic separation and transportation techniques developed by [14], offers the capability to separate and process particles of very small size, with the expectation of enhanced yield as described above.

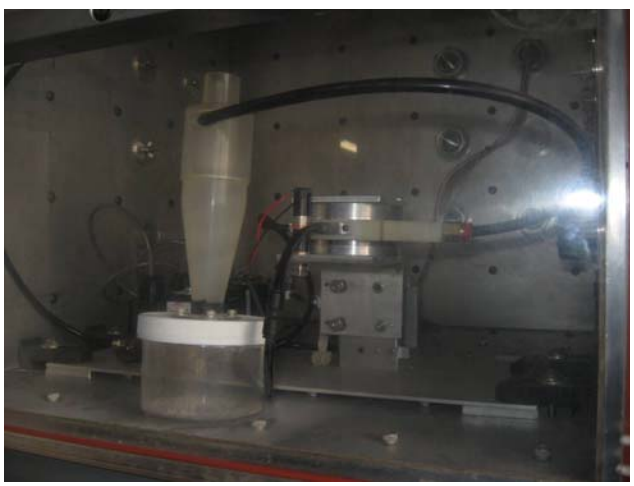


Figure 4. Honeybee's pneumatic transfer system proof of concept, in a vacuum chamber.

Pneumatic separation and transport gives us the potential to obtain the vast majority of the Moon's resources in a simple and economical way, anywhere on the Moon. For oxygen production (as well as other volatiles), the richest part of the regolith (the dust) can be separated *in-situ* from the bulk soil. Only a small fraction of the regolith will be transported, because the majority of the solar wind gases are contained within the smallest fraction.

Conclusion: We are still working to understand how the amount of each solar-wind gas varies geographically. In addition to the overall increase of some volatiles in specific areas, there is evidence that some areas are depleted in one volatile and enriched in another [17]. As we continue to improve our prospecting methods for solar-wind volatiles, we are also developing the technology for extracting these consumables. The next step is a trade study to quantify the savings gained in mass and power for this system, in comparison to other proposed methods.

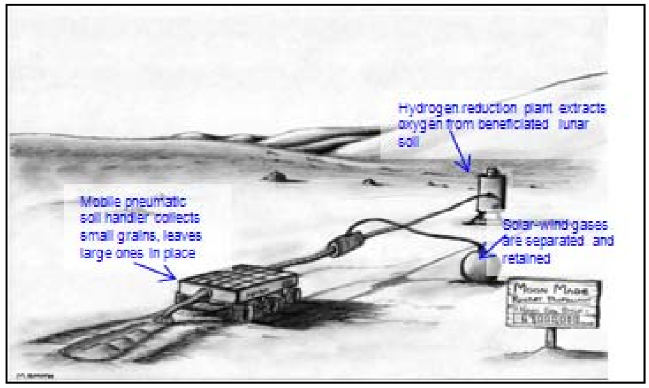


Figure 5. Concept of a mobile pneumatic regolith collection and transport system.

[1] Haskin, L.A. (1992) *Lunar Bases and Space Activities of the 21st Century II*, 393-396. [2] Wszolek, P., et al. (1973) *Proc. Fourth Lunar Sci. Conf.*, 1693-1706. [3] Gibson Jr, E., et al., (1974) *NASA L. B. Johnson Space Center, Houston, Tex.* [4] Bustin, R., et al. (1984) *Lunar & Planetary Sci. XV*. 112-113. [5] Krahenbuhl, U. (1980) *Lunar Planet Sci. Conf. 11th*, 1551-1564. [6] Bustin, R. and Gibson, E.K. (1988) In *2nd Conf. on Lunar Bases and Space Activities of the 21st Century*, NASA/JSC, Lunar and Planetary Institute; 437-445. [7] Bustin, R., (1990) *CR-187363*, NASA. [8] Cooper, B.L., et al. (2011) *A Wet vs. Dry Moon: Exploring Volatile Reservoirs and Implications for the Evolution of the Moon and Future Exploration*, 6056. [9] PNNL, (2006) *Contractor Report*, NASA, 21 pp. [10] Helmke, P. and Corey, R. (1989) In *Lunar Base Agriculture*, American Society of Agronomy, Inc., Crop Science Society of America, Inc., and Soil Science Society of America, Inc.; 193-212. [11] Ming, D. and Henninger, D., (1994) *Advances in Space Research*, *14*, 435-443. [12] Heiken, G. and McKay, D. (1976) *Lunar Science VII*, *Special Session Abstracts*. 49-54. [13] Criswell, D.R. and Waldron, R.D. (1982) In *Space Industrialization*, CRC Press, Inc.; 1-54. [14] Zacny, K., et al. (2008) *SPACE 2008*, 1-23. [15] Zacny, K., et al. (2010) *AIAA Space 2010*, [16] Cooper, B.L., et al. (2010) *Proceedings of the 12th International Conference on Engineering, Science, Construction, and Operations in Challenging Environments (Earth & Space 2010)*, 66-73. [17] Gibson, E.K. and Johnson, S.M. (1971) *2nd Lunar Science Conference*, 1351-1366.

Investigation on practical production methods of lunar concrete. Naoko Hatanaka, Japan Manned Space Systems (Otemachi Bldg., 1-6-1, Otemachi, Chiyoda-ku, Tokyo 100-0004, Japan, hatanaka.naoko@jamss.co.jp)

Introduction: Lunar concrete is one of the possible materials obtained by ISRU on the Moon. It is composed of approximately 17% of cement, 78% of aggregate and 5% of water. All the components of lunar concrete except 0.5 wt% of hydrogen (to produce water) are abundant on the Moon. However, even though the necessary elements for cement exist on the Moon, the typical minerals of cement materials on the Earth, such as lime stone, iron ore, bauxite created by sedimentation or weathering, cannot be found on the Moon. In short, all minerals on the Moon are rather uniform and unnecessarily rich in SiO_2 and poor in CaO to apply the typical cement production methods. Therefore, a special technique called vacuum pyrolysis was proposed by T. D. Lin [1], as a promising method to produce cement from lunar materials. This cement production method utilizes the difference in volatility of elements (FeO> MgO> SiO_2> CaO> Al_2O_3), and evaporates the highly-volatile elements, FeO, MgO, and SiO_2, and condenses the low volatility elements, CaO and Al_2O_3. Theoretically, as impurities evaporate, High Alumina Cement (HAC) can be manufactured as an evaporation residue.

Purpose of this research: Since the lunar cement production by vacuum pyrolysis had never been experimentally proved, this research aimed to investigate the feasibility of the cement production method. The actual chemical composition of the evaporation residues should be investigated to confirm that the evaporation of CaO does not initiate until SiO_2 has almost completely evaporated. Otherwise, it results in extremely Ca-poor cement with low strength. In addition to the cement chemical composition, the conversion efficiency from lunar soil to cement, the evaporation rate of elements (cement production speed), and the associated oxygen production by the evaporation reaction had never been investigated by previous research. The lack of knowledge about the associated oxygen generation in previous research resulted in wrong designs of lunar concrete plant facilities and overestimation of mass and power budgets. Therefore, this research aimed at revealing the production processes, facilities, and their mass and power budgets based on the mechanism of the cement and oxygen production processes and its experimental data.

Moreover, along with the chemical composition change of evaporation residues, various HAC with different SiO_2 contents can be manufactured. From an energy and cost saving point of view, the material processing rate should be minimized by employing either high SiO_2 content cement (low SiO_2 evaporation from lunar soil) or glassy highland soil as pozzolanic material. However, neither the properties of high SiO_2 content cement in the lunar cement chemical compositions nor the pozzolanic reactivity of the glassy lunar soil have ever been studied. Hence, the hydration products, hydration reactivity and strength property of various cements were investigated, applying different hardening accelerators and curing temperatures.

Thus, this research examined the following three topics:

(1) Feasibility of cement and oxygen production by vacuum pyrolysis
(2) Properties of cement with different SiO_2 content and cooling conditions
(3) All processes, facilities, mass and power budgets of a prototype lunar concrete plant based on vacuum pyrolysis and proper curing method of concrete

Results:

(1) Feasibility of cement and oxygen production by vacuum pyrolysis: Firstly, to reveal the feasibility of cement and oxygen production by vacuum pyrolysis, lunar highland soil simulant was manufactured. Then, the stimulant was evaporated in a vacuum furnace at 1937K, 1994K and 2045K. The following results were obtained by the experiment:

I. It was proved that the vacuum pyrolysis technique enables to produce High Alumina Cement, containing $CaO \cdot Al_2O_3$ (it is called CA for cement chemistry), a high hydration reactivity component, as a major component. CaO/Al_2O_3 ratio is 0.66, and varied in SiO_2 concentration depending on evaporation processing time.
II. The practical chemical compositions of lunar cements were clarified, and chemical composition change of evaporation residues was drawn by extrapolation lines
III. The evaporation rates of lunar soil simulant were measured at three different temperatures. Then, a versatile formula representing the relationship among the processing temperature, the evaporation rate and the evaporation surface area was acquired

(2) Properties of cement with different SiO_2 content and cooling conditions: In response to the proof of the feasibility of lunar cement production, lunar cement

simulants were manufactured based on the obtained chemical compositions in the vacuum pyrolysis experiment. The lunar cements were CaO/Al_2O_3=0.66 and varied in SiO_2 concentration (5%, 10%, and 15%) and crystal conditions (glass or crystal). Then, the hydration products, hydration reactivity and strength property of the cements were investigated with various mixture compositions and curing temperatures (20, 40, and 100 ºC). For cost effective lunar concrete production, this study assumed to apply a cement/concrete composition which requires low cement processing mass, by means of

- Production of high SiO_2 content cement
- Replacement of cement with glassy highland soil

At the same time, the lunar concrete should have sufficient properties to be applied in the severe lunar environment:

- Marginal strength property to support loads and avoid penetration by meteorite impacts
- Stability of the structure by generating stable C_3AH_6 ($3CaO \cdot Al_2O_3 \cdot 6H_2O$) hydrates instead of unstable C_2ASH_8 ($2CaO \cdot Al_2O_3 \cdot SiO_2 \cdot 8H_2O$) to prevent the dehydration and the structure failure of lunar concrete

As a summary, some methods to generate stable C_3AH_6 hydrates which create high strength concrete were investigated. From the experimental results, the following conclusions were obtained:

I. Mixing with water at 20ºC was found not effective for all the lunar cements to produce stable hydration products C_3AH_6 within a short time period before vacuum exposure. Therefore, some activation is necessary to manufacture stable concrete structures.
II. For low SiO_2 content cement, activation by mixing 0.1-1.0% of Li_2CO_3 or curing more than 40 ºC is sufficient to generate C_3AH_6 within 3 days. Moreover, those mortar specimens developed 30MPa of compressive strength after the conversion reaction.
III. In the case of high SiO_2 content compositions, the hydration reaction was not observed with water at 20 ºC. Hardening accelerator and high temperature curing were found to be effective to initiate the hydration reaction. However, the obtained hydration products were mainly unstable C_2ASH_8, and it was converted into C_3AH_6 at 100 ºC. Therefore, a high curing temperature of more than 100 ºC was found to be necessary to manufacture stable concrete with high SiO_2 content compositions.
IV. As a conclusion, the high temperature and high pressure curing method called Dry-Mix Steam Injection method (DMSI method) is considered to be the best method for low cost concrete production, due to no necessity of hardening accelerator and applicability of high SiO_2 content concrete [2]. The necessity of extensive thermal control denotes that precast panel assembly instead of on-site casting is more rational, since on-site casting requires extremely large thermal control systems.

(3)All processes, facilities, mass and power budgets of a prototype lunar concrete plant based on vacuum pyrolysis and proper curing method of concrete: Then, the necessary processes and facilities for lunar concrete production which employs the vacuum pyrolysis technique and DSMI method were clarified. Then, the mass and power budgets of the lunar concrete plant were estimated by sizing terrestrial facilities. Experimental results, lunar soil physical properties and lunar environmental factors were also taken into account. Estimated budgets indicated that

I. The mass of a concrete plant with less than 350 tons of annual concrete production capacity is less than 20 tons.
II. The employment of lunar In-Situ production reduces the launch mass down to 9.5% to 5.5% in the case of an annual concrete production from 100 to 500 tons. Then, mass production of concrete is demonstrated to be more cost effective.

Conclusions: From this research, the feasibility of lunar cement production was confirmed. Also, the concrete production method to generate stable and strong hydrate C_3AH_6 was revealed and suggested.

Reference:

[1] T. D. Lin, Concrete For Lunar Base Construction, Symposium on lunar bases and space activities of the 21th century

[2] T.D. Lin and Sam Chou, Concrete Made with Dry-Mix/Steam-Injection Method.

Abstract: An infrastructure, in the form of permanent facilities, is required for recurring and long-term space exploration, with assets amortized across numerous missions. Power facilities are extensible in order to meet changing Outpost needs, exploiting advantages offered by ISRU-derived production. It is expected that Aluminum cable may result from late first-generation, or early second-generation Lunar ISRU plant.

The modular PMAD architecture manages the complexities of the Lunar Surface, supporting operations at remote sites, with modular subsets that are directly applicable to large-scale nuclear-powered/propelled spacecraft. The architecture supports unattended operation, and translation of transport spacecraft components to outpost facilities on arrival.

The PMAD architecture features a distributed, modular grid that aggregates, and distributes power to/from diverse sources/sinks of various scales and technologies. This power format implements aviation-legacy, 400 Hertz power in a 3-phase, "delta" configuration that directly drives high-efficiency, multiple-horsepower motors, including propellant pumps. The 3-phase delta configuration also accommodates the lack of a coherent ground on the Lunar surface.

The PMAD grid also offers extensible modularity, regenerative noise filtering, power factor correction, etc. *Efficient transmission lines operate at high voltage to minimize power loss and transform to high current for distant loads. State-of-the-art, radiation-tolerant, high-current High-Voltage Vacuum Tube Technologies (HV VTT) assure reliability. Grid expansion is achieved through first-generation use of ISRU-derived drop-in VTT components, Aluminum cable, and glass and ceramic products in the form of insulators, transformer and inverter toroidal cores.*

Integrated Distributed Control Authority (DCA) supports evolving control demands using a dispersed grid management that is accessible to (optional, external) control centers through Supervisory Control and Data Acquisition (SCADA) protocols using Power Line Communications (PLC). To avoid interference with surface traffic, uninsulated transmission lines are buried in parallel trenches at a shallow yet safe depth. This method is compatible with Alternating Current, but is impractical for Direct Current, and is a safe method where contact between two or more phases is required before a hazard could exist, since there is no coherent ground.

The modular PMAD architecture will be mapped into the Lunar Shipyard Architecture *as a lead project, and will then be available as a reference architecture for users to modify into derivatives or variants.*

Keywords: extensible modularity, long-distance transmission, energy aggregation, energy distribution, regenerative noise filtering, power factor correction, autonomous control, SCADA

SUPLANTING GRAVITY WITH CENTRIFUGAL FORCE FOR SIEVING AND PROCESSING REGOLITH UNDER MICRO-GRAVITY C. B. Dreyer[1], O. Walton[2], and E. P. Riedel[3], [1] Colorado School of Mines, Department of Mechanical Engineering, 1600 Illinois St, Golden CO 80401; Ph (303) 273-3890; email: cdreyer@mines.edu; [2] Grainflow Dynamics, Inc., 1141 Catalina Drive, PMB 270, Livermore, CA 94550-5928; Ph (925) 447-4293; email: walton@grainflow.com, [3] Ned Riedel Engineering, LLC, 150 South 31st Street, Boulder, CO 80305, (720) 596-4820; email: ned@riedel-eng.com

Introduction: In any microgravity environment movement and/or processing of regolith will have to rely on means other than gravity flow. Under any reduced gravity conditions, such as a lunar environment, the cohesion of fine granular materials will make handling and processing operations that utilize gravity function significantly different from similar operations under terrestrial conditions. Minimum openings of gravity-flow hoppers will need to be much larger [1], vibrational sieving will not function well for the smallest sizes [2], the effective Geldart classification of powders for fluidization [3] will be shifted so that larger-size powders are considered to be category C, cohesive-powder. Many of these issue can be addressed through the use of mechanical or pneumatic conveying for transport of regolith, and through the utilization of centrifugal force in processes, such as sieving and fluidized beds, that depend on a body force for part of their function. A centrifugal-sieve separator can provide efficient gravity-level-independent size classification of granular feedstock, like lunar regolith, utilizing centrifugal force as the primary body-force, combined with shearing flow and vibratory motion. A prototype centrifuging sieve demonstrated the ability of a rotating cylindrical screen with induced axial flow of regolith on the inside to separate size fractions of JSC-1a lunar simulant. The cylindrical screen separates particles, with the fines passing through the outer wall screen, and the coarse material passing axially through the continuous feed system. The prototype was designed for semi-autonomous operation during reduced-gravity flights, and/or under vacuum conditions, and other concept designs which are fully micro-gravity compatible, utilizing no gravity-flow components for feeding or extracting regolith size fractions, have been developed.

Centrifugal Sieve Concept: Terrestrial size separation methods for dry materials often depend on gravity. For very fine particulates, the gravity-force is often supplemented with either vibration or forced shearing over a sieving screen. Centrifugal sieves can likewise utilize either vibration or shearing flow to enhance separation. When vibratory and mechanical blade sieving screens designed for terrestrial conditions were tested under lunar- gravity [2], they did not function well. Utilizing centrifugal force as the primary body-force, combined with shearing flow and vibratory motion, the centrifugal-sieve separator can provide efficient gravity-level-independent size classification of granular feedstock like lunar regolith. The centrifugal-sieve can operate in low-gravity (1/6-g and 3/8-g) and micro-gravity as well as utilize multiple feedstock sources. Granular materials naturally stratify during shear-flow with larger particles rising to the top. The centrifugal sieve size-separator utilizes the natural size stratification of flowing granular solids. A schematic of the concept is shown in Figure 1. Material enters from the right into a rotating cylindrical screen. A helix/screw inside the screen rotates at a slightly greater rate, to shear the material bed and move it to the output end. Fines are forced through the screen by centrifugal force. Coarse material is moved to the end and leaves the screen.

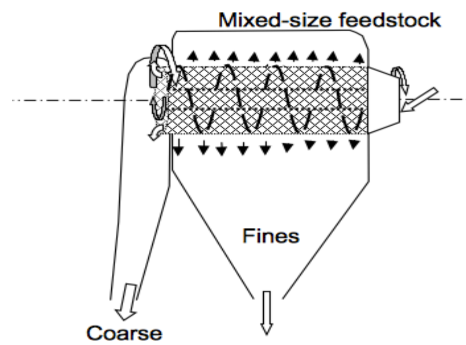


Figure 1. Schematic of centrifugal sieve concept

Microgravity Test Apparatus: A test apparatus using a size-separating screen at the outside of the flow to separate particles, with the fines passing through the outer wall screen, and the coarse material passing axially through the continuous feed system was built for use on NASA micro-gravity aircraft (Figure 2). The test apparatus is designed for semi-autonomous operation during reduced-gravity flights, and/or under vacuum conditions. A carousel of test-sample aliquots provides up to 20 pre-measured quantities of regolith simulant (~200g) to the centrifuging sieve. Testing of multiple operating conditions without opening an outer containment shroud is possible with this system. Two separate output-stream receptacle carousels of 20 containers each collect the fine and coarse material from each discrete-operating-condition test. Sieving performance in size distribution and mass delivered to the two output streams can be determined in post-flight analysis.

Operating at a centrifugal g-level of 1.5g on the screen wall in gravity, the centrifugal sieve was able to separate coarse oversize material (larger than 5mm diameter) from lunar regolith simulant JSC-1A, and to separate the size fraction of JSC-1A smaller than 100-microns from the material larger than that cutoff size (Figure 3). The rotational speed of the screen was 188 rpm and the auger/brush was 60 rpm greater. The 100 µm screen achieved roughly 50% of the material being separated into each receiver bin (Figure 4).

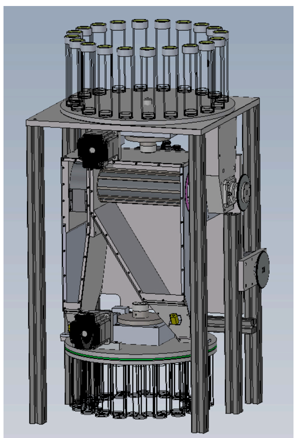


Figure 2. Centrifugal sieve micro-gravity aircraft flight test apparatus

Figure 3. Centrifugal sieve ground testing. Left: 4.6 mm screen. Right: 100 µm screen, top video still, bottom post test.

Figure 4. Sieved 100 µm JSC-1a. Left oversize, right fines which passed through a 100 µm screen.

Fluid Bed Processing – A common mode of processing granular solids is in fluidized bed, and they are also under consideration for a various resource recovery processes on the moon. Powders are typically categorized for fluidization according to the Geldart [3] classification as: C – cohesive (very fine), A – aeratable (non-bubbling, uniform fluidization w/air under ambient conditions), B – bubbling fluidization, D – spouting bed (large particles) see Figure 5.

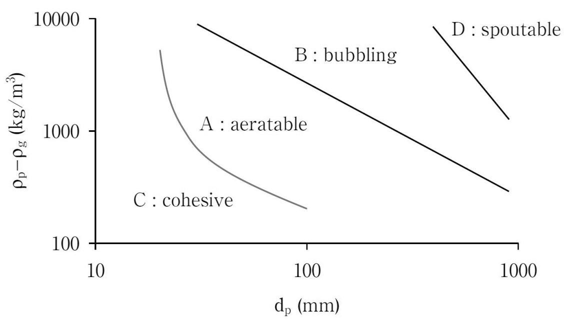


Figure 5 Geldart [3] classification of powder fluidization properties, by size and density.

Qian et al [4] examined the effects of the body-forces acting on particles in fluidized beds through the use of a rotating cylindrical chamber with a porous frit on the outer wall, so that fluidizing gas traveled from the outer radius to the center region of the rapidly rotating (centrifuging) cylindrical fluidized bed. Williams et al. [5] examined an extrapolation of Qian et al's relationship in the opposite direction, by looking at fluidization of glass and alumina powders under *reduced* gravity conditions (during parabolic flights). They found that the boundaries of Geldart classification changed with g-level such that that a given powder will behave more cohesively in a fluidized bed at reduced gravity than it does under terrestrial fluidization. Suplanting gravity with centrifugal force, after Qian et al [4] allows more cohesive powders to successfully fluidized – offering a solution for fluidized bed processing under reduced gravity conditions.

Conclusions: The feasibility of utilizing centrifugal force as the primary body-force for sieving granular feedstock like Martian, Lunar or Phobos regolith was demonstrated. The approach of a centrifugal sieve can provide efficient gravity-level-independent size classification of granular feedstock. Centrifugal force can, likewise, supplant gravity in other body-force dependent regolith processing operations, like fluidized beds.

References: [1] Walton (2012) in *Moon: Prospective Energy and Material Resources*, ed. Badescu, Springer-Verlag, [2] Ramé,et al. (2010), Zero-G Aug 13-14, 2009 Flight Final Report, NASA-GRC, [3] Geldart, D. (1973) *Powder Technology* **7**:285-292 [4] Qian et al (2001) *AIChE Journal*, **47**(5) p1022-1034, [5] Williams et al (2006) *Granular Matter*, **10**(2), 139-144.

AN ISRU SYNTHETIC BIOLOGY PLATFORM FOR FOOD PRODUCTION IN SPACE. J. Cumbers, NASA Ames Research Center, Education Associates Program (USRA), Synthetic Biology Program, Mail Stop 239-20, Bldg N239 Rm 215, P.O. Box 1, Moffett Field, CA 94035-0001, USA. John.Cumbers@nasa.gov.

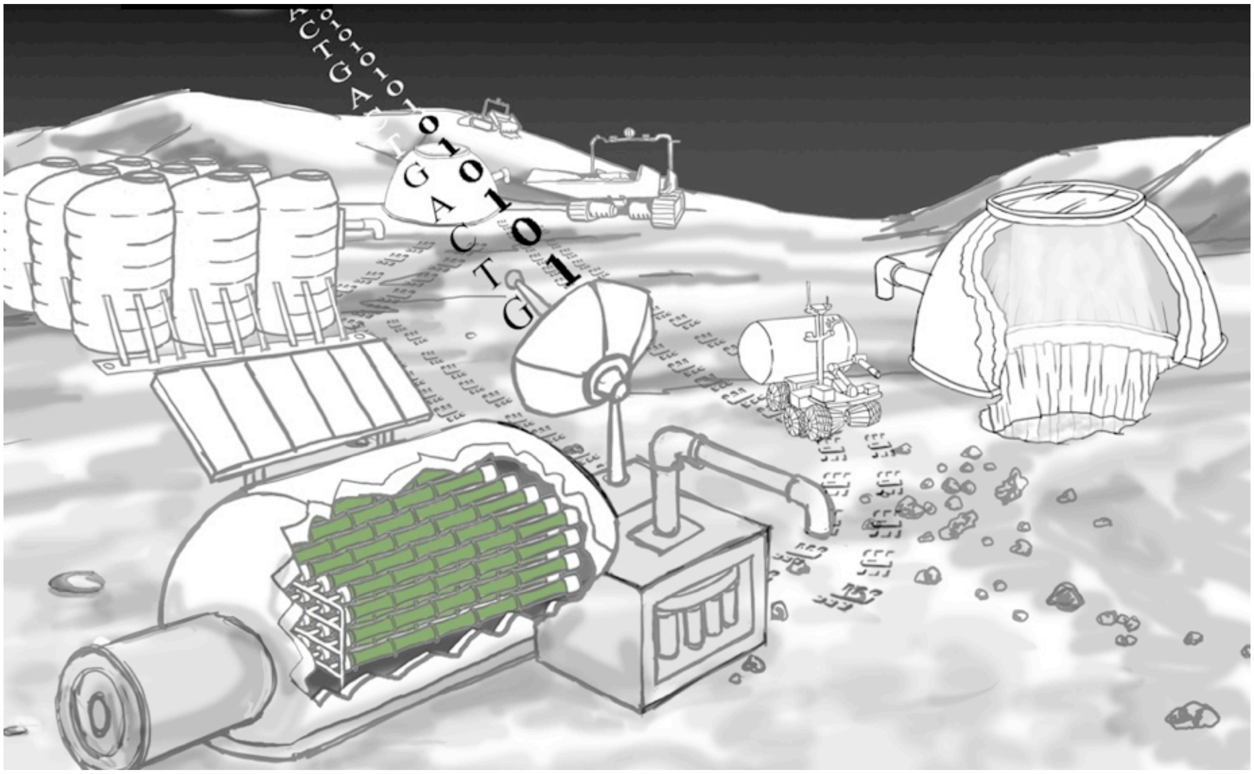


Figure 1: Concept mission involving the synthesis of food producing organisms *in situ* on the lunar surface.

Introduction: The production of food in space is one where biology offers a clear advantage over chemical or physical processes. This abstract outlines a scenario for food production on the moon using *in situ* resources.

Water and volatiles on the moon: Previous studies of lunar ISRU indicated that there was no role on the moon for biology unless enough water or carbon dioxide was discovered [1,2,3]. The Clementine [4], Moon Mineralogy Mapper [5] and Lunar Crater Observation and Sensing Satellite or LCROSS [6,7] have all now established firmly that there is a large amount of water ice to be found on the moon, both in the permanently shadowed craters of the South Pole [7] and in the subsurface of the North Pole [5]. As well as water, the plume thrown up by the LCROSS impact indicated the presence of a number of other elements as shown in Table 1. When compared to the elements required for life (S,C,H,N,O,P and S) it can be seen that nearly all are present in the lunar ice, including significant amounts of carbon containing molecules (0.4 % by mass). This evidence makes the lunar ice a valuable commodity, not just because of the elements that it holds, but because of the possibility of using these elements for biological ISRU.

Compound	Chemical name	% Relative to H_2O	% by total mass
H_2O	Water	100	5.60
H_2S	Hydrogen sulfide	16.75	0.94
NH_3	Ammonia	6.03	0.34
SO_2	Sulfur dioxide	3.19	0.18
C_2H_4	Ethylene	3.12	0.17
CO_2	Carbon dioxide	2.17	0.12
CH_3OH	Methanol	1.55	0.09
CH_4	Methane	0.65	0.04
OH	Hydroxide	0.03	0.002

Table 1: *Compounds identified by spectroscopy in the LCROSS ejecta plume* (Colaprete et al. 2010).

Food from lunar resources: For long-term settlement of space, self-sufficiency is a necessity and food production is one area that neither chemical nor physical methods can provide a solution for. The amount of dry food required per person per day is around 682 g [8]. A shielded or underground bioreactor could be used to grow the cyanobacterium Spirulina (*Arthrospira platensis* and *Arthrospira maxima)* on the lunar surface using these *in situ* resources [9]. Spirulina is sold on Earth as a dietary supplement and is a complete protein source with approximately 50% protein content by mass [10]. 2.67 kg of carbon dioxide would be required to produce 682 g of food (80% of PAR photons X 78% used for carbon fixation X 10 % Glucose per photon X Mass CO_2 X (Glucose mass / CO_2 mass) = max total biomass). If a 4-day batch cycle were run in a 682 L bioreactor, enough food could be produced per day to feed a single astronaut. This setup would require 682 L of water which could theoretically be obtained by processing 12,179 Kg of lunar ice regolith every 4 days which would also provide 14.61 kg of CO_2 [9]. Energy for this bioreactor could come from solar or nuclear power.

This technical demonstration above would show that food can be produced from *in situ* resources on the lunar surface. Synthetic biology could then come into play as a technology for improving the nutritional content, flavor and texture of the Spirulina.

Synthetic biology: Synthetic biology is practically a massless technology for engineering complex function into biological organisms. Once a genome synthesis device is placed on the surface of a moon or a planet, new organisms could be designed, built and tested for functionality on Earth. For example, a new version of the genome could be designed to produce organisms with higher protein content, or to taste better. Once demonstrated to have an enhanced ability, the new sequence for these updated organisms could be then sent to the destination of choice where the organisms could be synthesized *in situ.*

References: [1] Johansson (1995) Space Resources, NASA SP 509 (Vol. 3, p. 222-237). [2] Brown et al. 2008, In 37th COSPAR Scientific Assembly. Montréal, Canada. (p. 383). [3] Dalton, B.P. & Roberto, F.F. 2008, *Lunar Regolith Biomining: Workshop Report*. [4] Nozette et al., (1994) *Science,* vol. 266, no. 5192, pp. 1835-1839. [5] Pieters, C.M. et al. (2009) *Science,* vol. 326, no. 5952, pp. 568-572. [6] Colaprete et al. (2010) *Science,* vol. 330, no. 6003, pp. 463-468. [7] Schultz, P.H., et al., (2010). *Science,* vol. 330, no. 6003, pp. 468-472. [8] Held, J., (2007). *International Journal of Logistics,* vol. 10, no. 4, pp. 351. [9] Montague, M, et al., International Journal of Astrobiology, in press. [10] Pandey, J.P. & Tiwari, A. 2010, *Journal of Algal Biomass,* vol. 1, pp. 20.

Figures of Merit for Lunar Simulants.

Frederick A. Slane[1] and Douglas L. Rickman[2],

[1]Space Infrastructure Foundation (731 N Tejon Street, Colorado Springs, CO 80903, freds@spacestandards.org), [2]NASA/MSFC (full Global Hydrology and Climate Center NSSTC/MSFC/NASA 320 Sparkman Drive, Huntsville, AL 35805, doug.rickman@nasa.gov).

Introduction: At an earlier SRR the concept for an international standard on Lunar regolith simulants wa presented. The international standard, ISO 10788, Lunar Simulants, has recently been published. This paper presents the finalo content of the standard.

Therefore, we are presenting an update of the following: The collection and analysis of lunar samples from 1969 to present has yielded large amounts of data. Published analyses give some idea of the complex nature of the regolith at all scales, rocks, soils and the smaller particulates commonly referred to as dust. Data recently acquired in support of NASA's simulant effort has markedly increased our knowledge and quantitatively demonstrates that complexity. It is anticipated that future analyses will further add to the known complexity. In an effort to communicate among the diverse technical communities performing research on or research using regolith samples and simulants, a set of Figures of Merit (FoM) have been devised. The objective is to allow consistent and concise comparative communication between researchers from multiple organizations and nations engaged in lunar exploration. This paper describes Figures of Merit in a new international standard for Lunar Simulants. The FoM methodology uses scientific understanding of the lunar samples to formulate parameters which are reproducibly quantifiable. Contaminants and impurities in the samples are also addressed.

Additional Information: If you have any questions or need additional information regarding the preparation of your abstract, call Angel Abbud-Madrid at (303) 384-2300 or alternatively send an e-mail message to aabbudma@mines.edu.

SINTER MONITORING AND CONTROL OF LUNAR SOIL SIMULANT JSC-1A.
G. A. Konesky, K–Plasma, Ltd., 3 Rolling Hill Rd., Hampton Bays, NY 11946, g.konesky@att.net

Introduction: Sintered lunar soil has been proposed as a basic construction material [1] for such diverse applications as roadways, launch pads, dust control, thermal and radiation protection, and basic construction elements such as bricks, columns, panels, etc. as part of an In-Situ Resource Utilization (ISRU) effort. Various methods of sintering have been explored including simple radiant heating [2], microwaves [3], and focused solar energy [4].

Sintering involves the controlled melting at the grain boundaries to produce optimum mechanical properties. However, it is possible to over-sinter with excessive heating and/or duration [5]. For example, optimally sintered lunar soil simulant JSC-1A is mechanically strong and robust, and of moderate density, while over-sintered JSC-1A (melted) is brittle and overly dense. As little as 25ºC can make the difference between minimal sintering and total melting [2].

An in-situ electronic monitoring approach is used to develop an "electronic signature" of optimally sintered material to essentially know when to stop heating. Previously, this was largely a cut-and-try approach, dependent on starting material (JSC-1A, MLS-1, etc.), particle size distribution, and size and shape of the green body.

Impedance Spectroscopy [6] was originally considered as it is often used to analyze grains and interfaces (grain boundaries) of ceramics [7] and composites [8]. However, the sintering process evolves too quickly, especially in microwave heating, and the multi-frequency analysis process is unnecessarily complex. Monitoring a single frequency (1 kHz) and noting its departure from a predicted Arrhenius plot of ionic conduction, provides a simple method for end-point detection.

Theoretical Background: We consider a parallel plate electrode capacitive sensing arrangement with the lunar soil simulant placed between the plates. The following equivalent circuit [6, 9] can be drawn:

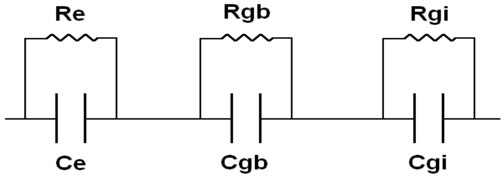


Figure 1. Equivalent circuit to measure impedance e=electrode, gb=grain boundary, gi=grain interior.

where Re, Rgb and Rgi, and Ce, Cgb and Ci are the RC circuit elements corresponding to the electrode, grain boundaries, and grain interfaces respectively. Typically, [9, 10] the grain interior has the lowest capacitance, followed by the grain boundary, and then the electrodes. These values may differ by an order or orders of magnitude. While the resistance elements are typically of the same order of magnitude, their value is highly temperature dependent and given by the Arrhenius equation [11]:

$$\sigma = A/T\, e^{-Ea\,/\,Kb\,T} \qquad (1)$$

where σ is the conductivity, A is the pre-exponential constant, T is the temperature, Ea is the activation energy, and Kb is Boltzmann's constant. The Arrhenius equation is best visualized by taking the natural logarithm of both sides of equation (1):

$$\ln(\sigma) = \ln(A/T) - (Ea/Kb)\,(1/T) \qquad (2)$$

An Arrhenius plot is then graphed using ln(σ) on the y-axis and 1/T on the x-axis. Under ideal conditions, the graph is a straight line whose slope is -Ea/Kb and y-intercept is ln(A/T). However, there are conditions where the Arrhenius plot may deviate from a straight line [12].

Consider the initial heating of the JSC-1A where increasing temperature provides increasing thermal energy to mobile ions, hopping through defects, to create a conduction current. As a general rule, for every 10ºC increase in temperature, the conduction will double. As we approach the onset of sintering, the contact area between grains increases, lowering the value of Rgb in figure 1. From this point onward as the temperature continues to rise, the conduction current will increase both through increasing thermal activation, and from increasing contact area between grains. The slope of the Arrhenius graph will increase, giving rise to a "convex" Arrhenius plot. Once the JSC-1A has completely melted, only thermal activation will, from that point onward in temperature increase, contribute to the increasing conductivity.

Experimental Setup: To test this idea, a simple setup was constructed using a 20 ml high-alumina combustion boat (CoorsTek P/N 65566) and a parallel plate capacitive electrode sensor. This sensor is made from two strips of type 304 stainless steel each 75mm long, 12mm wide and 0.1 mm thick and is separated by two ceramic insulators each 19mm long and 6.4mm in diameter, fastened to the ends of the parallel strips. Type 304 stainless steel wires 0.5mm in diameter are used to make external connections. The combustion boat and capacitive sensor are shown in figure 2.

Figure 2. Combustion boat and capacitive sensor.

Once the capacitive sensor is placed in the boat, JSC-1A is added until it is level with the top of the boat, with light tamping to level the surface as shown in figure 3. A typical charge is 28.4 grams.

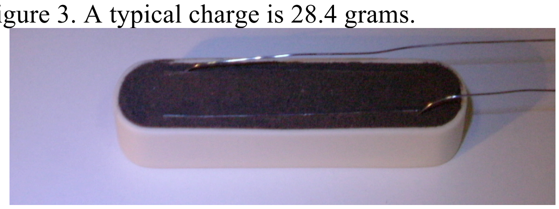


Figure 3. Combustion boat with sensor and JSC-1A.

An in-house constructed tube furnace was used, consisting of a Mullite tube 457mm (18") long with and ID of 31.75mm (1.25") with a 304.8mm (12") hot zone wound with Kanthal A1. Multiple mica end zone baffles provide a ±5ºC uniformity over the central 203mm (8") at a maximum operating temperature of 1175ºC. The loaded boat and baffles are shown being placed into the tube furnace in figure 4.

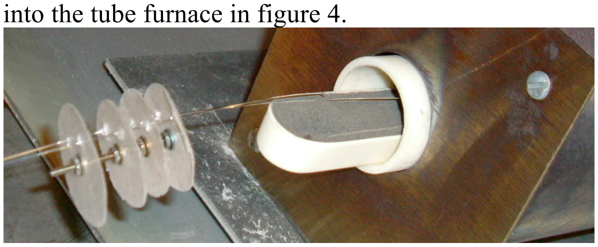


Figure 4. Boat and baffles being placed into furnace.

Conductivity was measured with a Sinometer VC6243 LC meter operating at 1kHz and 500mVpp.

A Hitachi 4800 Scanning Electron Microscope (SEM), provided by Brookhaven National Lab's Center for Functional Nanomaterials was used to image JSC-1A, and figure 5 shows it in a highly sintered state.

Analysis: Figure 6 shows the Arrhenius plot of the sintering of JSC-1A which has a relatively linear graph up to point A (about 1009ºC) where melting begins. Melting is near complete from point B (about 1143ºC) to point C (about 1175ºC, the furnace maximum). Optimum sintering will likely occur over interval A-B.

Conclusions: This initial investigation sought to demonstrate the feasibility of developing an electronic signature which tracks the sintering process as it occurs, and develop an end point detection for optimum sintering. Future work will try to correlate specific sintering morphologies with an electronic signature.

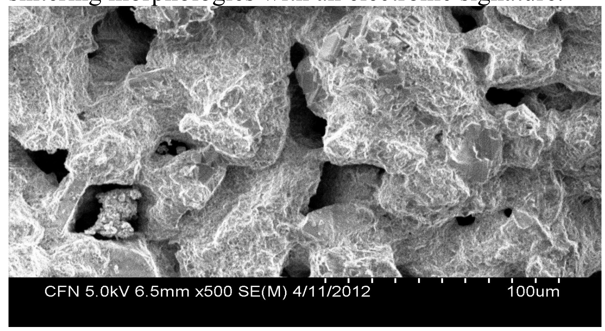


Figure 5. JSC-1A sintered for 1 hour at 1075ºC.

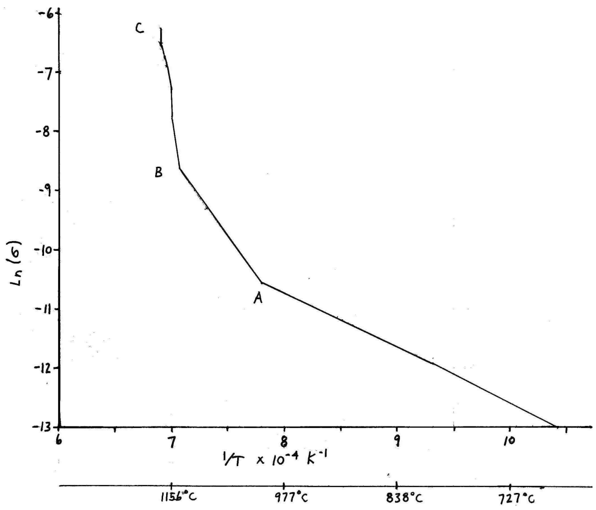


Figure 6. Arrhenius plot of the sintering of JSC-1A.

Acknowledgment: The author is grateful to the Center for Functional Nanomaterials, Brookhaven National Laboratory for access to the SEM, supported by the U.S. Dept. of Energy, Office of Basic Sciences, under Contract No. DE-AC02-98CH10886.

References: [1] Shirley F. et al. (1989) *A Preliminary Design Concept for a Lunar Sintered Regolith Production Facility,* Battelle, Columbus, Ohio. [2] Allen C. A. et al. (1992) *Proc. Space '92, 2,* 1209-1218. [3] Taylor L. A. and Meek T. T. (2005) *J. Aerosp. Eng. 18,* 188-197. [4] Smith B. (2010) *SRR/PTMSS.* [5] German R. M. (1996) *Sintering Theory and Practice,* John Wiley and Sons, NY. [6] Barsoukov E. and Macdonald J. R. (2005) *Impedance Spectroscopy,* John Wiley and Sons, NY. [7] Muccillo R. (2009) *J. Mater. Res., 24,5,* 1780-1784. [8] Talla J. A. et al. (2011) *J. Mater. Res. 26,22,* 2854-2859. [9] Bauerle J. E. (1969) *J. Phys. Chem. Solids 30,* 2657-2670. [10] Bauerle J. E. (1976) *Electrochim. Acta 21,* 303-310. [11] Bruce P. G. (1997) *Solid State Electrochemistry* Cambridge University Press, NY. [12] Truhlar D. G. and Kohen A. (2001) *PNAS 98,3,* 848-851.

POTENTIAL WATER RESOURCE DEPOSITS ON MARS: LOCATION AND SPATIAL RELATIONSHIPS TO REGIONS OF HIGH INTEREST FOR ASTROBIOLOGY AND SAFE SPACECRAFT OPERATIONS

Beaty, David W.[1], Abby Allwood[1], Deborah Bass[1], Jim Head[2], Jen Heldmann[3], Scott Murchie[4], and Jerry Sanders[5], [1]Jet Propulsion Laboratory, NASA/California Institute of Technology, USA, [2]Brown University, USA, [3]NASA Ames Research Center, [4]Johns Hopkins University, Applied Physics Laboratory, USA, [5]NASA Johnson Space Center, USA.

Introduction: Water is the single most important location-dependent resource for a potential future human mission to Mars. Therefore, an important consideration for planning the future exploration of Mars is understanding the location of these deposits, and their relationship to the regions of high scientific interest. The areas of overlap constitute valuable targets for potential robotic exploration in the near term and possible eventual human exploration in the longer term. Consideration of these locations can provide guidance to mission planners and technology developers for key mission parameters like elevation, latitude, terrain roughness, etc.

The Potential Significance of Water-based ISRU: Using the resources at the site of exploration for making mission critical consumables and products could significantly reduce the cost, mass, and risk of the future human exploration of Mars. The ability to manufacture propellants on Mars for crew ascent to orbit is considered mission-enabling. The last NASA human Mars Design Reference Architecture (DRA) 5.0 study concluded that making oxygen for ascent propulsion from carbon dioxide acquired and processed from the Mars' atmosphere could reduce the lander mass by over 30% (or >25 MT). The availability of water on Mars, along with atmospheric carbon dioxide, may be game-changing for the human exploration of the Mars surface. With water, not only might it be possible to produce oxygen life support and propulsion, but also water for the crew's needs, for radiation shielding, and and for fuels such as methane. Production of both oxygen and methane propellants could futher reduce the mass of Mars landers. To be considered a viable resource for processing, the water would need to be accessable, and the energy and mass of the hardware to acquire/process the water would need to be much less than just bringing hydrogen or fuel from Earth.

Water Resource Potential on Mars: We are currerntly aware of three broad classes of water-containing resource deposits of potential interest to the human exploration of Mars:

1. Shallow ice (occurring in several different geologic settings)
2. Surficial deposits of hydrated minerals
3. Potential liquid water in Recurring Slope Lineae (RSL) and possibly gully deposits

Surface Ice: Although the dominant reservoir of water ice is currently the north and south polar layered deposits (PLD), there is evidence that the spin axis-orbital parameters have changed over geologic time, and that variations in obliquity have mobilized polar ice causing it to be redeposited at low latitudes. Evidence for ancient non-polar, ice-rich deposits includes relatively young latitude-dependent mantles, and older pedestal craters, lobate debris aprons, lineated valley fill, and lobate deposits interpreted as tropical mountain glaciers. Remote sensing (neutron/gamma ray spectrometer and shallow radar) and geological observations of superposed craters provide evidence that tens to hundreds of meters of ice-rich material remains in the substrate and accessible in significant quantities at least down to mid-latitudes.

Surficial Deposits of hydrated minerals: The neutron spectrometer survey (Mars Odyssey, launched 2001) discovered large low-latitude regions with enhanced hydrogen concentration. These have subsequesntly been shown by the OMEGA and CRISM spectrometers on MEX and MRO to originate in hydrated minerals, which are interpreted to have formed in liquid water environments. These mineral deposits include phyllosilicates, sulfates, and carbonates, and may they contain enhanced water contents of up to ~13%. The mineral deposits are exposed in low-latitude areas lacking an ice-rich mantle. They are present at the surface, and thus could potentially be mined without need for removal of overburden. Concentrations of hydrated minerals occur at scientifically interesting sites where exploration of deposits possibly recording ancient habitats would be enabled by humans.

Recurring Slope Lineae Deposits – Possible Evidence for Melting Ice: Mid-latitude slope streaks in equator-facing darker areas identified in HiRISE images have a seasonal dependence—they appear and systematically grow in a downslope direction in the summer and fade in the winter. Dozens of known and candidate occurrences all occur between 30°-50° latitude. They occur on sunward-facing slopes and are active during the warmest season. Their form and behavior are consistent with overland brine flows, and they are hypothesized to form from the melting of shallow mid-latitude ice. They have been intensely studied by MRO; besides marking potential shallow ice they are among the most likely current surface habitats for life.

Relationship to areas of scientific interest:

A primary driver for the scientific exploration of Mars is the search for the signs of life, either extinct or extant. The sites of interest to these two options are somewhat different.

Regions of interest to the search for extinct life:

To first order, the presence of water-laid sedimentary rocks serves as a proxy for areas of potential interest in the search for evidence of past life. It is possible to infer the distribution of sedimentary rocks in general from observations of stratified rocks in HiRISE and MOC images, and to identify the subset formed in water from OMEGA and CRISM spectral signatures of aqueous minerals. The depositional environments of many apparently aqueous sedimentary rocks is still uncertain, but their presence serves as a first-pass filter for potential astrobiological interest.

In addition, a number of potentially interesting locations were studied in detail as part of the site selection process for MSL. The science objectives of MSL led to a focus on sites that are potentially very relevant to the search for past life, so the MSL candidate sites represent a relatively small selection of specific sites that are much better understood in terms of their relevance for the search for evidence past life on Mars.

A map of MSL candidate sites plus sedimentary rock outcrops inferred from current orbital data was constructed. Although this set of sites may not be a complete representation of regions of interest for the search for ancient life, it is sufficient to identify many regions where a mission might access suitable rocks in the search for ancient biosignatures.

Regions of interest to the search for extant life: The search for extant life on Mars focuses on regions where liquid water may exist to support the existence of martian biota. Three classes of features on Mars with the highest potential for hosting extant life include 1) gullies, 2) ice, and 3) RSLs. Geologically young martian gullies are primarily found at mid-latitudes and some may have formed by liquid water flowing on the martian surface. Although which were formed by water is debated, some gullies may nonetheless provide a habitable niche for martian life. Ground ice represents another possible martian habitat, particularly where the ice may have been recently warmed to provide meltwater and/or thin films of water to support life. The RSL features are one location where ongoing melting may occur, resulting in possible briny flow features during the warmest parts of the martian year. If this interpretation is correct, then RSLs may be the premier target of interest for extant life.

Planetary Protection Implications: There are important potential relationships between some of these types of resource deposits and planetary protection that may affect when and how they may be accessed by possible future human explorers. In terms of protecting Mars and possible native biota, we need to understand which environmental niches could be occupied by hitch-hiking terrestrial organisms. Of the kinds of deposits mentioned above, current understandings are:

- Terrestrial organisms cannot live in hydrated minerals.
- We do not know of terrestrial organisms that could reproduce in martian ice at martian temperatures. However, they might be able to do so in melted ice, which may be the result of approaching ice with power sources.
- The biological significance of the RSLs is currently almost completely unknown.

Summary and Conclusions: For robotic missions to the martian surface with lifetimes of one Mars year or longer (like MSL), we currently are focused on sites that are within the latitude range 30°S to 30°N (because of thermal design issues associated with surviving the winter), at elevations of -1.0 km or lower (to minimize EDL risk), and that have a relatively smooth, flat place >20 km across in which to land (again related to EDL risk). There are also going to be comparable considerations for the potential future human exploration of Mars.

It is clear from this analysis that there is considerable overlap between regions of interest to the scientific exploration of Mars and the potential sites of future water resources for human exploration. Some of these resources lie within the current latitude and elevation constraints described above. However, many regions of potentially high interest are also located outside these limits. The portfolio of sites for future human exploration would be significantly expanded if technologists developing both ISRU and mission system technologies made these systems viable at expanded latitude limits of 40°S to 40°N, an elevation limit of at least +1 km (crucial to accessing southern latitudes), and at landing sites that have topographic hazards internal to the landing error ellipse. It is also clear that information on the types, distribution, and character of potential water resource deposits needs to be collected to inform future PP policy decisions.

MARS REGOLITH WATER EXTRACTOR. Robert Zubrin, Heather Rose, Christopher Hinkley, and Mark Berggren. Pioneer Astronautics, 11111 W. 8th Ave, Unit A, Lakewood, CO 80215 USA, Zubrin@aol.com

Introduction: The Mars Regolith Water Extractor (MRWE) is a system for acquiring water from the Martian soil. In the MRWE, a stream of CO_2 is heated by solar energy or waste heat from a nuclear reactor and then passed through a vessel containing Martian soil freshly removed from the ground. The hot CO_2 causes water absorbed in the Martian soil to outgas, whereupon it is swept along by the CO_2 to a condenser where ambient Martian cold temperatures are used to condense the water from the CO_2. The Mars Odyssey Neutron Spectrometer data suggests concentrations of water greater than 2 percent in equatorial regions.

The MRWE eliminates the requirement to transport hydrogen to Mars in order to make methane/oxygen propellant, and allows all the propellant needed for a Mars to Earth return flight to be manufactured on Mars using a Sabatier/electrolysis (S/E) cycle, without any need for auxiliary oxygen production. By eliminating the need to transport fuel, oxygen, and water to Mars, the MRWE will have a major effect in reducing the mass, cost, and risk of human Mars exploration.

Pioneer Astronautics carried out a six-month, NASA Johnson Space Center SBIR Phase I program in 2011 to demonstrate proof-of-concept of the MRWE. Robert Zubrin was the Principal Investigator for Pioneer. Aaron Paz was the Contracting Officer's Technical Representative for NASA JSC.

Background: In the Mars Direct plan and the 1993 JSC Design Reference Mission, hydrogen required to support the S/E cycle is transported from Earth. This poses a modest mass issue for these plans, since both of them incorporate a Reverse Water Gas Shift reactor, and thus only need to transport an amount of hydrogen to Mars equal to about 5% of the total propellant produced. However the bulk and hard cryogenic properties of liquid hydrogen impose design complexities on the mission, so much so that some analysts, such as Sanders[1], have defined its transport as a tall-pole concern. However, if water could be obtained on Mars, all of the issues with the S/E cycle would vanish. There would be no need to launch or transport hydrogen across interplanetary space, and the extra oxygen the S/E cycle needs would be provided by electrolysis of the water at the same time that it yields the hydrogen. The question arises, where can we get water on Mars? There is nearly pure water ice near the poles, but we don't want to have to confine our operations to such regions. There is some water in the atmosphere, but only in such dilute quantities (0.01%) as to make its acquisition too energy-intensive to be practical. This leaves the soil.

Analyzing the 2003 water equivalent Hydrogen Abundance data from the Mars Odyssey Neutron Spectrometer shows the water content at the equator between 2 and 10 percent by weight. In approximately half of the equatorial regions of Mars there are areas of higher concentrations averaging 6 to 10 percent water by weight. Data is from The Global Distribution of Hydrogen on Mars[2]. Thermogravimetric experiments on clays (Na and Ca smectites) and a smectite (Chabazite) show that these minerals can load 10-22% of water by mass at the equatorial subsurface conditions of Mars, which may partially explain the observation of high water abundance.

MRWE Hardware: *Figure 1* schematically shows the MRWE system. The arrows correspond to the movement of the carbon dioxide through the MRWE. The pump forces CO_2 into the gas heater, where it is heated before entering the regolith dehydration chamber. The CO_2 then heats the regolith causing the water to vaporize. The mixture of CO_2 and water vapor then move toward the plate heat exchanger where heat transfers to the pure dried CO_2 moving in the opposite direction. The gaseous mixture then moves into the condenser, where the water drops out and moves to the collection tank. The pressure of the system is regulated by the CO_2 tank and thus the overall system pressure can be easily changed.

The MRWE vessel was designed and built in order to limit heat transfer to the regolith dehydration chamber and to concentrate the system's energy on the regolith and the water within that regolith. This regolith dehydration chamber incorporated a double-walled design, in which a vacuum could be pulled between the inner and outer shells (much the same as a thermos). By evacuating the space of all air particles, there are limited conduction paths for the heat to take into the outer, more massive shell. This design aims to reduce heat lost to the environment and to keep the vast majority of the energy in the regolith for vaporizing the water. Exterior insulation was installed on the vessel in order to limit losses from any conductive heat transfer along the inner-to-outer wall connection points.

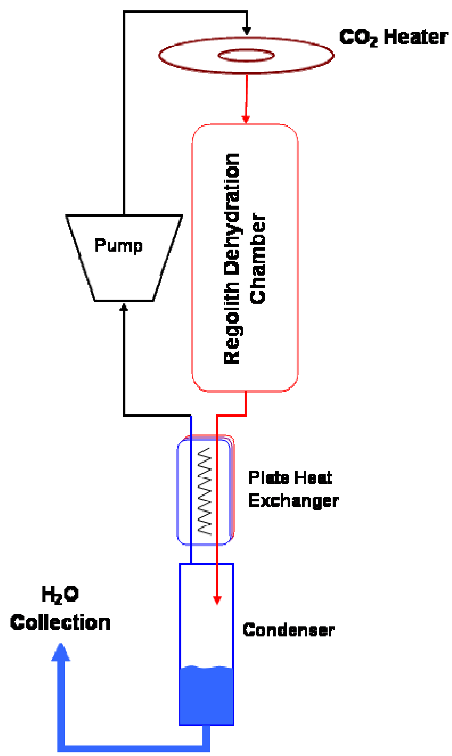


Figure 1: MRWE System Schematic

In order to encourage the heat to move from the center of the vessel through the bulk of the simulant toward the walls, a solid stainless steel disk of slightly smaller diameter than the vessel was added at the bottom of the regolith (resting above a porous zirconia support). *Figure 2* shows how this forces the gas to move radially outward from the gas injection tube and then down through the regolith bed.

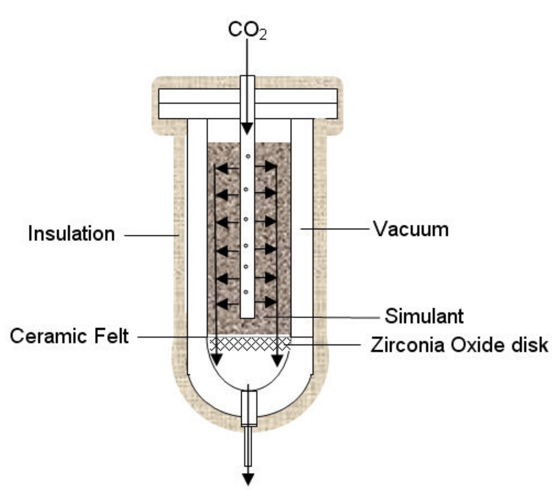


Figure 2: MRWE Vessel Schematic

Experimental: JSC Mars-1 simulant was spiked with water at target concentrations in the five to ten percent range. The water was thoroughly blended into the soil prior to feeding the extraction vessel.

The MRWE was tested over a range of CO_2 flow rates and operating pressures. Vessel temperatures between 240 and 400°C were targeted during the test program. Most of the observed water extraction took place during the first 30 to 60 minutes of a batch cycle.

Operating results showed that higher operating pressures significantly improved water extraction rates. In one of the later experiments at a vessel pressure of about 75 psi and a CO_2 flow, the average water production rate over 60 minutes was about 6 grams per minute. About 90 percent of the available water was extracted.

A systems analysis showed that the MRWE requires about 3 kWe of the total 33 kWe of a complete SE/electrolysis system scaled to support the NASA Design Reference Mission (30 metric tonnes of liquid methane/oxygen propellant). Much of the MRWE electrical power requirements are for the gas compression subsystem.

Conclusions: The Phase I MRWE system produced a maximum water production rate of 337g per hour or roughly 8 kg of water per day using a single pump and a simulant regolith with an initial water concentration of 5 percent. Supported by 1.04kW of electrical pump power, this system yielded a water production rate of 325 g per kWe-h. The MRWE would eliminate the requirement to transport hydrogen to Mars in order to make methane/oxygen propellant, and allow all the propellant needed for a Mars to Earth return flight to be manufactured on Mars using the S/E cycle without any need for auxiliary oxygen. A scaled down version of the MRWE could also produce all of the water needed to enable a Mars Sample Return using *In-Situ* Propellant Production.

The ability to extract water from Mars will also serve to supply the crew of a Mars missions with copious supplies of water itself, which after propellant, is the most massive logistical component of a Mars mission. Eliminating the need to transport fuel, oxygen, and water to Mars, will reduce the mass, cost, and risk of Mars exploration.

References:

[1] Sanders, G. "In-Situ Resource Utilization on Mars – Update from the DRA 5.0 Study," AIAA 2010-799, 48th Aerospace Sciences Meeting, January 4-7, 2010, Orlando, Florida.

[2] Feldman W.C., T.H. Prettyman, W.V. Boynton, S.W. Squyres, D.L. Bish, R.C. Elphic, H.O. Funsten, D.J. Lawrence, S. Maurice, K.R. Moore, R.L Tokar, and D.T. Vaniman, "The global distribution of near-surface hydrogen on Mars", Sixth International Conference on Mars, 2003, Pasadena, California.

INTERFACIAL WATER AS AN ISRU OBJECTIVE: A PROPOSED INVESTIGATION WITH INTERNAL REFLECTANCE SPECTROSCOPY. O. Igbinosun[1] and S. Wood [2] Department of Earth and Space Sciences Box 351310, University of Washington, Seattle WA 98195, [1]osaig@uw.edu, [2]sewood@ess.washington.edu

Introduction: Water on Mars is always of interest to the scientific community but an understanding of how local resources can be utilized for human space missions need also be addressed. ISRU (In-Situ Resource Utilization) can significantly reduce the mass of consumables needed for manned space missions, thus reducing the mass needed to disembark from Earth. Materials for life support (such as oxygen and water), rocket propellant, construction materials, and energy are just a few examples of potential resources.

There are three dominant reservoirs of water on Mars—polar regions, the atmosphere, and the subsurface. However, interfacial water, water that exists at interfaces (i.e. thin liquid films present at the interface between mineral grains and ice) could be a more useful site for extracting consumable water. Spectral data suggests that minerals, such as zeolites, are present on the surface of Mars. Zeolites exhibit a micro-porous structure, providing significant surface area for water adsorption. Conditions that would allow individual mineral grains to maximize water adsorption could potentially hold up to ~1.5 times their weight in water (e.g. a kg of soil yields 1.5 kg water).

Studies have shown that extracting atmospheric water vapor via molecular sieve adsorption at Mars conditions is feasible [1], but the volume of water acquired from the atmosphere would not be sufficient to support manned missions. This is due to the paucity of water available in the atmosphere of Mars (~10 precipitable microns [global annual average] [8]). WEH (water equivalent hydrogen) values equator-ward of the polar regions suggest significant amounts of water in the near surface. However, the availability of this water and its extractability is unknown.

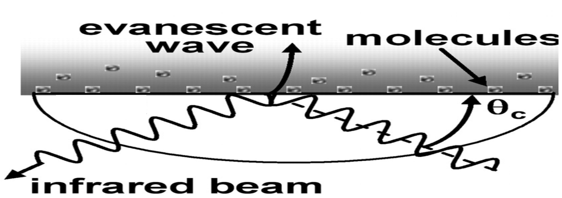


Fig.1

Methods: Internal reflection spectroscopy (IRS) exploits the evanescent field of internally reflected light (Fig. 1). As light is attenuated by a surrounding medium, an absorption spectrum of the medium can be obtained. Room temperature observations of water adsorption on silica surfaces utilizing IRS via a silicon crystal have been performed [2]. These experiments show that adsorbed water can be quantified at a range of relative humidities (Fig. 2). Modifying this technique to include fiber optic cables will allow us to determine how much adsorbed water exists during a diurnal temperature cycle on Mars. Premilinary results show a strong absorption via the evanescent field at 1935 nm (asymmetric stretch/bend) of water for a 15cm declad section at room temperature (Fig. 3).

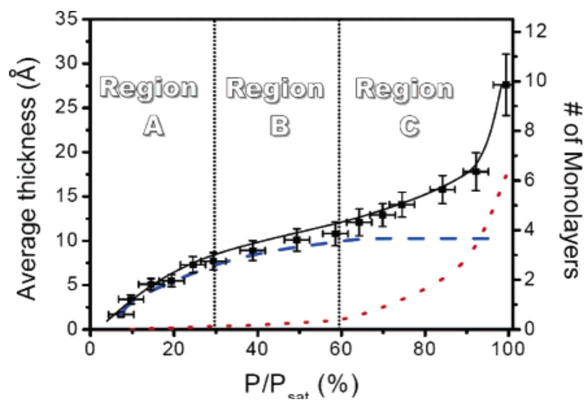


Fig. 2 [2]

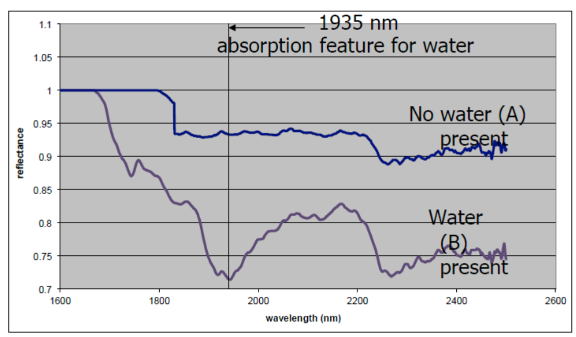


Fig. 3

Quantification of adsorbed water layer structure will be achieved by in situ observation of Mars soils at appropriate environmental conditions. Adsorption processes will be observed using fiber optical cables coupled to a spectrometer to observe changes in discreet O-H stretching/bending absorption bands (e.g. 3230, 3400, and 1630 wave numbers). Data collected from this experiment will be used to model adsorption water layer structure relative to water vapor partial pressure and temperature on diurnal time scales. The stability of these layers on temporal timescales can indicate how much water could be available for mining purposes.

References:

[1]Schneider, M. (2003). "Experimental Investigation of Water Vapor Adsorption by Molecular Sieve Zeolite 3A under Simulated Martian Atmospheric Conditions". MS thesis.[2]Asay and Kim (2005) J.Phys.Chem,109,16760-16763. [3] Janchen et al (2006) Icarus, 180, 353-358.[4]Anderson and Morgenstern (1973) Permafrost:Second International Conference Proceedings, 257–288. [5]Rivkina et al (2000) Appl Environ Microb, 66 (8), 3230–3233. [6]Ostroumov and Siegert. (1996) Adv Space Res. 18(12), 79–86. [7]S.J. Gregg and K.S.W. Sing, Adsorption, Surface Area and Porosity, 1982. [8] Smith (2002)JGR107(E11),5115,doi:10.1029/2001JE001522, 2002. [9] Feldman, W. C., et al. (2004), Global distribution of near-surface hydrogen on Mars, J. Geophys. Res., 109, E09006, doi:10.1029/2003JE002160.

TITLE: Charming Asteroids & Comets - The HUMMINGBIRDS/CHARM (HC) Asteroid/Comet Engineering Science Service (ACESS) Missions

A concept is described for multiple missions that will intercept and "interview" target NEOs/NEAs. The "charming" aspect of this concept is the requirement that we send a minimum of 2 vehicles to each target. A Charm is a gathering of Hummingbirds. The HC missions are intended to meet the clear guidance driven by the NEO/NEA communities; "Observe & Touch" and provide this capability "Early & Often". There are several excellent mission concepts coming forth to meet the remote "observational" need, for example NeoCAM and NESS. The HC missions are intended to meet the "tactile", "touch" component. "Early" and "often" drives the need for Overwhelmingly Cost Effective (OCE) systems requiring simplification and reduced complexity and necessitates that there need be a "many-off", production mode approach implemented in spacecraft design, build, and availability. HC is highly motivated by the concept of providing a "service" to the NEO/NEA communities. HC enables unique opportunities at each target in providing complete characterizations of target properties. Each "charm" includes a Touch & Go vehicle (TAG) that "flits" in close to the target and provides up-close visual and tactile data along with an Observer/Communications (ObsComm) vehicle that relays both TAG and ObsComm video along with instrument data streams from both vehicles. Modern technologies in avionics for spacecraft control, communications, and navigation permit the Hummingbird to be small enough that multi-spacecraft missions can be launched on the more moderate-sized rockets. Since the Hummingbirds vehicle designs are identical, no redundancy is implemented in their design, thus reducing the cost of implementing that complexity. The complete application and advantages in using Hummingbirds/Charm concept in small body missions are covered in the paper.

PROPERTY CLAIMS TO SPACE RESOURCES, THE LAW, AND THE FUTURE OF PROPERTY RIGHTS IN SPACE G. W. Nemitz. Orbital Development, 148 Blue Lakes Blvd N. #112, Twin Falls, Idaho 83301 nemitz@orbdev.com

Introduction: The presentation will briefly review a property claim that was made, and the lawsuit that followed[1]. Then discuss the OST of 1967 and the Moon Treaty in relation to private property claims. Continues with speculation on how officially recognizable claims may be established; and in summary, outlines the two most likely answers to the question of private property in space.

References: [1] Nemitz G. W. (2001-2003) http://www.erosproject.com.

SPACE / MULTI WORLD PROPERTY RIGHTS, 2012-2015: When, Where, How? Steve Durst, International Lunar Observatory Association (ILOA), 65-1230 Mamalahoa Hwy D20, Kamuela HI 96743, USA, info@iloa.org, 808-885-3474

Physical presence at extra-terrestrial bodies is likely the single most important factor in property rights realization ("Possession is 9/10ths ..."). When, Where and How physical presence / property rights determination likely will occur can be anticipated: In 2012, on Mars, USA Rover Opportunity from 1 January, and USA Lander / Rover Curiosity NET 6 August; in 2013, on Moon, PRC Lander / Rover Chang'e-3 near Equator; in 2014, on Moon, GLXP Independent, Private Landers / Rovers near Equator, at South Pole, and India-Russia Chandrayaan-2; in 2015, on Moon, ILOA Lander Observatory at South Pole / Mons Malapert, and GLXP Independent, Private Landers / Rovers.

The justification, basis, and principle on which Space / MWPR are claimed is primary to the realization and success of the appropriating individual. Claims of Moon and / or Mars acreage and of individual asteroids will be strongest, most effective, enduring, productive and successful when based on the most fundamental and dominant American, Western, and Universal secular principles of Liberty / Freedom and Equality / Justice. The first of the 'truths self-evident" in the USA Declaration of Independence, as well as founding principles of the UN Charter, liberty and equality together safeguard the imperatives of individual freedom and common heritage so necessary for the strongest realization of MWPR -- on Moon, Mars, asteroid or beyond.

When the ILO-X Precursor aboard the Moon Express 1 lander touches down on the Moon in 2014, the initials 'SD' on one of the lander legs will serve as initial enabling claim to ownership of 1 acre of the lunar surface, supported by the strongest Libertarian / Egalitarian principled justification for my 1-acre claim, or for any other 1-acre claimed by any of Earth's 7+ billion individuals.

Abstract

THE SPACE PIONEER ACT

By

Wayne N. White, Jr.

SpaceBooster LLC
318 Isleta Blvd. SW
Albuquerque NM 87108
wnwhite@spacebooster.com

This presentation will explain the elements of the Space Pioneer Act. The Space Pioneer Act is draft legislation to enact mining law, salvage law, and real property rights to enable and encourage private development and settlement of outer space.

Planetary Resources Pre-Posession: That other 1/10th of the law

Charles Wesley Faires[1]
[1]Private Sector Delegate - 47th Legal Subcommittee - United Nations Committee on Peaceful Uses of Outer Space
(2065 Country Ridge Road, Milton, Georgia 30004 USA)
E-mail: wes@orions-belt.com

Formal Recognition: As mankind prepares to accept the task of launching commercial interests off-planet, it is our responsibility to ensure that the transition occurs free of any Earthly shackles. To this end, my contribution concerns an issue at the heart of Outer Space legislation, whose implications affecting a core foundational element of private space-faring interests have persisted for the better part of a century. Since 1967, one question, answer to which affects the whole of humanity on an infinite scope, has been a thorn in the side of space law: Does the Outer Space Treaty outlaw off-planet property for private citizens, or does it not? Private property rights were neither provided for or deemed unlawful within the text of Article II of the 1967 Outer Space Treaty. For 50 years, however, the debate has raged on. It is my aim to forever lay this controversy to rest with a definitive answer based not on treaty opinions or citations, but documentary evidence, utilizing appropriate legal channels leading to a decision executed by the competent authority responsible: A formal determination on the legality of a private individual's claim to property on a celestial body under the Outer Space Treaty, was officially rendered.

The Truth On Space Property: Through issuance of The Great Seal of the USA, the legal validity of a document claiming private ownership of off planet resources was determined in 2008 by the Secretary of State who, in full faith and credit, deemed the document fit for international legal use[1]. Such formal Authentication affirms that no part of the document conflicts with any domestic or international statutesxxx; global responsibility for authorization and continuing supervision is upheld by the arm of the US government charged with the task of interpreting and applying treaty law in a manner consistent with the corresponding interests of all states party[2]. A private sovereign claim to celestial body, this legal instrument was executed in absolute compliance with the Outer Space Treaty, setting precedent as *prima facie* evidence that such claims are **legal under the current framework.** A major roadblock now removed, this can serve as a stepping stone as the concept of private sovereignty beyond national borders begins to solidify. Instead of being killed in the cradle, there is infinite room for the application of the human right to property throughout the cosmos. The remaining sections cover potentialavenues for growth, and the hindrances that should be dealt with in a timely fashion.-

Forward progress at the National Level: The Space Settlement Initiative's proposal calls for new entities on the national level emerging to administer celestial property claims[3], however, the full scope of "National Appropriation" forbidden by the Outer Space Treaty has not been defined. Without clear definition of "national appropriation," it is unclear to what extent forward progress on a national level is hindered. In the Law of the Sea Treaty, "appropriation" is defined as exercise of sovereignty[4]. Further steps toward recognition of mineral claims through national legislation was not explicitly ruled out. The USA enacted the Deep Sea-Bed Hard Minerals Act (DSHMA), whose function was to recognize territorial claims by private entities on the ocean floor under international waters without assertion of sovereignty[5]. The precedent set by the DSHMA is not so easily rubber-stamped into similar national legislation concerning Outer Space. The scope of "national appropriation" is not spelled out in the Outer Space Treaty. It is possible that *any and all* new legislation enacted on the national level designating an existing agency with the task of recognizing off-planet property claims would be in violation of the non-appropriation clause in Article II. Without clear definition of "national appropriation," it is unclear to what extent forward progress on a national level is hindered.

Supranational Threats to Sovereignty: Though seeds have been planted, a regime charged with task of managing property and mineral claims on celestial bodies does not exist within the framework of the United Nations[6]. The only supranational entity concerned with territorial claims outside national borders is the International Sea Bed Authority, its powers designated within the Law of the Sea Treaty, whereby the deep sea-bed is governed by the Common Heritage principle - Private property is outright forbidden, private citizens placed under the authority of a top-down regime[7]. The Moon Treaty threatens to apply this same kind of governance across the solar system[8], and contrary to popular belief, *is* a "treaty in force", and *is* gaining signatories and support on a yearly basis. A new treaty, favorable to property rights, would require unanimous consent within UNCOPUOS - Such a treaty would conflict with the interests of the Moon Agreement's 13 or so signatories. As long as this treaty is in force, hope for a commercially viable solution under the framework of the United Nations is mathematically impossible.

Conclusion: Having at last confirmed the legality of off-planet private property claims under the current legal framework, further action is needed to ensure the interests of the private sector, favorable to property rights, are reflected in future legislation. We should think twice about pressing for such action on the national level, as this may constitute exactly the type of "national appropriation" that is prohibited in the Outer Space Treaty. <u>It is time for direct action by private citizens on the international level.</u> Here, the legislative climate affecting individual sovereignty beyond national borders is downright hostile. Treaty law negatively affecting off-planet property rights must be eliminated at the source. Decisions affecting humanity as a whole shall no longer be rendered in proceedings closed to the public. The only way to fully insure our interests are protected is through establishment of a permanent platform through which private citizens/natural persons may interact directly with the treaty-making process of the United Nations Committee on Peaceful Uses for Outer Space.

References:

[1] US Department of State Authentication #09005779-1 11/21/08

[2] Treaty on Principles Governing the Activities of States in the Exploration and Use of Outer Space, including the Moon and Other Celestial Bodies, *Article VI*

[3] Space Land Claim Recognition: Leveraging the inherent value of Lunar land for billions in private sector investment by Douglas O. Jobes and Alan B. Wasser, The Space Settlement Institute, 2008. (www.space-settlement-institute.org/Articles/LCRbrief.pdf)

[4] Third United Nations Convention on the Law of the Sea (henceforth, UNCLOS) *Art. 137, para. 1*

[5] 30 USC Chapter 26 – Deep Sea Bed Hard Minerals Act

[6] Agreement Governing The Activities Of States On The Moon And Other Celestial Bodies (1979), Art. XI para. 5

[7] UNCLOS *Art. 136, Art 137, para. 2-3*

[8] Agreement Governing the Activities of States on the Moon and Other Celestial Bodies, *Art. I (scope), Art. XI (governance)*

Update on SASRA activities for 2011/2012. A.M. Neale, SASRA (president@sasra.co.za)

Introduction: The South African Space Resources Association (SASRA) was founded as a voluntary association on 19 February 2011. The initiation of SASRA was presented at the PTMSS/SRR in June 2012[1]. Since that time SASRA has been registered as a non-profit company, has seen a number of successes, and has initiated a couple of additional projects. This paper compares SASRA's current state with its goals presented in June 2012, and discusses its challenges and way forward.

Reconciliation of objectives and projects: SASRA was founded with three objectives, and the non-profit company adopted these objectives with slight modification.

- Awareness (5 successes)
- Technical contribution (3 successes)
- Education (2 successes)

The "future" project presented in 2011[1] is listed below, with its updated statuses:

Project	Status
Structural lunar soil simulant	Delayed pending prototype lunabot
PISCES student design	Shelved
NASA lunabotics	In progress
Paper on lunar mine design, possibly sand mining	Completed
Paper on evaluation of pneumatic excavator	Shelved
Mining innovation overlap	Restructured

Achievements to date: SASRA is an opportunity based organization, and has worked on a number of endeavors which could not have been planned for. These are mentioned below.

- Conference presentation at the "Robotics and Mechatronics Conference of South Africa 2012", with the paper entitled "Space Mining Application for South African Mining Robotics"[2].
- The above paper is to be republished as an article in the robotics edition of EngineerIT. That edition of EngineerIT includes an article where the author was one of the interviewees
- Dual author conference paper at AIAA, entitled "A Mining Engineering Approach to Mining Lunar Regolith"[3].
- SASRA co-hosted a robotics evening with the CSIR and IEEE. The evening included a presentation by the author on "The Ingredients of a Space Faring Civilization" and tele-operation demonstration with PISCES.
- Two articles in "Mining Weekly", with the author as the the main interviewee[4,5].
- A software application on the NASA Lunabotics was developed and donated to the competition, resulting in Bronze Sponsor status for SASRA
- Started looking for Earth investors for Space Mining Technologies. A paper submitted to SRR/PTMSS this year details the initial work.
- Successfully hosts 1 social event per month, with the technical meetings running in between.
- Established social media channels (ie Facebook and Twitter) to spread awareness.

Current and future projects: A number of projects have been taken on, the progress of which will be presented:

- Ore Genesis: An educational game based on the "Alchemy" concept. This game is aimed at teaching the players about space mining, and acts as a conceptualization tool for more advanced games and simulations.
- Mxit University. A learning platform targeted at the demographic with little access to bandwidth and/or without smart phones. The concept can be migrated to more sophisticated platforms at a later stage. This vehicle is also intended to train and grade SASRA members on Space Mining knowledge.
- Lunabot: SASRA is building a prototype Lunabot, with the intention of attracting interest in the NASA Lunabotics.
- Space Mining Wiki: An online collaborative effort to capture the literature and news regarding different aspects of Space Mining
- Earth Application: continued work looking for Earth clients interested in Space Mining Technologies

Challenges and the way forward: SASRA is experiencing a number of challenges. The proposed solution is a mindset change towards being more business orientated. The mindset change is discussed in the presentation. The challenges are listed below.

- Time (voluntary part time company)
- No remuneration for people doing work
- Little money to invest in projects
- Lack of member involvement
- Lack of members benefit

Conclusion: The 2011/2012 year has been rewarding for SASRA, even if all the planned tasks were not completed. Challenges are foreseen for the 2012/2013 year, but plans are in place to deal with the challenges.

References:

[1] Neale, A.M. (2011) *South Africa Awakens to Space Resources.* 2^{nd} PTMSS/SRR. Ottawa, Ontario.

[2] Neale, A.M. (2011) *Space Mining Application for South African Mining Robotics.* RobMech. Pretoria.

[3] Kluge, P. and Neale, A.M. *A Mining Engineering Approach to Mining Lunar Regolith.* 50^{th} AIAA ASM. Nashville.

[4] *Mining Weekly (2011) Mining engineer wants SA to position itself as a mining-in-space resource hub.* 2 September.

[5] *Mining Weekly (2012) Advances in autonomous robots seen as key to unlocking asteroid mining*. 10 February.

2012 NASA Lunabotics Mining Competition: Taxonomy and Results

Robert P. Mueller[1] and Gloria A. Murphy[2]

[1]Surface Systems Office, National Aeronautics & Space Administration (NASA) Kennedy Space Center, FL 32899, USA

[2] Education Programs & University Research Division, National Aeronautics & Space Administration (NASA), Kennedy Space Center, FL 32899, USA

NASA's Lunabotics Mining Competition is designed to promote the development of interest in space activities and STEM (Science, Technology, Engineering, and Mathematics) fields. The competition uses excavation, a necessary first step towards extracting resources from the regolith and building bases on the moon. The unique physical properties of lunar regolith and the reduced 1/6th gravity, vacuum environment make excavation a difficult technical challenge. Advances in lunar regolith mining have the potential to significantly contribute to our nation's space vision and NASA space exploration operations.

The competition is conducted annually by NASA at the Kennedy Space Center Visitor Complex. The teams that can use telerobotic or autonomous operation to excavate a lunar regolith geotechnical simulant, herein after referred to as Black Point-1 (or BP-1) and score the most points (calculated as an average of two separate 10-minute timed competition attempts) will win the on-site mining category of the competition and earn points towards the *Joe Kosmo Award for Excellence* and the scores will reflect ranking in. The minimum excavation requirement is 10.0 kg during each competition attempt and the robotic excavator, referred to as the *"Lunabot"*, must meet all specifications.

We will review each Lunabot design fielded in the 2012 NASA Lunabotics Mining and classify them in a taxonomy. By providing a framework for robotic design and fabrication, which culminates in a live competition event, university students have been able to produce sophisticated lunabots which are tele-operated or autonomous. Multi-disciplinary teams are encouraged and the extreme sense of accomplishment provides a unique source of inspiration to the participating students, which has been shown to translate into increased interest in STEM careers.

Our industrial sponsors and partner organizations (Caterpillar, Newmont Mining, Harris, Honeybee Robotics, USA, AIAA, ASCE) have all stated that there is a strong need for skills in the workforce related to robotics and automated machines. In 2012, over 59 university teams from 8 countries participated. More students and the public were engaged via internet broadcasting and social networking media. This is expected to be of value for actual future space missions, as knowledge is gained from testing many innovative prototypes in simulated lunar regolith.

More information is available at www.nasa.gov/lunabotics/.