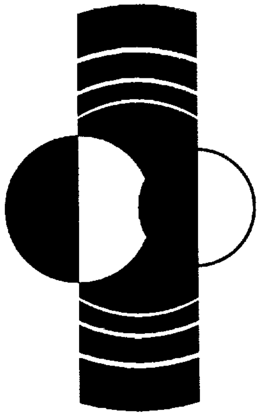

SPACE RESOURCES UTILIZATION ROUNDTABLE

October 27–29, 1999

Colorado School of Mines
Golden, Colorado

LPI Contribution No. 988

Space Resources Utilization Roundtable

October 27–29, 1999

Colorado School of Mines
Golden, Colorado

Sponsored by

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PREFACE

This volume contains abstracts that have been accepted for presentation at the Space Resources Utilization Roundtable, October 27–29, 1999, in Golden, Colorado. The program committee consisted of M. B. Duke *(Lunar and Planetary Institute)*, G. Baughman *(Colorado School of Mines)*, D. Criswell *(University of Houston)*, C. Graham *(Canadian Mining Industry Research Organization)*, H. H. Schmitt *(Apollo Astronaut)*, W. Sharp *(Colorado School of Mines)*, L. Taylor *(University of Tennessee)*, and a space manufacturing representative.

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

AGENDA

	WEDNESDAY, OCT. 27	THURSDAY, OCT. 28	FRIDAY, OCT. 29
7:30 a.m.	Registration, Breakfast	Breakfast	Breakfast
8:30 a.m.	Welcome, T. Bickart, President, Colorado School of Mines Introduction to Workshop, M. Duke Space Mining, N. Melnikov & Nagovitsyn New Space Industries, D. Smitherman	Mining, Processing - Lunar Regolith, L.Taylor - Lunar Geophysical Exploration, K. Stokoe et al - Lunar exploration strategies, K. Joosten Mining technology - Mining Lunar ice, R. Gustafson - Safety, W. Sharp et al	Working Group Wrap-ups - Exploration - Mining - Refining/processing - Transportation/ Infrastructure - Economics/Legal - Manufacturing
10:00 a.m.	Break	Break	Break
10:15 a.m.	Working groups - Exploration - Mining - Refining/processing - Transportation/ Infrastructure - Economics/Legal - Manufacturing	Transportation, Infrastructure - Space Tourism, T. Rogers - Reusable space transportation – Lockheed-Martin - Program architecture, S. Nozette - Space-based economy, N. Komerath et al - Lunar missions, P. Lowman	Making Space Resources into a Respected Discipline - NASA's ISCP program, G. Sanders Panel - H. Schmitt - A. Binder - M. Duke - J. Lewis
12:00 p.m.	Lunch, H. Schmitt	Lunch, A.Binder	Lunch
1:30 p.m.	Exploration - Asteroids, K. Reed - Asteroids, S. Ostro - Asteroids, R. McMillan - Asteroid Exploration, E. Reitman - Asteroid materials extraction, J. Lewis	Working groups - Exploration - Mining - Refining/processing - Transportation/Infrastructure - Economics/Legal - Manufacturing	Close
3:00 p.m.	Break	Break	
3:15 p.m.	Economics, Legal - Lunar Power System, D. Criswell - Resource ownership, D. O'Donnell - Mineral economics, B. Blair - The View from Merrill Lynch, T. Forman	Manufacturing - Acoustic shaping, S. Wanis & N. Komerath - Combustion processing, F. Schowengerdt - Solar energy conversion H. Perko - Plasma refining technology, K. Prisbrey - Technology for PV production, N. Marzwell	
5:00 p.m.	Reception	Taking Stock	
6:00 p.m.	Dinner Working Group meetings	Dinner + Program – W. Mendell	

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ECONOMICS OF LUNAR MINERAL EXPLORATION

Brad R. Blair
Division of Economics and Business
Colorado School of Mines

ABSTRACT

Exploration of space is increasingly being rationalized by the potential for long-term commercial payoffs. The commercial use of lunar resources is gaining relevance as technology and infrastructure increase, and will depend on an adequate foundation of geological information. While past lunar exploration has provided detailed knowledge about the composition, geologic history and structural characteristics of the lunar surface at six locations, the rest of the Moon remains largely unexplored. The purpose of this paper is to describe traditional methods and decision criteria used in the mineral exploration business.

Rationale for terrestrial mineral exploration is firmly entrenched within the context of economic gain, with asset valuation forming the primary feedback to decision making. The paper presents a summary of relevant knowledge from the field of exploration economics, applying it to the case of space mineral development. It includes a description of the current paradigm of both space exploration and terrestrial mineral exploration, as each pertains to setting priorities and decision making. It briefly examines issues related to space resource demand, extraction and transportation to establish its relevance.

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Lunar Solar Power System and Lunar Development

Dr. David R. Criswell
16419 Havenpark Dr., Houston, TX 77059-6010
281-486-5019 (ph. & fax), dcris@swbell.net

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The LSP System consists of pairs of bases on opposing limbs of the Moon that capture sunlight, convert solar power to microwaves, and beam the power to receivers on Earth called rectennas. Redirector satellites in orbit about Earth can provide load-following power to receivers that cannot view the Moon. The low intensity beams, 5 to 20% the intensity of sunlight, are unaffected by rain, clouds, or dust. A person can obtain 2 kWe from only 10 m^2 of rectenna surface when the beam operates at ~ 200 We/m^2 or ≤ 20% of the intensity of sunlight (1, 2, 3).

Studies indicate that a demonstration LSP can supply energy at lower cost (≤ 3 ¢/kWe-h) than conventional terrestrial options such as fossil, nuclear, or terrestrial solar plants (4). LSP can provide greater levels of power (≥ 20,000 GWe) than all other proposed large-scale systems. The mature LSP can provide power at ≤ 1 ¢/kWe-h, possibly much less. Note that 1 ¢/kWe-h implies ~200 $/Y-person for 2 kWe/person. Low-cost, abundant, and clean electric power can stimulate economic growth and benefit human health in the Developing Nations.

The Moon exists. Small factories can be sent to the Moon that output 100s to 1000s of times their own mass in power collection and transmission systems. The LSP components are built on the Moon directly from lunar materials and installed on the Moon near where they are built.

LSP installations create huge net new wealth on the Moon. Suppose, averaged over 100 years, that the LSP System sells 20,000 GWe at 1 ¢/kWe-h to rectennas in the rectennas on Earth. Gross sales are 1.7 T$/Y. Costs will be ~ 0.1 T$/Y. Net profit, before taxes, is ~ 1.6 T$/Y. The 100 year-long cash stream has a present value of 25 T$ at a 7%/Y discount rate (5).

Suppose 10% of the stock is held by LSP employees who organize, build, and operated the lunar power bases. At any one time approximately 25% would be on the Moon. Their present discounted value would be ~ 125 M$/person and their annual earning would be ~ 8 M$/Yr. The following table shows the per capita wealth on the Moon resulting from a distribution of wealth characteristic of a high technology economy. The per capita "human resource" value is slightly higher than major sports figures in the United States and considerably lower than Mr. William Gates and other major early investors and employees of *Microsoft*. If 100 million Earthlings bought 30% of the stock at $20,000/person their ROI would be ~ 4,900$/Y or 24%/Y.

The LSP Systems are based on well understood technologies in electronics, radar, conventional materials and manufacturing. Most of the key demonstrations can be done on Earth (6). Many key demonstrations have already been performed (7). The LSP

System can enable humanity to begin producing net new wealth from clean, abundant, and affordable net new solar electric energy.

2050 Wealth per Person	Average Total $	human resources	produced assets	natural resources
LSP/Moon	$\$120 \bullet 10^6$	$\$100 \bullet 10^6$	$\$22 \bullet 10^6$	$\$12 \bullet 10^6$

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SPACE RESOURCE ROUNDTABLE RATIONALE. Michael B. Duke, Lunar and Planetary Institute and the Colorado School of Mines.

Recent progress in the U. S. Space Program has renewed interest in space resource issues. The Lunar Prospector mission conducted in NASA's Discovery Program has yielded interesting new insights into lunar resource issues, particularly the possibility that water is concentrated in cold traps at the lunar poles. This finding has not yet triggered a new program of lunar exploration or development, however it opens the possibility that new Discovery Missions might be viable. Several asteroid missions are underway or under development and a mission to return samples from the Mars satellite, Phobos, is being developed. These exploration missions are oriented toward scientific analysis, not resource development and utilization, but can provide additional insight into the possibilities for mining asteroids. The Mars Surveyor program now includes experiments on the 2001 lander that are directly applicable to developing propellants from the atmosphere of Mars, and the program has solicited proposals for the 2003/2005 missions in the area of resource utilization. These are aimed at the eventual human exploration of Mars. The beginning of construction of the International Space Station has awakened interest in follow-on programs of human exploration, and NASA is once more studying the human exploration of Moon, Mars and asteroids. Resource utilization will be included as objectives by some of these human exploration programs. At the same time, research and technology development programs in NASA such as the Microgravity Materials Science Program and the Cross-Enterprise Technology Development Program are including resource utilization as a valid area for study. Several major development areas that could utilize space resources, such as space tourism and solar power satellite programs, are actively under study.

NASA's interests in space resource development largely are associated with NASA missions rather than the economic development of resources for industrial processes. That is why there is an emphasis in NASA programs on propellant production on Mars – NASA plans missions to Mars, so could make use of those propellants. For other types of applications, however, it will be up to market forces to define the materials and products needed and develop the technologies for extracting them from space resources. Some leading candidates among the potential products from space resources are propellants for other space activities, water from the Moon for use in space, silicon for photovoltaic energy collection in space, and, eventually, ^{3}He from the Moon for fusion energy production.

As the capabilities for manufacturing materials in space are opened up by research aboard the International Space Station, new opportunities for utilization of space resources may emerge. Whereas current research emphasizes increasing knowledge, one program objective should be the development of industrial production techniques for space. These will be based on the development of value-added processing in space, where materials are brought to the space facility, processed there, and returned to Earth. If enough such space processing is developed that the materials transportation requirements are measured in the hundreds of tons a year level, opportunities for substituting lunar materials may develop.

The fundamental message is that it is not possible to develop space resources in a vacuum. One must have three things: a recoverable resource, technology to recover it, and a customer. Of these, the customer probably is the most important. All three must be integrated in a space resource program. That is what the Space Resource Roundtable, initiated with this meeting, will bring together.

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Successfully Mining Asteroids and Comets

Dr. Leslie Gertsch, Michigan Technological University
Abstract for Space Resources Utilization Roundtable
Colorado School of Mines
October 1999

Many "minor" solar-system bodies contain substantial resources that are necessary for developing and maintaining robust human activity in space. Whether asteroids and comets in near-Earth space contain mineable reserves instead of just mineral resources depends on two factors -- economics and technology -- that will determine the success or failure of long-term space activity, just as they determine the success or failure of industries on Earth.

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LUNAR POLAR ICE: METHODS FOR MINING THE NEW RESOURCE FOR EXPLORATION

Robert J. Gustafson (gustafsonr@orbitec.com) and Eric E. Rice (ricee@orbitec.com)
Orbital Technologies Corporation (ORBITEC™)
Space Center, 1212 Fourier Drive, Madison, Wisconsin

Introduction: The presence of ice in permanently shadowed depressions near the lunar poles and determination of its properties will significantly influence both the near- and long-term prospects for lunar exploration and development. Since data from the Lunar Prospector spacecraft indicate that water ice is likely present (the instrument measures hydrogen which strongly suggests the presence of water), it is important to understand how to extract it for beneficial use, as well as how to preserve it for scientific analysis. Two types of processes can be considered for the extraction of water ice from the lunar poles. In the first case, energy is transported into the shadowed regions, ice is processed in-situ, and water is transported out of the cold trap. In the second case, ice-containing regolith can be mined in the cold trap, transported outside the cold trap, and the ice extracted in a location with abundant solar energy. A series of conceptual implementations has been examined and criteria have been developed for the selection of systems and subsystems for further study.

Background: The Moon is an attractive source of resources for the development of near-Earth space and beyond because it is close to Earth, has a small gravity field, and contains most of the elements important in the development of space capabilities. The most significant problem of lunar development is the scarcity of fuel for spacecraft. Although oxygen is present in abundance in the minerals of the lunar regolith, no concentrated source of hydrogen or hydrocarbon fuels is known to exist. If rocket fuel must be imported from the Earth to launch payloads from the Moon, it is very difficult to devise a low-cost Moon-to-space transportation system. However, if both fuel and oxidizer can be obtained locally, a reusable transportation system that can reach Moon-orbit space at low cost may be feasible. This is the promise of lunar water ice. Water can be electrolyzed on the Moon or in space to support a low-cost, Moon-based transportation system.

Models for the existence of ice in permanently shadowed polar cold traps have been discussed for nearly 40 years. The plausible sources of water on the Moon are micrometeoroids, the reaction of solar wind protons with the lunar surface, and comets. To understand the likely form and properties of the lunar ice, one must consider the rates of accretion of water to the Moon, losses during ballistic migration of water molecules across the lunar surface to the cold traps, losses from the cold traps, and regolith interactions.

The existence of water ice on the Moon could represent relatively pristine cometary or asteroid material that has existed for millions or billions of years. Robotic sample return missions or in-situ sampling and study would determine the characteristics of the ice. Information on the net accretion rate, the composition, and the distribution of the ice may provide more information about sources of water on the Moon. Measurement of the lunar ice deposits will help scientists to constrain models of impacts on the lunar surface and the effects of meteorite gardening, photdissociation, and solar wind sputtering. In particular, it may be possible to deduce compositional information about comets from ice layers, if these have been preserved from the impact of large comets on the Moon. Water ice on the Moon represents a valuable resource for scientific investigation and future space exploration.

Ice Recovery Approaches: There are three basic approaches to extracting lunar ice. The first involves the in-situ heating of ice/regolith without excavation. The ice is heated and water vapor is collected at the surface by freezing, so that it can be hauled mechanically out of the shadowed area, or liquid or gaseous water is transported by pipeline from the cold trap. The second approach is to excavate the ice/regolith mixture, but process it in a furnace situated in the cold trap, transporting liquid or gaseous water from the cold trap to a collection site outside of the shadowed area. A third option is to excavate the ice-rich regolith and transport it from the cold trap to a sunlit area for processing.

Each of the ice recovery approaches considered is composed of several elements:

- *Ice/Regolith Preparation or Collection* - This includes any conditioning of the lunar ice and regolith that is required before it can be processed. It also includes the collection of the ice-rich regolith and placement in the reaction chamber, if required.
- *Energy Source* - This is the source of all the energy required in the extraction process. Energy requirements include the excavation equipment,

reaction chamber, and transportation before and/or after processing.

- *Energy Delivery to Shadowed Area* - This is the method that energy is delivered to the excavation and extraction sites. This could include power cables, microwaves, reflectors, fuel cells, batteries, chemical reactors, pipes, etc.
- *Water Ice Extraction Process* - This is the method that the water is being separated from the regolith. Some possible methods include distillation, mechanical separation, filtration, etc.
- *Ice/Regolith or Water Transportation* - This is the method of transport of the ice or ice-rich regolith out of the shadowed area.

Ice Extraction Systems: For purposes of analysis and evaluation, three extraction system scenarios were developed: (a) In-situ Ice Extraction via Microwave Heating; (b) Local Extraction of the Ice/Regolith Mixture with GPHS-RTG (General Purpose Heat Source - Radioisotope- fueled, Thermoelectric Generator) Thermal Processing and Steam Pipe Transport; (c) Local Drag Line Extraction of the Ice/Regolith Mixture with Solar Thermal Processing Outside the Permanent Shadow. These system approaches were developed to represent a number of different subsystems. They represent three combinations of the many possible subsystems that could compromise a complete extraction system.

Before a detailed mining and water extraction system can be designed and evaluated, the properties of the lunar water ice need to be accurately determined. The obvious choice is to send a robotic lander into the one of the lunar poles. The robotic lander could directly measure some of the important characteristics of the ice. An alternative to this approach is to simulate the lunar ice in a laboratory setting here on Earth. Lunar ice simulators would allow scientists to study the ice deposition process and measure the physical properties of ice and regolith mixtures in a terrestrial laboratory. The simulators would allow various ice and regolith mixtures to be formed and tested. Physical properties, such as hardness, water-regolith cohesion, compressive strength, and shear strength could be directly measured under conditions similar to those found in the cold traps near the lunar poles. At a larger scale, the simulator could provide a test bed for testing subsystems and complete systems for ice extraction.

The purpose of this study was to assess the approaches to extract and use water ice located in the permanently shadowed cold traps at the lunar poles. As part of this effort, models were developed of the physical properties of the lunar ice and the environment in which it exists. Various extraction concepts have been developed. Criteria were also developed to evaluate the various system approaches. Data from the Lunar Prospector spacecraft has verified the existence of ice on the Moon. As a result, it will be very important to understand how to extract it for beneficial use and preserve it for scientific analysis. This project will serve as a base to do that in the near future.

Acknowledgment: The basis for the work reported here was supported by the NASA Johnson Space Center (Duke et al, 1998). Dr. Michael B. Duke was the Principal Investigator for the effort. He was supported by a team of highly qualified engineers and scientists including: Dr. Eric E. Rice, Robert J. Gustafson, William H. Knuth, Christopher P. St.Clair, Dr. Martin J. Chiaverini, Daniel J. Gramer, and William J. Rothbauer. The support of B. Kent Joosten, NASA Johnson Space Center's Technical Monitor, is gratefully acknowledged.

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ACOUSTIC SHAPING: ENABLING TECHNOLOGY FOR A SPACE-BASED ECONOMY

N.M.Komerath, C.A. Matos, A. Coker, S. Wanis, J.Hausaman, R.G. Ames, X.Y. Tan,
School of Aerospace Engineering
Georgia Institute of Technology

This abstract presents three points for discussion:

(1) Key to the development of civilization in space, is a space-based marketplace, where the need to compete in earth-based markets is removed, along with the constraint of launch costs from Earth.
(2) A body of technical results, obtained by the authors' team, indicates promise for non-contact manufacturing in space, of low-cost items required for human presence in space. This is presented along with various other techniques which hold promise.
(3) The economics of starting a space-based production company are heavily dependent on the presence of a rudimentary infrastructure. A national-level investment in space-based infrastructure, would be an essential catalyst for the development of a space-based economy. Some suggestions for the beginnings of this infrastructure are repeated from the literature.

Snapshot of space-based activities, 1999

The vast majority of human activity in space today is related to telecommunications and remote sensing. Offshoots of military initiatives, both have revolutionized earth-based markets, providing order-of-magnitude leaps in several technologies. Launch costs from Earth to low Earth orbit range from the claimed $4000 per kg to $29500 per kg depending on the size, sophistication and need for attention. The risk of satellite failure, and the extreme cost of repair, if at all possible, increase launch costs.

For obvious reasons, earth-based markets, and high launch cost per unit mass, dominate current thinking on space-based business. The criteria for space-manufacturing concepts are [1,2]:

1. the existence of an Earth-based market where high prices can be commanded for an extended period (examples: drug and crystal manufacture), or mass-market delivery can be achieved at a low per-customer cost (example: communication technology.
2. A 3-to-5 year Return on Investment is seen as being essential for space-based business concepts [3].

All of this constricts the rate of expansion economic activity in space. Grand dreams abound, of going to find water on the Moon to convert into propellant, or going to asteroids to mine platinum, or to Pluto to bring back Helium-3 [4]. Again, these are driven by the same criteria given above.

Point 1: Space-Based Markets

As long as attention is focused on high-value precious metals and fuels, only a low-level, subsistence economy appropriate for the frontier prospector can develop. It takes infrastructure to develop a true high-level economy. Economic activity migrates to places which offer basic infrastructure, first because people can find jobs creating products and services for other who live there, and eventually because it is convenient to live there. The process is self-sustaining and self-expanding, as the economy moves to higher and higher levels. This infrastructure is built from low-tech materials such as concrete, silicon dioxide and aluminum oxide, and base metals, not from platinum and Helium-3. The markets for these materials and products are thus in space, not on Earth. The creation of such a production economy implies demand for attendant services, and offshoot production plants, all dependent on space-based markets, not earth-based ones. Production of concrete from lunar materials has been considered, and the technology exists [5,6].

Point 2: The Technology of Acoustic Shaping

The concept of Acoustic Shaping has been studied at Georgia Tech through ground and flight experiments. In microgravity, resonant sound fields can form pulverized material into specified surface shapes. Flight experiments show good prospects for producing flat and curved panels, using materials such as pulverized solids and binder liquids, with non-contact, automated processing using sound generated in closed, pressurized containers. The shapes are appropriate for fuel tanks, heat shields, greenhouses, habitats, and plumbing. Success has the potential to accelerate human activities beyond Earth, by enabling mass-production of the paraphernalia essential to human activities. The ground-based research, numerical predictions and flight experiments needed to develop this technology are outlined in refs. [7-9].

Point 3: The Argument for Infrastructure

Recently, a team of Georgia Tech students under the guidance of the author, studied the avenues to develop their concept for space-based manufacturing of pressure vessels, heat-shields, and other low-tech, high-volume paraphernalia of extra-terrestrial human civilization. Their conclusion regarding the economics of the venture [9] was confirmed by the experience of the other student teams in the NMB program [10]:

Development of a basic infrastructure is a crucial step to every such endeavor. Such an infrastructure is beyond the capability of private enterprise to develop, since the payback period is far too long. It is well within the scope of what government can accomplish. However, with such an infrastructure developed, it is feasible and realistic to make a profit in space, focusing on space-based markets, and with significant independence from the vagaries of earth-based markets or individual space-mission programs.

Three basic items were identified for consideration by government agencies:

1. The establishment of a pressurized "industrial park" in low earth orbit using STS external tanks, a concept

proposed in [4,11]. This would vastly reduce the cost of setting up production facilities of moderate size, needed to produce useful items in large enough quantities. Studies have shown than the "delta-v" needed to boost the external tank into orbit, rather than letting it fall into the Indian Ocean, is of the order of 100 mph, which appears to be achievable at an acceptable cost in STS payload.

2. The development of a robotically-operated, solar-powered electromagnetic mass driver facility on the moon. The "delta-v" needed to reach orbital speed from the moon, with moderate acceleration, can be achieved using a launcher of moderate length [4,9]. Such a facility would facilitate many enterprises which seek to establish mining operations or usage of lunar materials.
3. "Transit Systems" such as the "Cyclers" proposed by Aldrin [12] or tethers [13] will reduce transportation costs dramatically.

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RETURN TO THE MOON: A NEW STRATEGIC EVALUATION

Paul D. Lowman, Jr.
Goddard Space Flight Center
Greenbelt, MD 20771

Abstract

This paper reviews the value of a new lunar program, initially robotic and eventually manned, in the light of developments since the 1991 Synthes Group study of the Space Exploration Initiative. The objective is to evaluate a return to the Moon in comparison to proposed Mars programs as a focus for American space exploration with humans in the next century. The Moon is demonstrably accessible, hospitable, useful, and interesting. Lunar programs are inherently faster and less risky from a programmatic viewpoint than comparable Mars programs such as Mars Direct. The dominant reason for a resumption of manned lunar missions, focused on a single site such as Grimaldi, is to rebuild the infrastructure for missions beyond Earth orbit, the last of which was in 1972. A transitional program, corresponding to the 10 Gemini missions that bridged the gap between Mercury and Apollo, was considered absolutely essential by the Synthesis Group. Further justification for a return to the Moon is the demonstrated feasibility of a robotic lunar observatory, concentrating on optical and infrared interferometry. Many unsolved scientific questions about the Moon itself remain, and could be investigated using telerobotic lunar rovers even before the return of humans. Mars is unquestionably more interesting scientifically and far more hospitable for long-term colonization. A new lunar program would be the most effective possible preparation for the human exploration, settlement and eventually the terraforming of Mars. Lunar and Mars programs are complementary, not competitive. Both can be justified in the most fundamental terms as beginning the dispersal of the human species against uncontrollable natural disasters, cometary or asteroidal impacts in particular, to which mankind is vulnerable while confined to a single planet. Three specific programs are recommended for the 2001-2010 period: Ice Prospectors, to evaluate polar ice or hydrogen deposits; a robotic lunar observatory; and a manned lunar base and observatory.

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SPACEWATCH DISCOVERY and STUDY of ACCESSIBLE ASTEROIDS

Robert S. McMillan
Lunar & Planetary Laboratory, University of Arizona

Spacewatch is an exploration for asteroids and comets throughout the solar system, from the space near Earth to beyond the orbit of Neptune. Among other things, Spacewatch has reported positions of about 200 000 asteroids, mostly in the main belt, discovered seven objects beyond the orbit of Neptune, eight Centaurs between the orbits of Jupiter and Neptune, and (most relevant to this Roundtable) about 200 Earth-approaching objects since large-scale Spacewatch surveying was begun a decade ago. In addition to discovering new objects, Spacewatch determines the statistical properties of the various populations of asteroids and comets according to their orbital characteristics and absolute magnitudes.

Here we use the term "Earth Approacher" (EA) to include both asteroids and comet nuclei whose orbits bring them close to the Earth at times, whether or not their orbits cross the Earth's. "Close" is defined to be within 0.3 AU, or 5×10^7 km. This term is more precise than "Near Earth Object" (NEO) or "Near Earth Asteroid" (NEA) because most of the time these objects are not "near" Earth, in the sense of a cloud following the Earth.

Spacewatch observing methods and equipment have been described [1-10]. The principal differences between Spacewatch and other surveys for asteroids are its deeper limiting magnitude, greater dynamic range of magnitudes, sensitivity to a wider range of angular speeds, and smaller area coverage. Approximately 2000 square degrees are surveyed per year with the 0.9-m telescope of the Steward Observatory on Kitt Peak in southern Arizona. On slow-moving objects the limiting V magnitude is 21.5, about 2 mag fainter than the MIT/Lincoln Labs' LINEAR survey [11]. Point sources with angular rates between 3 arcsec/hr and (for bright objects) one degree/hr have been detected.

Spacewatch was the first to discover an asteroid with a CCD, first to discover an asteroid with software, first to discover an EA with a CCD (1989 UP), first to discover an EA with software (1990 SS), and has discovered about 25 per cent of all EAs known to date. About 20 per cent of the EAs Spacewatch discovers are larger than 1 km in diameter and 26 per cent are smaller than 100 m. Spacewatch's faint limiting magnitude and ability to detect very fast moving objects (VFMOs) yield a higher proportion of small EAs than in the discoveries by some of the other EA search programs. Notable discoveries of small EAs by Spacewatch include the smallest known asteroid (1993 KA2 with absolute magnitude H=29.2 => 4-9 meters diameter), the closest observed approach of any EA to the Earth (1994 XM1 at 105 000 km), and the most rapidly rotating EA (1998 KY26 in 10.7 min). This is so rapid that it cannot be held together by gravity alone, so it is the best example of a monolithic asteroid. 1998 KY26 is also more accessible to spacecraft than any other asteroid with a well known orbit [12]. Lest anyone think that an asteroid only 30 m in diameter is "merely a small rock, not worth visiting", one should realize that a solid sphere 30 m in diameter with a density of 2.5 has a mass of 35 000 metric *tons*. It will be impossible to deliver that much mass into space from the surface of the Earth for the foreseeable future. 1998 KY26 also has a surface area greater than half an acre, in case a space station [13] were to be built around it.

Spacewatch observations are providing information about the processing history of the population of small EAs as a whole. The number of discoveries of EAs by Spacewatch from 1989-1992 already showed an enhancement in the numbers of asteroids smaller than 100 m in diameter compared to a power-law extrapolation from larger sizes [14]. This can be explained if the EAs originate in the main belt and there are bumps in the size distribution of larger main belt asteroids [15, 16]. Analysis of Spacewatch observations of the main belt showed there are indeed departures from a power law distribution of absolute magnitudes [17]. A more comprehensive analysis of the statistics of all EAs discovered by Spacewatch (in preparation) will provide a lower limit on the total number of EAs greater than a given size.

Knowledge of the cohesion of asteroid material is relevant to mining. Spacewatch discoveries can provide the shape of the size distribution of EAs in the 40m-600m range of diameters where cohesion makes the transition between gravity and mechanical strength [18]. Furthermore, lightcurves and rotation periods of these objects can be observed [12]. With enough statistics on rotation periods, the fastest rotation as a function of size should reveal the largest size of monolithic pieces, again a parameter useful for developing mining techniques.

Our new 1.8-m telescope [19] will extend our limit by a magnitude in the year 2000. The field of view will be 0.8 deg in diameter and the image scale will be 1.0 arcsec/pixel using the same type of detector we presently have on the

0.9-m telescope. The 1.8-m telescope will find small EAs more efficiently, and will recover EAs that are faint on their return apparitions.

To make Spacewatch more efficient in covering sky area, we have ordered four 2048x4608 three-side buttable CCDs with 13.5 micron square pixels, comprising a total of 37.7 million pixels. Delivery from EEV, Inc. in the UK is expected in Feb. 2000. A mosaic will be made of these CCDs to cover a field 2.4 degrees in diameter at a scale of 1 arcsec per pixel. The correction lenses required for this wide field have been received and the new primary mirror blank required for the 0.9-m Spacewatch Telescope has been ordered. The mosaic should be operational in 2001. With it we will cover sky ten times faster with the same limiting magnitude, and thereby discover hundreds of EAs per year.

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ROLE OF MINING IN SPACE DEVELOPMENT. N. N. Melnikov[1] and O. V. Nagovitsyn[2], [1,2]Mining Institute of Kola Science Centre of Russian Academy of Sciences. 24 Fersman st. Apatity, Murmansk region, 184200 RUSSIA.

Introduction

Human expansion in Space is inconceivable without the creation of a comfortable habitat. The occupation of Space bodies can be similar to colonization of uninhabited regions of the Earth, but it will be significantly different. On the Earth, humans can use products from living things, in Space mineral resources are the only resource. This fact predetermines a crucial role of mining in Space.

Necessity of space mining

It is obvious that mining operations in space are necessary for two basic purposes:

1. Production of useful component (metals, ^{3}He, energy etc.) to sale them in the Earth markets. In this case mining is the main purpose of an expedition into Space. Large-scale mining and power companies may finance and realize these works.
2. Maintaining the presence of mankind in deep space. Mining will provide materials and energy for constructing extraterrestrial bases, space ships and life support. Mining is actually the auxiliary manufacturer of any super task in Space. The expenses for their operations are only a part of total cost of the project.

There is one main difference in an orientation of results of mining activity: in the first case it is the Earth, in the second - Space. Let's consider a little bit more in detail reasons and consequences of these different approaches.

First one assumes, that the situation can arise when to extract some minerals more favorable in Space rather on the Earth. An exhaustion of traditional earthly sources of raw material, their absolute absence, ecological problems, growth of manufacture and the population of a planet can promote this. However, such factors as perfection of technologies of processing, invention of new materials and power sources, circulation of the of secondary materials, development of new sources such as a shelf and deeper ocean zones are resisted this. Ecological harm of earthly manufacture counterbalances is not smaller ecological harm of rocket technologies. While the history of development of industrial mankind shows, that all tasks in manufacture were solved at the expense of earthly resources. We can not forget about possible catastrophic for earthly economics consequences of occurrence of superfluous amount of a material for example in a consequence of development metal asteroids [1, 2]. In foreseeable prospect, in our opinion, the Earth will be self-sufficient by major metals, materials and energy, that will predetermine absence of such type of mining works in space.

The presence of a supertask is sole necessary for application of the second type of mining. It will involve the private investors or will force to spend money from goverment sources. There is the incomplete list of such motives:

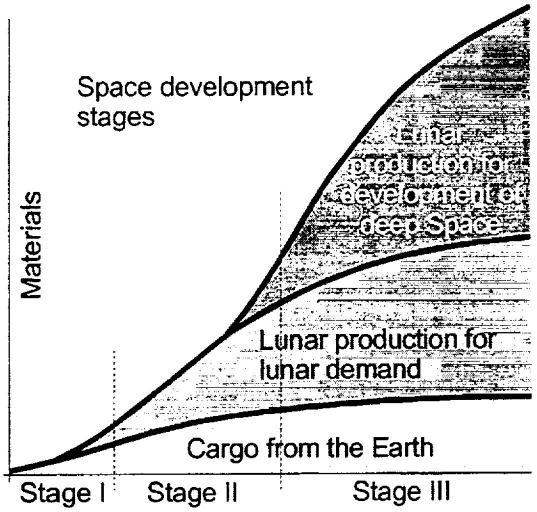
1. Scientific tasks for knowledge of Solar system, Galaxy, Universe.
2. Overpopulation of the Earth and migration on other bodies of Solar system.
3. Defense of the Earth from mythic space threat - comet, meteorites, aliens, from each other.
4. Religious motives.
5. Tourism, sport, rest, treatment.
6. Show field for advertising companies.
7. Satellit communications.
8. Space ecological monitoring of the Earth and prediction of weather.
9. Improvement of life quality of the terrestrial mankind from Space.
10. Political aspiration of the various states, nations or communities.

Inequality of these motives promotes their various combinations. Some of these topics are question of belief but sometimes it plays a great role for a movement forward.

Stages of development in space

The development of space was begun in 1957 and till now is gone forward. However, near space is accustoms - not further 40 000 kms from the Earth. Thus all necessary components of all parts of the human space machine are made on the Earth from earthly materials and energy. There is no also speech to use extraterrestrial resources (energy of solar batteries is unique exception), and consequently about mining activity in space.

We admit, that the supertask has induced to begin scale development extraterrestrial resources. It will be possible to separate some important stages space development by an attribute of an origin of materials and their use:



It is meant, that the development of the Moon is an absolutely necessary first step in deep space. At the first stage the all necessary will be delivered mainly from the Earth. It is a stage of initial development. It is necessary to develop initial production and processing of first portions of lunar raw material. The type of mining is open pit mainly. Regolith is only processed. The second stage begins with self-reproduction of lunar technological units, large-scale construction of inhabited and industrial buildings. The mining goes into deep of the Moon. The hard rocks are involved in processing. To the beginning of the third stage the production capacity is sufficient for a construction from local materials of almost whole spectrum of accessories for a structure of starting platforms and space ships for reaching of other space bodies. Owing to great cost of the interplanetary travel the similar order of development will repeat on all significant steps of mankind from a planet to a planet, from a star to a star and further.

Extraterrestrial mining technologies

Owing to fast technical progress it is possible to do the assumptions rather future extraterrestrial mining technologies not further of several tens years forward. I.e. it is possible to speak about mining technologies for the first stage of development of space. The unusual natural conditions outside of the Earth will result in selection and creation of space mining technologies with use both traditional, and new decisions [3, 4]. It is impossible also to miss development of technologies not having direct connection with mining technologies, but able to render revolutionary influence on them. The progress of the computer sciences, gene engineering, nanotechnology etc. may give large hopes for a change of future mines.

Presently, most urgent task is a choice of minig technologies for the first stage space development. They should combine small weight and high operational characteristics. The special attention is deserved the decisions with converting such conditions of a lunar surface as high difference of temperatures, small gravity, vacuum, property of regolith into technologies which allow to create self-reproductional infrastructure of manufacture with the smallest expenses for transport from the Earth. Such technologies with combining of processing will produce initial reserves of water, oxygen, metalls, rocket fuel. The best candidates for such mining technologies are the various variants drum slushers-scrapers [5, 6, 7]. The further researches are necessary for perfection of these technologies with a main task - reduction of weight and increase of reliability of devices.

Conclusion

Various needs for raw material in space and the various properties of space resources will dictate that space mining will require a wide application of a variety of applied mining technologies. On the one hand, the number of basic principles for mining technologies is limited; on the other hand, we see drastic differences in applications of technologies on the Earth for different environments (on land and in the depth of the seas). As space science differs from Earthly science, it is fair to assume that space mining will be significantly different from Earthly analogues. Only imagination and the development of new ideas will make future space mines possible.

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A COMMERCIAL/LUNAR RESOURCES EXPLORATION CONCEPT. S. Nozette, Code 8131, Naval Research Laboratory, Washington DC 20375, USA.

Lunar polar volatile deposits could have impact on future space system development. If these deposits are localized and can be exploited without complex, mass and energy intensive regolith moving and chemical processing, they might be economically utilized to support space activities in the next 10-30 years. Examination of potential system architectures, which use lunar polar volatilize, can provide requirements for future robotic lunar exploration required to further characterize these deposits

Trends in the Geosynchronous Orbit (GEO) communications satellite industry suggest synergies between lunar development and commercial and military uses of space. About 120-200 GEO spacecraft are deployed every 10 years. Since the energy required to reach GEO and lunar orbit are equivalent operations in one domain can impact the other. This has already been successfully demonstrated by Hughes Space and Communications (HSC) use of a lunar gravity assist (LGA) to rescue a previously useless communications satellite. Trends in GEO technology and broadband markets suggest high power (50-100 kW) systems and large apertures could be in demand for a variety of commercial and military application within 10-20 years. In addition various space control, missile defense, and reconnaissance system concepts envisioned for deployment in this period will be mass and area intensive. These could have synergies with lunar exploration and development

The replacement of current GEO energy storage with regenerative fuel cells using H20 will probably be required to achieve high power (50-100 kW) GEO systems. This represents about 1-200 tons of H20, worth about $3-6B at current launch costs, for 100 GEO systems. Providing this H20 from the moon may be economical if the costs of lunar operations are contained. Alternatively, these revenues may offset the costs of a lunar development program. If the lunar exploration infrastructure can share a portion of the communications revenues of the GEO systems it supports, in addition to being reimbursed for commodities, an economically attractive system might emerge as 100, 100 kW GEO systems could generate $600 B over their 15 yr. life.

The use of current commercial GEO technology allows the emplacement of 1-2 MT on the lunar surface and 15 kW of solar array in lunar orbit for about $220 M, assuming DOD and commercial industry practices. Such precursors will be needed to establish the state of the lunar deposits and emplace infrastructure (e.g. comm./nav aids). While not immediately commercial, an exploration program could exploit existing capabilities and create new synergies with the GEO industry by development and flight qualification of future systems. A potential near and long-term system architecture and associated technical and programmatic possibilities will be presented.

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RADAR RECONNAISSANCE OF NEAR-EARTH ASTEROIDS. S. J. Ostro, Jet Propulsion Laboratory, California Institute of Technology, Mailstop 300-233, Pasadena, CA 91109-8099, ostro@reason.jpl.nasa.gov.

Groundbased radar observations of NEAs can help identify space resources with commercial potential and can dramatically reduce the cost and risk of the initial spacecraft missions to those objects. The near-Earth asteroid (NEA) population is thought to contain ~1500 objects as large as a kilometer, ~300,000 as large as 100 meters, and more than 100,000,000 as large as 10 meters. More than 10% of the NEAs are more accessible in terms of mission delta-V (i.e., fuel required) than the Moon, Mars, or the moons of Mars. Fewer than 1000 NEAs have been found, but the discovery rate is increasing rapidly. Once an asteroid is discovered (necessarily by wide-field optical telescopes), radar can provide otherwise unavailable information about its size, shape, spin state, and surface properties if it approaches within the range of the Goldstone (California) or Arecibo (Puerto Rico) radar telescopes.

Asteroids generally appear as unresolved points through groundbased optical telescopes, but radar measurements of the distribution of echo power in time delay (range) and Doppler frequency (radial velocity) can yield images with resolution as fine as a decameter. Image sequences that furnish adequate orientational coverage can be inverted to construct geologically detailed 3-D models, to define the rotation state precisely, and to constrain the object's internal density distribution. Estimates of radar scattering properties characterize the surface's cm-to-m-scale roughness as well as its bulk density, which for asteroids depends primarily on porosity and metal concentration. A useful spin-off of radar detection is orbit refinement that simplifies navigation of flyby and rendezvous spacecraft.

The existence of accurate physical models for small NEAs permits realistic modeling of the close-orbit dynamics of robotic or piloted spacecraft. Maneuvering spacecraft in the vicinity of irregularly shaped, small asteroids is extremely challenging, and orbit geometry and stability depend strongly on object shape and spin state.

Radar detections of 55 NEAs (see the tables and references in http://echo.jpl.nasa.gov) have established the extreme diversity of the population and have revealed several objects in detail. Radar reflectivities span an order of magnitude, with the highest indicating a nearly entirely metallic composition (asteroid 1986 DA) and the lowest indicating very low-density material (e.g., 1986 JK). Asteroid surface roughness ranges from negligible (1986 DA) to extreme (e.g., 1992 QN). Spin periods range from 11 minutes to more than a week, and shapes range from very regular to grotesque. Geographos is more than twice as elongated as any other NEA that has been spatially resolved. Castalia and Bacchus are bifurcated, 1982 TA has a triangular pole-on shape, and Golevka is the most angular object imaged so far. 1998 ML14 is spheroidal, with protrusions that suggest a rock-pile configuration. High resolution images of Toutatis reveal a geologically complex, heavily cratered object in a slow, non-principal-axis spin state. Toutatis' internal density distribution appears to be uniform; the surface's centimeter-to-decimeter-scale roughness also is uniform and is consistent with at least 1/3 of the area being covered by small rocks.

Numerous craters are visible on the best-resolved objects, but many other topographic depressions and constructs also are evident. The population apparently includes monolithic objects as well as unconsolidated rubble piles, but in most cases it is impossible to distinguish these possibilities.

Radar and optical observations recently revealed the physical characteristics of 1998 KY26, an approximately 30-meter-wide, monolithic spheroid that is an order of magnitude smaller than any other solar system object ever studied in detail, and that rotates an order of magnitude faster than any other solar system body. 1998 KY26 is more accessible to spacecraft rendezvous and roundtrip missions than any other asteroid with a well known orbit. It appears to be mineralogically similar to carbonaceous chondrites, the most primitive and volatile-rich meteorites. This object's mass may be 10 to 20% chemically bound water, making it a fine candidate for resource exploitation.

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SOLAR ENERGY CONVERSION USING IN SITU LUNAR SOIL.

Howard A. Perko, Research Assistant, Center for Engineering Infrastructure and Sciences in Space, CE Dept., Colorado State University, Fort Collins, CO 80523; howie@engr.colostate.edu

Introduction: The success of future long duration robotic and manned missions to the Moon and a permanently human occupied lunar base depends on the ability to generate electric power on the Moon. It has been suggested that solar cells might be manufactured on the Moon using silicon and titanium extracted from the lunar soil [1]. However, this requires the delivery and operation of materials handling equipment and a fairly sophisticated manufacturing facility.

It has been shown that the lunar soil itself is capable of generating considerable electrostatic charge due to changes in illumination [2] and secondary electron emission [3]. These phenomena combined with high photoconductivity, considerable spectral absorption, and the abundant radiation on the Moon, suggest that solar energy conversion might be performed using in situ lunar soil. The possibility of generating electricity from the lunar soil was explored for a hypothetical Schottky barrier photovoltaic cell consisting of an aluminum wire mesh bearing on a thin layer of compacted fine lunar soil underlain by a metallic foil.

Photovoltaic Cell: The photovoltaic effect is the development of voltage by the flow of electromagnetic-stimulated, electron-hole pairs within an electric field usually produced by energy differences at a material junction [4]. When a metal is placed in contact with a semiconductor, a Schottky energy barrier is created that can cause the flow of electron-hole pairs due to the difference in work function between the two materials [5]. When lunar soil is stimulated by radiation, it has a conductivity near the semiconductor range. Therefore, it is postulated that a Schottky barrier will develop between metal in contact with lunar soil.

The current density, J, for a Schottky barrier as a function of voltage, V_D, is given by [6]

$$J = R^{*}T^{2}\exp(-N_{b}e/kT)\,[\exp(V_{D}e/kT)-1] - eG \qquad (1)$$

where T is temperature (K), e is fundamental electron charge (1.6×10^{-19} C), k is Boltzmann Constant (1.38×10^{-23} JK^{-1}), N_b is barrier energy (eV), R^* is the Richardson Constant ($Acm^{-2}K^{-2}$) and G is the rate of electron-hole pair generation (pairs $s^{-1}cm^{-2}$). For the lunar soil, barrier energy is expected to be the work function of the soil (5.5 eV [7]) plus the band gap (13 eV for quartz [8]) minus the work function of the metal (4.08 eV for aluminum [9]). The Richardson Constant is equal to 120 times the ratio of effective electron mass over the mass of a free electron. It is anticipated that this ratio is close to uniformity for the lunar soil. The rate of electron-hole pair generation can be assumed to equal the number of photons absorbed by a material [6]. Photon absorption was determined by integrating the extraterrestrial solar irradiance [5] times the measured absorption for a sample of mature lunar soil [10] over all wavelengths.

The resulting relationship between current and voltage in a lunar soil photovoltaic cell is shown in Fig. 1. The power generating region of the curve is the area where voltage is positive and current is negative, forward current. The internal resistance in the photovoltaic cell, r_D, must be considered in order to determine power available to an external load, P, which is given by [6]

$$P = -A_{D}\,[V_{D} + r_{D}J]\,J \qquad (2)$$

where A_D is the area of the photovoltaic cell. Internal resistance is the dividend of lunar soil thickness (assumed 2 mm) and A_D times lunar soil photoconductivity (10^{-10} ohm/cm^2 [10]).

Combining Eq. (1) and Eq. (2) and solving for the maximum power indicates that the lunar soil photovoltaic cell produces 0.24 mW per m^2 area at a voltage of 6.9 V and current of 3.5 nA.

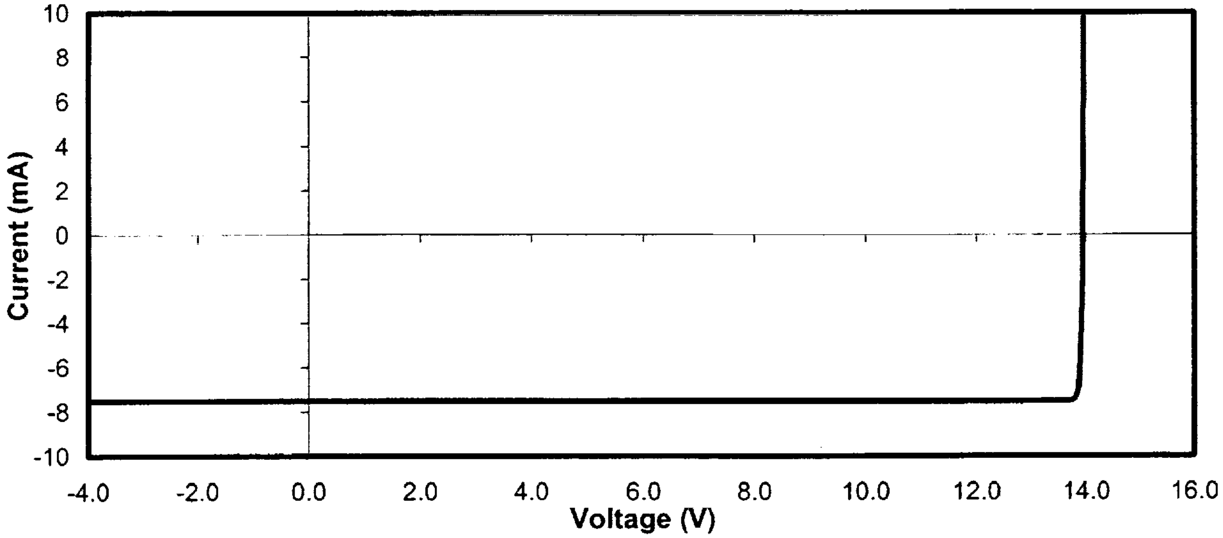

Fig. 1 Current-Voltage Relationship for Lunar Soil-Aluminum Shottky Barrier

Discussion: The resulting power output from the soil photovoltaic cell is obviously insufficient to merit practical consideration. However, the exercise does provide insight into a new mechanism for the electrostatic buildup of charges on the lunar surface. The possible development of a Schottky barrier at the illuminated interface of metal and lunar soil could generate a potential difference of as much as 13.9 V, as seen in Fig. 1. This phenomenon may have important consequences with regard to the use of sensitive electronics on the surface of the Moon, and it may play an important role in dust adhesion. The foregoing thought experiment is also an example of attempting to benefit from the material and environmental properties on the Moon, rather than approaching them as design constraints.

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THE APPLICATION OF THERMAL PLASMAS TO ORE REDUCTION FOR IN SITU RESOURCE UTILIZATION. Keith A. Prisbrey, Aaron B. Sayer, Wenming Wang, and Patrick R. Taylor, University of Idaho.

Thermal plasma technology has potential utility for metal ore reduction in low gravity, low pressure or vacuum, in situ applications, such as on Mars. Two types of reactors are discussed: Inductively Coupled Plasma and Transferred Arc Plasma. Both are evaluated in terms of thermodynamic potential for reducing oxides such as silica, rutile, hematite, and alumina. Reactor design and fundamental considerations are outlined. Ratios of plasma reactor weight to product output rate are calculated from experimental laboratory results. The ICP reactor has a significant advantage in terms of low wear and few replacement parts, while the transferred arc system may be useful when electricity is the only source for chemical reducing potential. Proposed flow sheets are given and suggestions for detailed research identified.

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PROSPECTING NEAR-EARTH ASTEROIDS FROM THE GROUND.

K. L. Reed, Marconi Integrated Sy tems Inc., 16250 Technology Drive, MZ 6500-R, San Diego CA 92127, USA (kevin.reed@marconi-is.com).

Introduction: Asteroid prospecting solely by spacecraft is problematic due to the high cost of individual missions and the large number of asteroids needing evaluation. A less expensive initial data acquisition may be accomplished for the majority of near-Earth asteroids (NEAs) through the coordinated use of ground-based astronomical observing assets to increase the efficiency and data return of observation.

An intensive ground-based campaign of asteroid data acquisition using dedicated instruments and platforms could provide comprehensive knowledge about the physical parameters of a large number of NEAs at much less cost than a series of spacecraft missions. In this manner, a large population of NEAs may be assessed and decisions made regarding their further exploration and prospecting.

NEAs are a diverse population of bodies composed of a broad spectrum of materials [1]. Little is known about any individual NEA, but quite a bit may be generalized from the few observations that have been made. It is now quite certain that some NEAs are volatile-rich (e.g., H_2O) while others are metal-rich (e.g., Fe, Ni, Pt-group). In order for efficient preliminary planning for using asteroid resources, a reliable assessment must be made of possible resources existing on specific asteroids. This may be accomplished expensively, using a large number of spacecraft sent to an equally large number of asteroids, or cheaply, using ground-based assets to assess the usefulness of individual asteroids for specific resource needs.

Data obtained using V/NIR spectrophotometry, thermal bolometry and spectroradiometry, polarimetry, and radar delay-Doppler imagery can infer parameters such as asteroid size, shape, rotation rate, pole position, surface mineralogy, surface temperature, gross regolith development, surface porosity, surface cohesion, surface metal abundance, thermal parameters, albedo, and surface roughness [2–11]. Combining these measurements with current knowledge in geochemistry and meteoritics would aid in modeling the overall physical state of the asteroid. Once the composition and physical state of a specific asteroid are known, assessments of the resource content and extractability may be made for the specific asteroid so that a decision regarding follow-up work may be made.

Methodology: A system of two optical/infrared telescopes and a radar capable of high SNR delay-Doppler measurements are required for comprehensive, simultaneous observations of NEAs as they become observable. Observation simultaneity must be preserved as the rotational rates and pole positions are not known for the majority of NEOs and thus timing is critical for data comparison between observing platforms. This combination of instrument platforms would obtain in three to seven nights enough data to infer all the parameters expected above for a single NEA.

Measurements of an asteroid's physical parameters and their rotational variation all feed into a body of geological knowledge about the solar system. These parameters may be used to understand the geochemical constraints in internal structure and composition for a specific asteroid as well as relationships it may have with other NEAs [e.g., see 12–14]. Meteoritics especially provides a particular type of "ground truth" needed in ascertaining NEA resources from ground-based observations as meteorites are thought to be true samples of NEAs.

The Observational Campaign: Each observational technique (i.e., V/NIR, thermal, and radar observations) brings a unique capability to the overall physical modeling of a particular asteroid. Visible and near-infrared spectrophotometry provide data regarding the surface composition of an asteroid. Rotational variations in such data combined with geochemical knowledge provide insight into the petrologic and evolutionary history of the individual asteroid. Thermal infrared data taken at the same apparition geometry as the V/NIR data provide knowledge of the thermal inertia of the surface layers, a function of regolith evolution. An estimate of thermal properties, surface albedo variations, and projected area variations for the asteroid may also be calculated from the combined V/NIR and thermal data. Radar return analysis contains information about the asteroid's physical properties on many size scales for the body. Delay-Doppler-resolved radar features may provide a general shape model for the individual asteroid. This model may then be included with the thermal and V/NIR data to calculate a more precise estimate of the asteroid's thermal state, from which regolith properties may be deduced. Radar return analysis provides insight into the conductivity of the asteroid's surface as well as a possible estimate of its physical cohesion.

A ground-based, multi-platform NEA observation campaign must meet one important criterion in order to improve the chances of viable data output, simultaneity of observation. Most NEAs have unknown or poorly-constrained values for size, shape, rotation rate and pole position. Since the geometry of a particular asteroid observation from a specific platform is unknown, observations must be taken simultaneously so that a temporal correlation exists between radar, optical and infrared measurements. This correlation is needed so that characteristic features observed on an asteroid by a particular platform may be used in concert with signature features from the other platforms. For example, having no size, shape, or rotation data for a particular NEA, a flat topographic feature causing a unique dual-polarization radar signature can only be correlated with a radiometric variation in projected area if the observations are taken simultaneously,. To meet this important criterion, the platforms used in the observation program must be located in the same Earth hemisphere at similar latitudes so that they may obtain data simultaneously at similar geometries of observation. A three or four hour difference in observation time may prove uncorrectable for some of the possible observation geometries encountered.

The Groundwork: An initial evaluation must be made of the data which may be obtained using V/NIR spectrophotometry, thermal bolometry and spectroradiometry, polarimetry, and radar delay-Doppler imagery and how it may be used in a comprehensive multi-sensor near-Earth asteroid data acquisition and analysis program. A methodology, including identification of prospective platforms for use, must then be derived through which an observing program may be initiated to best make use of these multi-sensor data capabilities. This initial evaluation would be a one-year effort with 1-3 people and would provide a basis for coordinating the larger program of observations.

Cost: The initial evaluation of capability and the derivation of a methodology for observing would cost between $200,000–600,000. It would entail assessing how the various data types may be consolidated in analysis, identification of observing platforms for use, and obtaining the needed permissions and contracts for their use. The result would be a plan through which the observing program may be initiated and executed.

The cost of a program of observations is extremely affordable given the value of the data return. The operation and maintenance cost of an optical telescope runs approximately $10,000-20,000 per day. The operation and maintenance cost for a radar site is possibly double, ranging from $20,000–40,000 per day. If two optical telescopes and one radar antenna are leased at the larger rates for both types, yearly O&M costs for the program as a whole would amount to $30 million. If the cost of one NASA Discovery mission to one NEA is used as a baseline (with a $150 million cost cap), this program could be run for 5 years. If 5–10 NEAs are observed per month (giving 3–7 nights of possible observations per asteroid, the same length of time usually given one observing run for a series of asteroids), 60-120 asteroids could be observed in a year. This would give detailed geological remote sensing information for a total of 300-600 near-Earth asteroids all for the same cost as one NASA Discovery mission.

New instrumentation will probably be needed by all the observing platforms as most astronomical observatories and radar sites do not have instrumentation that is efficient or useful for planetary work. Given the costs of new spectrometers, bolometers, and polarimeters, plus the cost of upgrading a radar site to obtain the needed measurements, an extra $30–50 million may be needed to initiate this program. If this funding is to be taken from the $150 million Discovery-type cap, the mission duration may need to be shortened to 3-4 years, thus decreasing data return. If the lease rates quoted above are in any way overestimated (as they most likely are), no shortening of the mission is needed and the upgrade money may be had from a detailed accounting of true costs.

From simple order-of-magnitude cost accounting this observing program has already proven itself to be cost-efficient and high-value.

Results: The results of such a ground-based observation campaign would be a large database of raw observations and derived physical parameters for a large population of NEAs. These data would serve as a basis for studies of NEAs as impact threats and as raw materials resources and answer scientific questions regarding the nature and evolution of asteroids. A coordinated ground-based observation campaign is a significant method to maximize the data return while minimizing cost in studying the near-Earth asteroids for use in resource exploitation or threat mitigation.

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SOME IMPLICATIONS OF SPACE TOURISM FOR EXTRATERRESTRIAL RESOURCES

21-16

T. F. Rogers
The Space Transportation Association (STA)
Arlington, VA

The Purpose and Scope of the Roundtable "to bring together people with ideas about what will be useful products in the space environment with those who know how to produce materials on Earth." When considering extraterrestrial resources in the context of their use in support of general public space tourism it is important to broaden this definition of Scope in certain ways.

The first stages of extraterrestrial space tourism will probably take place in the Earth's lower atmosphere – far from the Moon or the planets, and even well below Earth orbit.

Sophisticated aircraft could take tourists up to altitudes approaching 20 miles for short periods. And the earliest of fully reusable space transportation vehicles should be able to reach some 50 miles in altitude for short trips. Later, Earth multi-orbit trips could be offered, to be followed by stays in residence in LEO hotels for days. In time, trips could take place to/from the Moon, eventually with stays there.

It should be appreciated that there are two most important extraterrestrial resources immediately available for space tourism use. They are not "materials" or "products," but are two vital space "resource intangibles":

- The resource of Perspective

  At high altitudes and in orbit, people could see the natural and man-made physical characteristics of the Earth and its atmosphere from a wholly new perspective. Too, they could view the cosmos with extraordinary clarity. In Lunar circumnavigational trips, they could view extraordinary terrain and, in stays there, do so in great detail.

- The resource of Microgravity

  Reductions in, and even the near absence of, the local force of gravity would allow people to experience and do things in extraterrestrial circumstances that cannot be experienced or done at the Earth's surface.

  For instance, all earthly athletic records will "be out the window." Imagine the "Space Olympics" broad jump and pole-vault records to be set in LEO. And playing tennis and golf on the Lunar surface.

Two material resources will be in immediate demand at LEO space tourism residences:

- The resource requirement of Electrical Energy

The International Space Station is expected to house some half-dozen professionals and, for their use and the conduct of scientific experiments, will have a solar electrical energy supply providing some 100,000 watts.

When as many people visit LEO as visit Antarctica today – some 10,000 per year – an average of 200 people at a time could spend a week there. This suggests an electrical energy supply requirement an order of magnitude larger than that of the ISS.

At least initially, this requirement will be met by local solar radiation converters. Later, it might be met by reception of electrical energy generated on the Moon and transmitted downward.

- The resource requirement of Water

  The water needs of hotel residents (and athletes) in LEO is difficult to quantify at present, since we cannot be certain of when the efficiency and effectiveness of water recycling for human use will become acceptable. But at least its initial availability is vital. And, it might be supplied from sources located on the Moon that is transported downward.

In time, perhaps extra-terrestrial materials could be used in the construction of LEO hotels and athletic arenas rather than transporting all of the parts up from the Earth's surface. But it is too early to speculate thereon. For we must first learn how to provide LEO residential volume at a unit cost (dollars per person/cubic foot) at costs orders of magnitude less than that of the ISS.

Space tourism will also be of value to extraterrestrial resource development other than as a market for such resources.

The ability to exploit extraterrestrial material resources will be seriously limited until the cost of surface-space transportation is sharply reduced – preferably by two orders of magnitude relative to the true average Shuttle trip cost.

Today nearly all activities underway to do so seek to employ more efficient vehicle technology and operations. The third way is to see space transportation serve a very large market. Space tourism would appear to be such a market. If even the size of the Antarctica tourism market were replicated in surface-LEO trips, this would provide an annual payload an order of magnitude larger than today's U.S. civil, military and private sector markets combined. And, in time, the market could be very much larger than this.

Finally, the major conclusions of the cooperative space tourism study conducted by NASA and STA will be presented, and the major findings of the first United States Space Tourism Conference, conducted by STA in late June, 1999, will be summarized.

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AN OVERVIEW OF NASA'S CURRENT IN-SITU CONSUMABLE PRODUCTION (ISCP) DEVELOPMENT ACTIVITIES AND GOALS.

G. B. Sanders, NASA/Johnson Space Center, Mail Code EP, Houston, TX. 77058, USA.

Introduction: Utilization of extraterrestrial resources, or In-Situ Resource Utilization (ISRU), is viewed as an enabling technology for the exploration and commercial exploitation of our solar system. It is fundamental to any program of extended human presence and operation on other extraterrestrial bodies that we learn how to utilize the indigenous resources. The chief benefits of ISRU are that it can reduce the mass, cost, and risk of robotic and human exploration while providing capabilities that the enable commercial development of space. A key subset of ISRU which has significant cost and risk reduction benefits for robotic and human exploration, and which requires a minimum of infrastructure, is In-Situ Consumable Production (ISCP). ISCP involves acquiring, manufacturing, and storing propellants for planetary ascent or Earth return vehicles, gases and water for crew and life support, and fuel cell reagents for power generation by using resources available at the site of exploration. Since propellant mass typically makes up 60 to 80% of the ascent or Earth return vehicle mass, In-Situ Propellant Production (ISPP) on the Lunar or Mars surface can significantly reduce the overall mass for the return vehicle needed to be brought from Earth. Systems analyses of human Mars missions have indicated that solely producing propellants on the surface of Mars by processing atmospheric carbon dioxide can reduce the initial mission mass required in low Earth orbit by approximately 20% as compared to carrying all required propellant to the Mars surface from Earth. An even greater leverage can occur for Mars missions when in-situ water can be processed.

The NASA Johnson Space Center (JSC) is currently trying to coordinate and focus the Agency's development of ISRU technologies and systems. Over the last three years, JSC has initiated an ISCP development program to support both robotic and human exploration ISRU missions. Near and midterm goals for the NASA ISRU development involve the production of propellants for Mars and Lunar ascent vehicles and hoppers, and consumables for robotic and human exploration such as; gases for scientific and pneumatic equipment; oxygen, water and gases for life support; and fuel cell reagents for rover and lander power generation. Long term goals for ISRU development include development of manufacturing and construction technologies and systems to support self-sufficiency, enhanced exploration, and commercial development of space.

ISCP Mission Concepts: Even though NASA currently does not have approved plans for human exploration missions beyond Low Earth Orbit (LEO), studies and mission design activities are being pursued to identify technologies and mission architecture concepts that can significantly reduce the cost or enable human exploration initiatives early in the next century. Strategic planning for human missions of exploration to Mars[1] has conclusively identified ISPP as an enabling technology, and ISCP as enhancing. To reduce the risk and validate the use of these systems on future human missions, both an extensive ground development program and flight validation of these systems are required.

Over the last few years, JSC has performed independent ISRU mission and process trade studies for robotic ISPP sample return and human Mars missions, as well as supported ISRU system definition and modeling in all of NASA's Exploration Office Mars Design Reference Mission activities. This has lead to the development of a top-level Mars ISCP mission evolution concept and the creation of an integrated technology, system, and flight program development plan, or 'Roadmap', for the development of ISCP technologies and systems. The Mars ISCP mission evolution concept is based on progressively evolving ISCP technologies to support a Mars human exploration mission as early as 2011. A major precursor to incorporation of ISPP into a human exploration mission is verification of its use in a Mars sample return mission utilizing ISPP in 2007.

Numerous studies have been performed on Lunar ISRU concepts, especially for the production of oxygen from oxygen baring ores in Lunar regolith[2], and removal of solar wind deposited hydrogen and helium-3. Since the Lunar Prospector neutron spectrometer data has been interpreted as indicating significant

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concentrations of hydrogen (potentially in the form of ice) exist in the vicinity of both poles of the Moon[3], new mission and design concepts for lunar ice extraction and utilization have been initiated. Even thought most recent ISRU development activities have been aimed at Mars, further effort will be made to ensure that the technologies being developed for lunar and Mars ISRU are synergistic with each other.

ISCP Technology & System Development: There are four major offices/programs within NASA currently supporting the development of ISRU related technologies and systems. These are the Office of Space Flight (OSF), Office of Life & Microgravity Sciences and Applications (OLMSA), Office of Space Science (OSS), and the Small Business Innovative Research and Technology Transfer (SBIR/STTR) Program.

In 1995, both JSC and Lockheed Martin Astronautics (LMA) performed studies of a Mars ISPP sample return (MISR)[4] mission. Due to the promising results of the studies, the OSF, through JSC, initiated Mars related ISCP development efforts focused on developing ISCP technologies and systems to support a MISR mission in 2005 or 2007, and human mission after 2011. This work was coordinated with the OSS Jet Propulsion Laboratory (JPL) Mars ISPP technology development program, and focused on developing the two most promising propellant production processes identified: Sabatier/Water Electrolysis (SWE) and the Zirconia Carbon dioxide Electrolysis (ZCE. Under this program, LMA developed and tested a complete SWE plant, and the University of Arizona and Allied Signal have both developed first generation ZCE breadboard units. Under the JSC-led ISRU subtopic for the SBIR program, alternatives to these initial processes have been identified. SBIR Phase I and Phase II awards to Pioneer Astronautics has shown that the Reverse Water Gas Shift (RWGS) process is a third major alternative for Mars ISPP/ISCP. Also, that other hydrocarbon fuels besides methane, such as methanol, ethylene, and toluene, are easily producible on Mars. This has opened up a large number of ISPP and ISCP architecture and mission concepts which are being pursued jointly by JSC and the Kennedy Space Center (KSC). The OLMSA has recently focused on developing ISRU technologies that are applicable to life science and microgravity processing. Technologies of interest include collection of buffer gases and atmospheric, surface, and subsurface water extraction on Mars. The Ames Research Center (ARC) is leading a team to examine subsurface drilling technologies for both science and resource extraction. Lastly, the Cross-Enterprise Technology Development Program (CETDP, under the OSS, has initiated efforts to fund development of low technology readiness and high leverage ISRU technologies to support both the Space Science and Human Exploration and Development of Space Enterprises. This program has only just been initiated. Proposals have been submitted to examine: Mars drilling, regolith volatile extraction, and micro chemical/thermal technologies.

ISCP Process & System Testing. To validate the benefits and performance of candidate ISRU technologies and systems, JSC has established the Mars ISRU System Technology (MIST) test facility. MIST has several chambers to support Mars environment simulation testing. All integrated MIP testing to date has been performed in MIST facilities. Also, Mars carbon dioxide (CO2) acquisition and oxygen liquefaction and storage subsystems have been tested. An integrated, end-to-end ISPP plant based on the Sabatier/Water Electrolysis (SWE) process is being prepared for simulated Mars environment testing in September of 1999.

ISCP Flight Demonstrations: JSC is leading the development of the first ISRU flight demonstration to Mars - the Mars ISPP Precursor (MIP) flight demonstration – which is manifested on the Mars Surveyor 2001 Lander. MIP will demonstrate the performance of critical ISPP technologies such as: Mars atmospheric carbon dioxide acquisition and compression using a sorption pump, oxygen generation based on solid oxide electrolysis of Mars atmospheric carbon dioxide (ZCE), advanced solar cell performance and degratation, techniques to reduce or mitigate the accumulation of dust on solar arrays, and night sky temperature measurement and the impact of dust accumulation on radiator performance. Proposals for the second Mars ISRU mission on the Mars Surveyor 2003 Lander have been submitted, and selection is expected in early November, 1999.

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PERSPECTIVES ON LUNAR HELIUM-3

Harrison H. Schmitt
(Department of Nuclear Engineering and Engineering Physics
University of Wisconsin, 1500 Engineering Drive,
Madison, WI. 53706-1687

Abstract

Global demand for energy will likely increase by a factor of six or eight by the mid-point of the 21st Century due to a combination of population increase, new energy intensive technologies, and aspirations for improved standards of living in the less-developed world (1). Lunar helium-3 (3He), with a resource base in the Tranquillitatis titanium-rich lunar maria (2,3) of at least 10,000 tonnes (4), represents one potential energy source to meet this rapidly escalating demand. The energy equivalent value of 3He delivered to operating fusion power plants on Earth would be about $3 billion per tonne relative to today's coal which supplies most of the approximately $90 billion domestic electrical power market (5). These numbers illustrate the magnitude of the business opportunity. The results from the Lunar Prospector neutron spectrometer (6) suggests that 3He also may be concentrated at the lunar poles along with solar wind hydrogen (7). Mining, extraction, processing, and transportation of helium to Earth requires new innovations in engineering but no known new engineering concepts (1). By-products of lunar 3He extraction, largely hydrogen, oxygen, and water, have large potential markets in space and ultimately will add to the economic attractiveness of this business opportunity (5). Inertial electrostatic confinement (IEC) fusion technology appears to be the most attractive and least capital intensive approach to terrestrial fusion power plants (8). Heavy lift launch costs comprise the largest cost uncertainty facing initial business planning, however, many factors, particularly long term production contracts, promise to lower these costs into the range of $1-2000 per kilogram versus about $70,000 per kilogram fully burdened for the Apollo Saturn V rocket (1). A private enterprise approach to developing lunar 3He and terrestrial IEC fusion power would be the most expeditious means of realizing this unique opportunity (9). In spite of the large, long-term potential return on investment, access to capital markets for a lunar 3He and terrestrial fusion power business will require a near-term return on investment, based on early applications of IEC fusion technology (10).

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SELF-PROPAGATING HIGH-TEMPERATURE SYNTHESIS FOR IN-SITU MATERIALS PROCESSING. F.D. Schowengerdt and J. J. Moore, Center for Commercial Applications of Combustion in Space (CCACS), Colorado School of Mines

Large-scale construction and manufacturing on the Moon or Mars, if done by conventional means, will require massive amounts of energy. Because the payload masses would be prohibitive, this energy will not come from either solar panels or fuel cells. For habitat construction and large-scale manufacturing *in-situ*, existing raw materials must be used for both the energy and the products.

One of the most promising processes for in-situ resource utilization on the Moon and Mars is self-propagating high-temperature synthesis (SHS), which is driven by exothermic reactions in packed starting powders. The end products often have unique microstructure and high porosity. SHS is attractive for materials production in remote space environments because: 1) no external energy is required to sustain the process; 2) atmospheric oxygen is not needed; 3) the powders can be packed into near-net shapes for subsequent forming and machining; and 4) the starting compounds are likely to exist on the Moon and Mars. The process could be used to manufacture habitat structural elements, insulation, filters, machine tools and a wide variety of machine parts.

We have produced metals, ceramics, glass-ceramics and metal-matrix composites using SHS. The systems studied are listed below, alongside a list of the highest elemental concentrations observed in the lunar regolith (NASA, 1986 - "The Riches of Space, Near-Earth Resources" U.S. Government Printing Office, Wash., DC, pp 152-181):

SHS Systems Studied by CCACS

Al_2O_3-SiO_2-MgO-TiB_2
Al_2O_3-CaO-TiB_2
Al_2O_3-BaO-B_2O_3-TiB_2
Ni_3Ti-TiB_2
HfB_2-Al
NiTi
TiB

Composition of Lunar Regolith	
Oxygen	42%
Silicon	19%
Aluminum	15%
Iron	12%
Calcium	13%
Sodium	0.3%
Potassium	0.1%
Magnesium	2.4%
Titanium	0.1%
Others	0.1%

The lunar regolith contains most, if not all, of the elements needed for the SHS reactions, and in approximately the same relative abundance that they are found on earth. Because of the other well-known similarities of the lunar and earth soils, it is likely that the starting compounds needed for the SHS systems studied so far in CCACS would be readily available. An energy source is required for ignition of the process. This could be concentrated solar energy or transported hydrogen.

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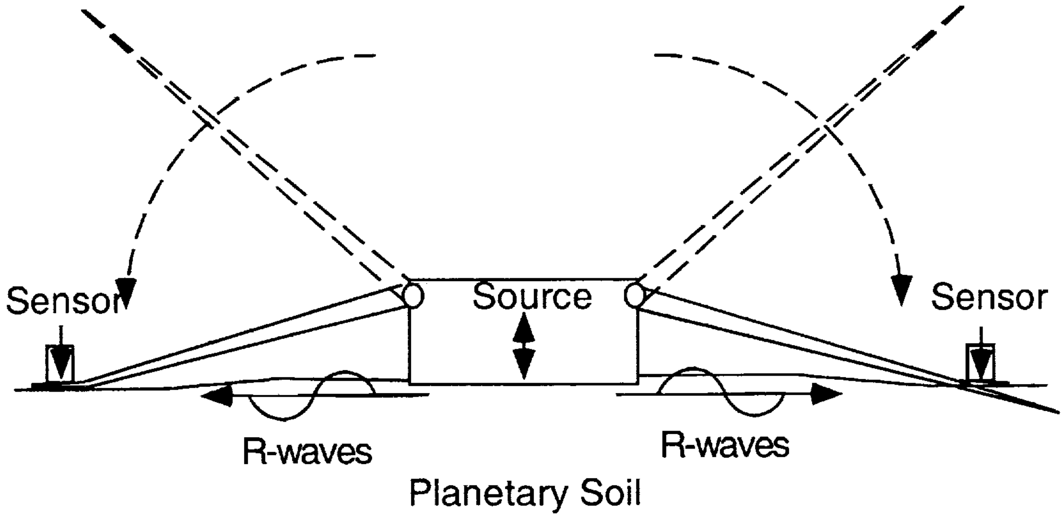
SUBSURFACE EXPLORATION FROM LANDER AND ROVER PLATFORMS WITH SEISMIC SURFACE WAVES.

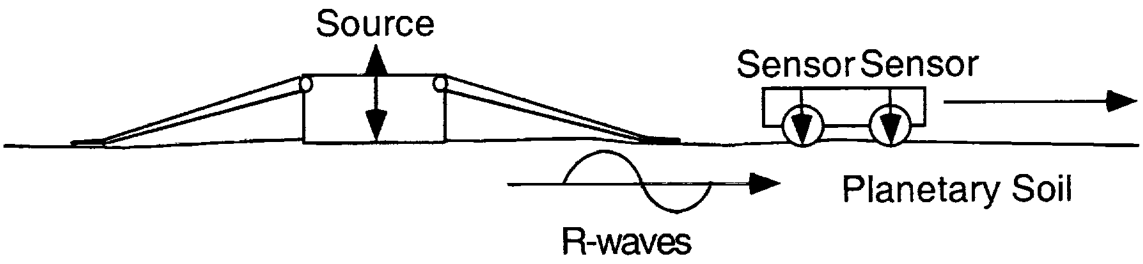
Kenneth H. Stokoe II[1], Stephen G. Wright[1], and W. David Carrier III[2], [1]University of Texas at Austin, Civil Engineering Department, Austin TX 78712 (kstokoe@mail.utexas.edu, swright@mail.utexas.ed), [2]Lunar Geotechnical Institute, 76 Woodside Drive, Lakeland FL 33813 (wdcarrier@prodigy.net).

To develop useful products in space environment, engineering evaluations of relevant geologic materials will have to be conducted early in the exploration phase. These evaluations will be required in the planning and design of constructed facilities and resource recovery operations. One emerging technology for such studies is based on the measurement and analysis of seismic surface waves of the Rayleigh (R) type. All measurements are performed in situ, are nondestructive, and require only instrumentation placed on the planetary surface being investigated. The product of each set of measurements is a profile of shear wave velocity versus depth at the test location. The profile can range from a one-dimensional to a three-dimensional image, depending upon the number and configuration of the measurements. The depth of the profile is proportional to the length of the instrumentation array, with exploration depths of 5 cm to 15 m targeted in this work. The resulting profiles can be used to evaluate or estimate the characteristics of the geologic materials in terms of: 1. layering and lateral continuity in the subsurface, 2. in situ densities and their spatial variations, 3. in situ strengths, 4. weathering processes (especially relative to exterior surfaces of rocks and boulders), 5. crater mechanics, 6. changes in the geologic materials with thermal changes, and 7. identifying ice and characterizing its lateral extent, depth and general composition (massive versus nodules).

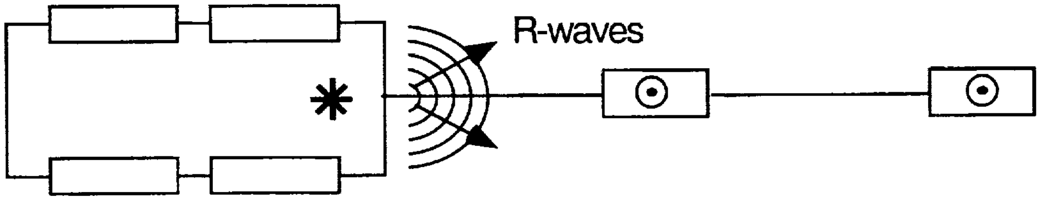
The proposed R-wave technology has a strong scientific basis which is founded on the nature of wave propagation in geologic and other solid materials. Further, this technology has been proven over the past 15 years in experimental and analytical investigations which have been conducted in both terrestrial and marine environments on earth. For application to planetary exploration, however, the R-wave instrumentation needs to be redefined, reconfigured and miniaturized for deployment from lander and rover platforms. In addition, software components and testing protocol have to be tailored and optimized for remote, unmanned operations. Some possible configurations of sources and sensors associated with lander and rover platforms are shown in Figure 1. However, this technology has the potential to be adapted to any physical system which lands on a planet. In addition, the technology is applicable to any mission which involves planetary geology, geophysics and/or geoscience studies. Finally, development of the technology for remote operation has significant potential use on earth. For instance, investigations of hostile environments such as deep-water seafloor sites or hazardous waste sites on land are excellent candidates.



a. All Instrumentation on Lander



b. Source on Lander and Sensors on Rover Wheels



c. All Instrumentation Associated with Rover: Source on Rover and Sensors on Tethered Receiver Platforms (Plan View)

Figure 1 Possible Configurations of Sources and Sensors for R-wave Testing of Planetary Soil and/or Ice from Lander and Rover Platforms

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SPACE WEATHERING AND THE FORMATION OF LUNAR SOIL: THE MOON AS THE MODEL FOR ALL AIRLESS BODIES IN THE SOLAR SYSTEM.

Lawrence A. Taylor, Planetary Geosciences Institute, University of Tennessee, TN 37996, USA (lataylor@utk.edu).

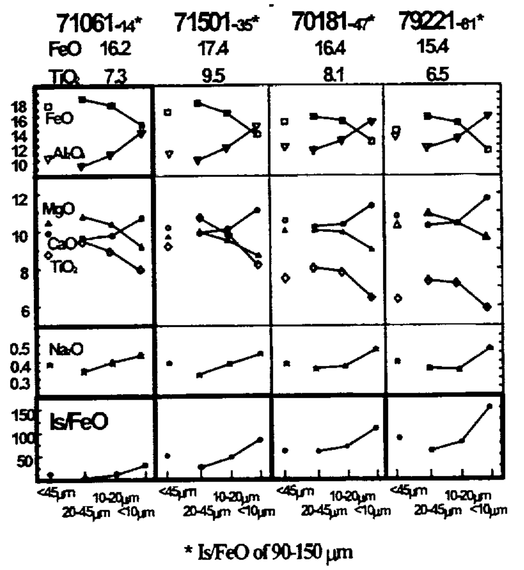
INTRODUCTION Detailed knowledge of the physical, chemical, and mineralogical characteristics of the lunar soil is requisite to understanding the complex processes that have formed this soil. The nature of the weathering processes on the Moon, although markedly different from those on Earth, are the same ones that occur on most relatively smaller, 'airless' bodies in the Solar System, such as asteroids (cf., Vesta, Eros) and moons such as Phobos and Deimos. Therefore, the effects of "*space weathering*" on the formation of lunar soils provides the ground-truth requisite to understanding regolith development on all airless bodies. Indeed, the immediate impetus for the renewed and intensified characterization of lunar soil is driven by the desire to refine remote sensing observations. With this new knowledge comes the fringe benefits that can be directed for efficient planning of practical utilization of lunar regolith at a Lunar Base.

Reflectance spectroscopy is used to determine the chemistry and mineralogy of heavenly bodies, such as the Moon. But, these accurate estimations of rock and mineral compositions are complicated by the nature of the pervasive lunar soil, which contains the cumulative optical effects of "space weathering," including impact-produced glasses, and agglutinates (aggregates of rock and mineral fragments bonded together by glass). A principal cause for the detrimental effects of space weathering concerns the accumulation of *"nanophase Fe^o"* (native Fe of single-domain size – 40-300Å) present in the agglutinitic glass, particularly in the finest fractions of the lunar soils. Indeed, it is the <45 μm fractions of the lunar soils that are most similar to and appear to dominate the spectral signal of the bulk soil. Larger size fractions are not representative of bulk soil properties [1]. The Lunar Soil Characterization Consortium [2-4] of L.A. Taylor, C. Pieters, R. Morris, D. McKay, and L. Keller, was recently established to scrutinize the <45 μm portions of lunar soils, particular from the maria. This endeavor has come up with some unexpected results.

The regolith (<1 cm = soil) was created entirely by the major weathering and erosional agents on the Moon, that is meteorite and micrometeorite impacts. It is micrometeorite particles (< a few mm) which have created the major portion of the soil - gardening and mixing the fragments [e.g., 5]. The larger impacts smash big rock into smaller pieces and move material great distances from its origin, but the actual soil development is a function of micrometeorite impacts. There are only three basic processes which form the lunar soil: 1) *comminution* -disaggregation or breaking of rocks and minerals into smaller particles; 2) *agglutination* - the welding of lithic and mineral fragments together by the glass produced by the quenching of micrometeorite-produced impact melt; and 3) *solar-wind spallation* and implantation. This last process is of minor importance.

The soil consists of rock, mineral, and glass fragments and agglutinates. The glasses, which typically make up 30-60% of a soil, are of three origins: 1) volcanic magma, 2) impact melt, and 3) impact-generated, vapor-deposited coatings [6]. The modal (i.e., vol%) amounts and chemistry of these phases were determined by X-ray digital-imaging analyses, with an EMP, on grain mounts of lunar soils, as detailed by Taylor et al. [7]. With these techniques, *it is possible to fully quantify lunar soils with respect to: 1) volume percentages of particle types (e.g., lithic fragments, minerals, agglutinates); 2) volume percentages of different mineral and glass phases (e.g., pyroxene, agglutinitic glass); and 3) average chemical compositions of the different mineral and glass phases.*

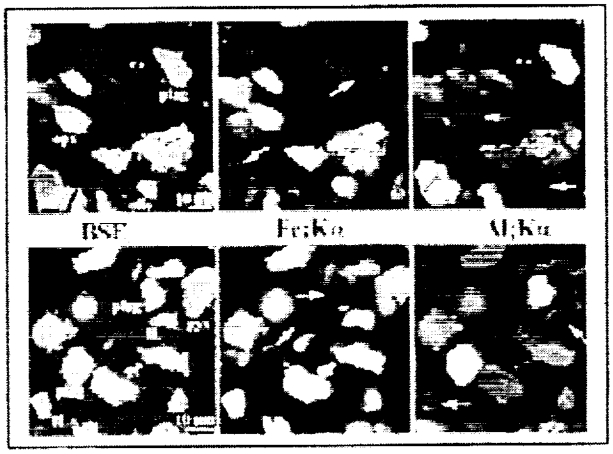
Fig. 1. Soil Chemistry



Soil Chemistry Four Apollo 17 soils were chosen for study based upon their similarities in FeO and TiO$_2$ contents, and for different degrees of maturity, given as Is/FeO values in Fig. 1. The bulk chemistry of these fractions was determined by electron microprobe analyses of fused-glass beads of 5 mg splits. As illustrated in Fig. 1, with decreasing grain size, FeO, MgO, & TiO_2 contents decrease, whereas CaO, Na_2O, & Al_2O_3 (plag components) increase for all soils. These chemical variations would appear to be coupled with the significant increase in agglutinitic glass and decrease in oxide (ilmenite), pyroxene, and volcanic glass. The increase in plagioclase components (CaO, Al_2O_3) in the finer strengthens the 'fusion of the finest fraction' (F^3) hypothesis [8], but also highlights the important role of plagioclase in the formation of agglutinitic glass.

I_S/FeO Values The abundance of nanophase Fe°, as determined by Ferromagnetic Resonance (FMR), is expressed as I_S. This is divided by the FeO content of the soil fraction resulting in I_S/FeO. This represents the proportion of the total iron in a sample that is present as nanophase Fe°, and allows comparisons to be made between soils, as well as between soil size splits. Effectively, I_S/FeO is directly related to agglutinitic glass content, which increases with maturity. Therefore, it is the standard by which the maturity of a lunar soil is expressed [9]. As shown in Figure 1, values of I_S/FeO increase with decreasing grain size, even though the bulk FeO contents are decreasing. That is, the percentage of the total iron that is present as nanophase Fe° has increased substantially in the smaller size fraction. Note that the increase in nanophase Fe° in smaller size fractions is significantly greater than the increase in agglutinitic glass content, with its single-domain Fe° component. This would seem to indicate that at least some of the Fe° is surface correlated, that is on the rims of soil particles, not only in agglutinitic glass. Recent findings [10-13], by members of the LSCC, of the major role of vapor-deposited, nanophase Fe°–containing patinas on most soil particles is a major break-through in our understanding of the distribution of Fe° within agglutinitic glass and upon grain surfaces.

Nanophase Fe as Rims Fig. 2 shows back-scattered electron (BSE) and X-ray map imaging of selected fine portions of mare soil 79921. Each grain in the 10-20 μm split of this mature soil possesses a thin-rind coating that consists mainly of Si- and Al-rich glass. But this glass also contains abundant nanophase Fe°. This was formed by deposition of a Fe-, Si-, Al-rich vapor created by the extreme temperatures reached during impacting processes of even micrometeorites. In Fig. 2, notice that the plagioclase, as shown by the Fe Kα X-ray map, contains these thin (~0.1 μm) coatings of glass but with noticeably higher Fe content than the interior of the plagioclase. In addition, by reference to the Al Kα X-ray map in Fig. 2, Al-rich rims can be seen on orthopyroxene $[Mg_2Si_2O_6]$, olivine $[(MgFe)_2SiO_4]$, and even ilmenite $(FeTiO_3)$, whereas these minerals do not contain appreciable Al in their crystal structures. Detailed HRTEM examination by Keller et al. (1999) has verified patinas of this composition on almost every soil particle in this mature soil. The presence of this rimming nanophase Fe° adds further complications to our knowledge of the ever-complex lunar soil. Specifically, what is the contribution of the nanophase Fe° in the agglutinitic glass versus that in the vapor-deposited rims, especially for the fine size fractions of the lunar soils, and the effects upon the I_S/FeO? This may have important and highly significant ramifications for the formational processes of the soil and the reflectance spectra remotely obtained. With respect to in-situ resource utilization of components of the lunar soil at a lunar base, the magnetic separation of the minerals and glass is probably too complicated to be used for any of the initial missions [14].



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ACOUSTIC SHAPING IN MICROGRAVITY: TECHNOLOGY ISSUES

S. Wanis, N.M.Komerath,
School of Aerospace Engineering
Georgia Institute of Technology

Through student participation in NASA flight tests, we have demonstrated the feasibility of forming complex and useful shapes in microgravity from pulverized material using sound waves, and correlated the shapes to mathematical predictions. The demonstrated potential is exciting, but the concept requires scientific studies before engineering design tools can be developed. The basics of the technology, the results to-date, and the outstanding issues are summarized.

The idea of Acoustic Shaping is simple. Sound waves exert some force on particles. With gravity removed, this force is enough to move the particles. In a reverberating container, solid particles are moved towards the nodes of the sound field. By driving different natural frequencies, one can generate nodal planes of various shapes. If the particles can be held in place long enough, either phase-change or chemical reactions can be used to form hard panels, just as if they were formed over solid molds. Bulky pieces needed for space stations and habitats, could be built using low-grade materials such as lunar dust or regolith, without heavy machine tools, dies and molds from earth. A space-based construction industry could become viable.

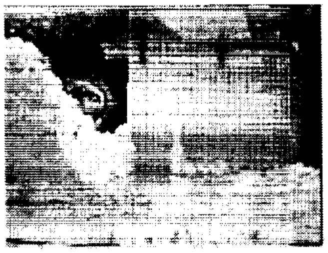

Figure 1: Styrofoam walls form in microgravity: 110 mode, 1250 Hz. From Wanis et al, 1998.

The phenomenon of Acoustic Levitation has been known since the late 1880s [1]. Previous work on Acoustic Positioning, surveyed in [2] had shown that a single particle would move to the point of lowest potential in the chamber. Little was known about the behavior of large groups of particles. Figure 1 shows an example of the answer. Styrofoam particles of random shape formed continuous walls, both straight and curved, inside the chamber. Similar results were obtained using heavier porous particles, hollow spheres of aluminum oxide, and of aluminum. Walls were 1-particle thick in most places. Gaps were filled by arriving particles. Recent results in 1-g show that solid particles and powder floating on liquid binders will also form into continuous walls.

The interaction of the sound with the wall boundary layer produces two secondary effects: a steady "acoustic streaming", and harmonics of the fundamental frequency. The streaming forms pairs of counter-rotating flow structures, as shown in [3], for the flow between two parallel, infinite walls for a longitudinal mode. The actual streaming flow in a rectangular box of finite aspect ratio is 3-dimensional, and we do not know all the time time scales of the motion. Enabling prediction of this flow for various geometries is a major research objective.

The streaming entrains and carries particles around the chamber. Now a second phenomenon takes over: the Acoustic Radiation Force [4] resulting from the interaction between the standing wave field and the sound scattered by the particles. The resulting net force is directed towards the nodes of the standing wave field. In the vicinity of nodal planes, this stabilizing radiation force dominates over the mean streaming drag, keeping the particles along the nodal planes. The fundamental longitudinal mode (100) produces straight parallel walls. Curiously, multiple walls are formed, even when there is only one nodal plane in the chamber. The measurements show harmonics, as predicted, along with the steady flow, by the streaming solution. By deliberately exciting the fundamental and selected harmonics, and controlling their amplitude and phase independently, simulations predict complex, intersecting wall shapes. Under some conditions, these remain stable; others are predicted to be transient.

The student flight experiments on the KC-135 [2,5] have nearly exhausted the list of questions which can be answered using this method for the time being. The conclusions are:

1. In micro-gravity, solid particles in a resonant chamber occupy stable surfaces parallel to nodal planes.
2. The surface shapes conform to predicted natural response of the chamber.
3. Symmetric, curved and complex shapes can be formed using higher-order modes.
4. The formation of stable, intersecting walls is predicted for combinations of harmonics.
5. By adjusting phase between drivers, shapes and locations can be continuously controlled.
6. Moderate particle loading in the chamber does not degrade acoustic performance.
7. Acoustic streaming transports particles to the stable surfaces.
8. Increased sound pressure amplitude increases the chaos level of the streaming flow.
9. Measurements of the velocity field in the chamber agree with the order of magnitude of the streaming flow predicted for a resonant longitudinal mode between infinite parallel walls.
10. The effect of g-jitter depends on its frequency content. Low-frequency jitter destroys walls by moving particles

away from nodes, while high-frequency jitter can be tolerated.

11. In stable microgravity, phase-controlled acoustic shaping appears to be straightforward.
12. Prediction of the sound fields required for each shape, and refinement of surface shapes, require detailed modeling of several phenomena.

Outstanding Problems and future work

A full-scale manufacturing facility in orbit would be robotically run. Materials in pulverized form will be delivered from low-gravity environments. For low-temperature formation, liquids would be injected in atomized form into the chamber, after the solids are formed into walls. Sintering operations would use radiant heating to melt the surface layers and then harden the walls by cooling. The formed panels would then be removed and post-processed for shipment to assembly points. The outstanding technical problems are:

1. Interaction between phase change of the material, and the acoustic field
2. Inverse design of the sound field required to form a given shape.
3. The properties of panels hardened without molds or high pressure, in microgravity.

Each of these is considered in the paper, along with other secondary issues, and the problems faced are shown to be tractable.

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