Hot Idea

posted December 23, 2004

Cosmochemistry and Human Exploration

--- Cosmochemistry plays an important role in developing local resources on the Moon and Mars, essential to sustained human presence in space.

NASA

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About 125 scientists, engineers, business men and women, and other specialists attended the sixth meeting of the Space Resources Roundtable, held at the Colorado School of Mines in Golden, Colorado. The meeting was co-sponsored by the Space Resources Roundtable, Inc. (a nonprofit organization dedicated to the use of space resources for the benefit of humankind), the Lunar and Planetary Institute, and the Colorado School of Mines. Presentations and discussions during the meeting made it clear that the knowledge gained from cosmochemical studies of the Moon and Mars is central to devising ways to use in situ resources. This makes cosmochemistry central to the human exploration and development of space, which cannot happen without extensive in situ resource utilization (ISRU). Cosmochemists at the meeting reported on an array of topics: the nature of lunar surface materials and our lack of knowledge about surface materials in permanently shadowed regions at the lunar poles; how to make reasonable simulated lunar materials for resource extraction testbeds, vehicle design tests, and construction experiments on Earth; and how to explore for resources on the Moon and Mars.

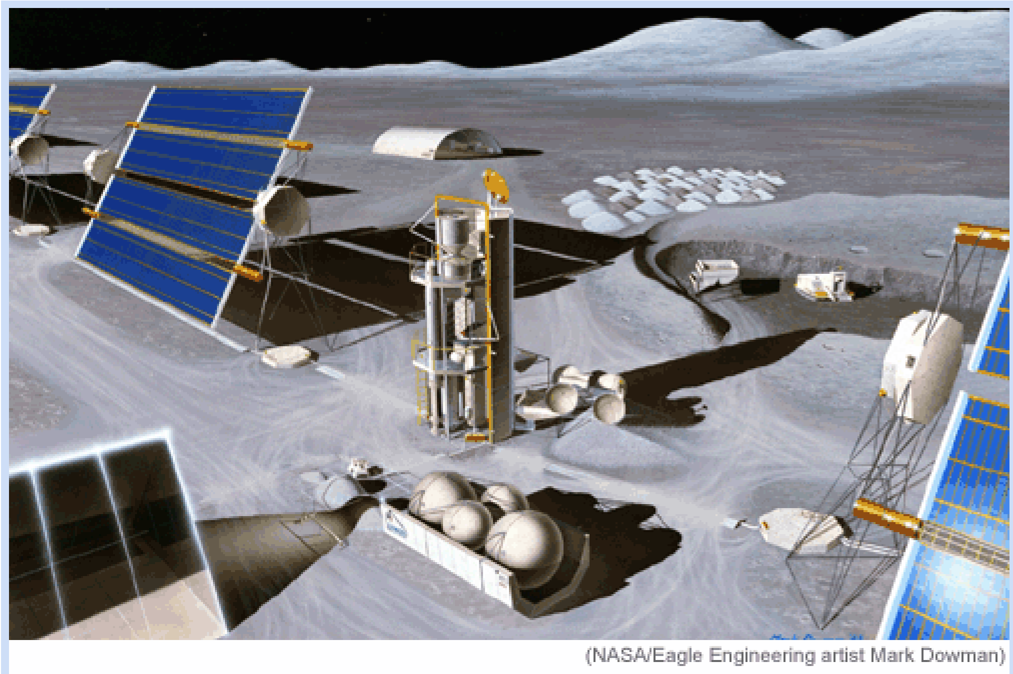
Reference:

Space Resources Roundtable VI, LPI Contribution No. 1224, Lunar and Planetary Institute, Houston. Abstracts available online courtesy of the Lunar and Planetary Institute. Presentations available online courtesy of the Space Resources Roundtable. [Links open in new window.]

ISRU Essential for Sustained Human Presence in Space

In January 2004, President George W. Bush announced a visionary plan to explore space, calling for sustained human presence on the Moon and then Mars. The plan emphasizes the use of the abundant resources of the Moon and Mars. In fact, sustained human habitation of the Moon and Mars is impossible without in situ resource utilization (ISRU). It is simply impossible to haul everything we need up from the deep gravity well of the Earth and plop it all down on the lunar surface, let alone onto the Martian surface.

Not only will the availability of resources--materials and energy--reduce the difficulty and cost of exploration programs, by "living off the land," but will allow commerce to take root outside of the Earth. Using space resources for propellant will reduce the cost of operating in space by allowing complex extraction systems built on Earth to replace the tremendous payloads of inert propellant that now must be transported into space. Using space resources to capture, transform, and transport energy in space will replace the need for heavy, expensive payloads lifted off Earth. Production of the raw materials of space for construction and manufacturing will ultimately sever the umbilical that, until now, has bound space travel to the Earth, and will allow self-sufficiency to take root beyond the boundaries of Earth.



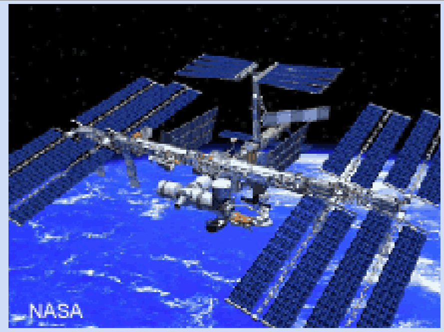
This NASA painting of the lunar landscape shows a concept for a pilot plant to produce liquid oxygen propellant derived from lunar raw materials. More than merely oxygen, this picture symbolizes ISRU--the use of in situ resources on the surfaces of other planetary bodies. [High resolution version]

Cosmochemists make up one of the main pillars of this exciting venture. They will find the resources on other planets--indeed, they already have identified and determined the chemical and mineralogical properties of several key resources such as the presence of helium-3 for use in nuclear fusion reactors or concentrations of ilmenite for use as a feedstock for oxygen extraction. Cosmochemists have been major players in devising ways to extract resources from the lunar regolith (much less work has been done for Mars). A prime example is the demonstration of extracting oxygen from the lunar regolith by reduction of ilmenite and glasses rich in iron oxide, which has been done independently by Lawrence Taylor (University of Tennessee) and Carl Allen and David McKay of the Johnson Space Center. There are many other examples. Cosmochemists will also be in the forefront of developing flight-ready testbed factories by providing expertise into the nature of lunar and Martian surface materials and by making mineralogical and chemical analyses of the products produced by prototype machinery. All that, while still continuing to extract the scientific secrets held by the Moon and Mars.

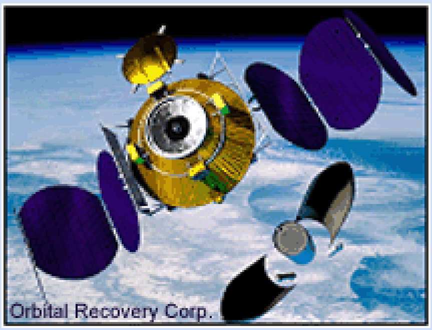
Vision for an Economic Market

Who's going to buy all those resources? Brad Blair, Mike Duke, Javier Díaz, and Begoña Ruiz (all at the Colorado School of Mines) are developing complex economic models of space development centered on propellant production from the Moon. Blair and his colleagues identified the potential markets, increasingly farther into the future, arranged below from top left to bottom right.

Fueling space science missions throughout the solar system

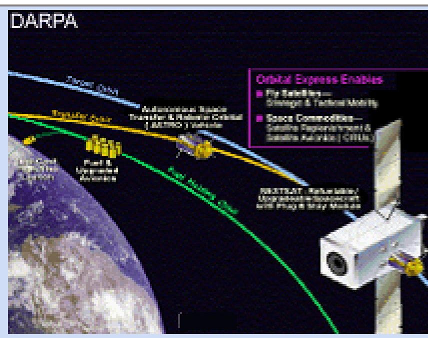


Supplying the International Space Station or its successor

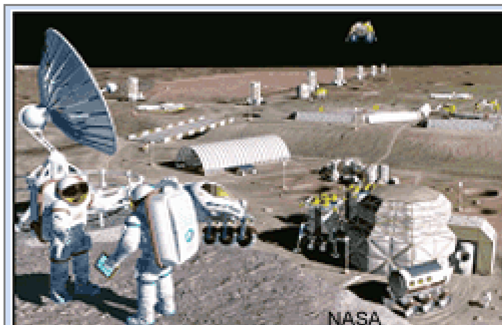


Refueling communication satellites in earth orbit
(Image from: Orbital Recovery Corporation.)

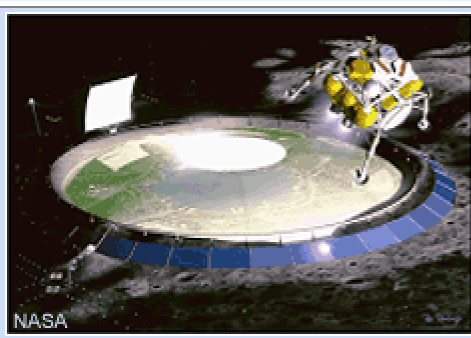
Providing fuel and materials for satellites that manage debris in low earth orbit



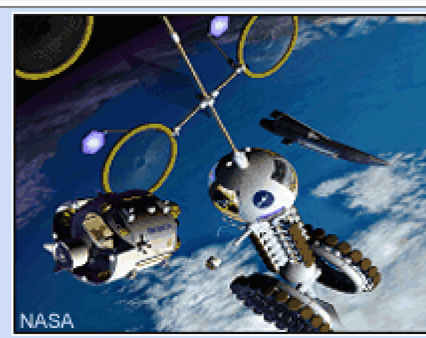
Refueling and maintaining reconnaissance and terrestrial remote sensing satellites in low earth orbit and in geosynchronous orbit



Providing fuel and life support to human exploration of the Moon and, eventually, Mars



Providing fuel, life support, and materials for sustained human presence on the Moon, including perhaps an elaborate solar-powered colony on the Moon that could market its products

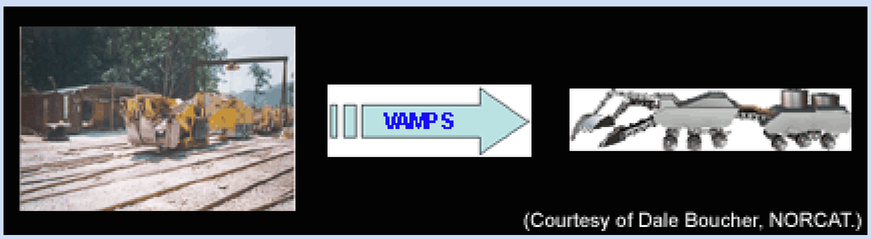


Produce, fuel, and maintain solar power satellites in earth orbit to provide energy to the planet

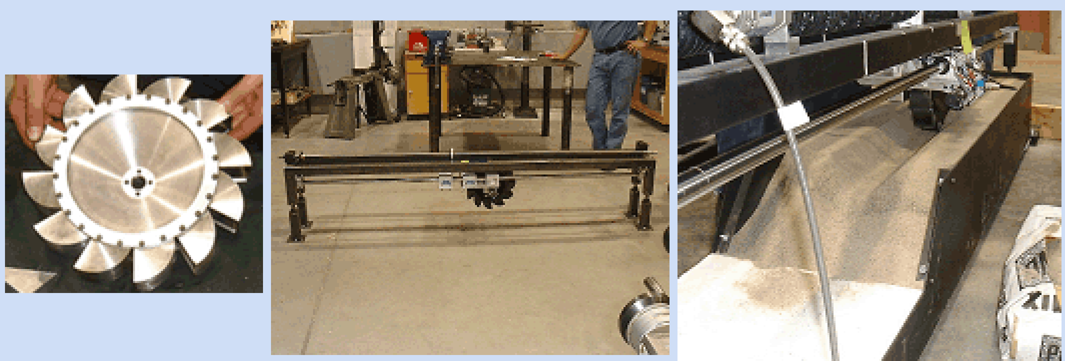
Not Your Daddy's Mining Gear

Dale Boucher and Jim Richard (Northern Centre for Advanced Technology, Inc., NORCAT, located in Sudbury, Ontario, Canada) shared their expertise in mining. It begins with searching for a potential resource (prospecting), which we have already started to do for the Moon and Mars through human (to the Moon) and robotic (to both) missions. Once identified you explore the prospect in detail (implying spacecraft that land on the surface), then mine it. The mined materials are usually beneficiated (minerals separated and concentrated), though this might not be necessary at first on the Moon. We then process the mined materials to make products (e.g., metallic iron, oxygen, water). This step produces some waste, that must be managed, and useful products. This is, among other things, applied cosmochemistry at its most artful.

The trick, Dale Boucher told Roundtable participants, is to transform traditional Earth-based mining equipment into efficient and light-weight gear to use on other planets. He calls it the VAMPS process: Eliminate Volatiles (we can't use drilling fluids, for example), Automate (make extensive use of robotics), Miniaturize (lower the size and mass), redefine the Paradigm (do things completely differently if need be), and Stabilize. The result is new mining equipment and approaches. An interesting example is the NORCAT design of a bucket wheel for excavating the lunar regolith. It is small, takes little power, but can excavate efficiently. Boucher and his team plan more tests with simulate regolith.

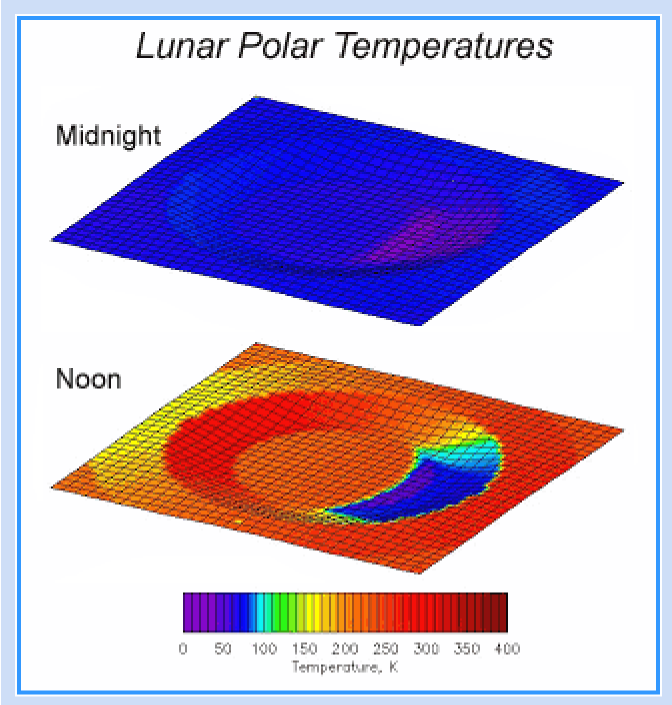


(Courtesy of Dale Boucher, NORCAT.)
The VAMPS process starts with traditional mining or construction equipment and changes it in suitable ways for use on another planetary body.


(Courtesy of Dale Boucher, NORCAT.)
Experiments with a bucket wheel excavator designed at NORCAT in Sudbury, Canada. Shown from left to right are the wheel with its buckets, the test platform, and the bucket wheel excavating sand during a test.

The Cold, Mysterious Lunar Poles

There are places on the Moon where the "Sun don't shine." These regions are located at the lunar poles, shaded by mountains formed by the rims of impact craters. They exist because the Moon's spin axis is tilted only a small amount from being perpendicular to the plane of its orbit, allowing mountains to cast long shadows and creating places in permanent shadow; see PSRD article: Ice on the Bone Dry Moon. These are cold places. Without direct sunlight, the only sources of heat are the background energy in the universe (only 3 Kelvin), reflected sunlight off distant hills, and heat flowing from inside the Moon. The heat from below would cause the temperature to be only about 25 Kelvin (-248 ^{o}C). There might be rare places that cold if they are not exposed to any reflected sunlight. Most receive some indirect sunlight, but they reach at most 80 Kelvin (-193 ^{o}C) even during the hottest part of the lunar day, and many places in permanent shadow get no hotter than about 60 Kelvin. At night the temperature falls to less than 50 Kelvin. Ben Bussey (Johns Hopkins University Applied Physics Lab), a leading expert on illumination conditions at the poles, enlightened the audience with an updated report on lighting conditions (see **PSRD** article: The Moon's Dark, Icy Poles).



(Courtesy of Ashwin Vasavada, UCLA.)

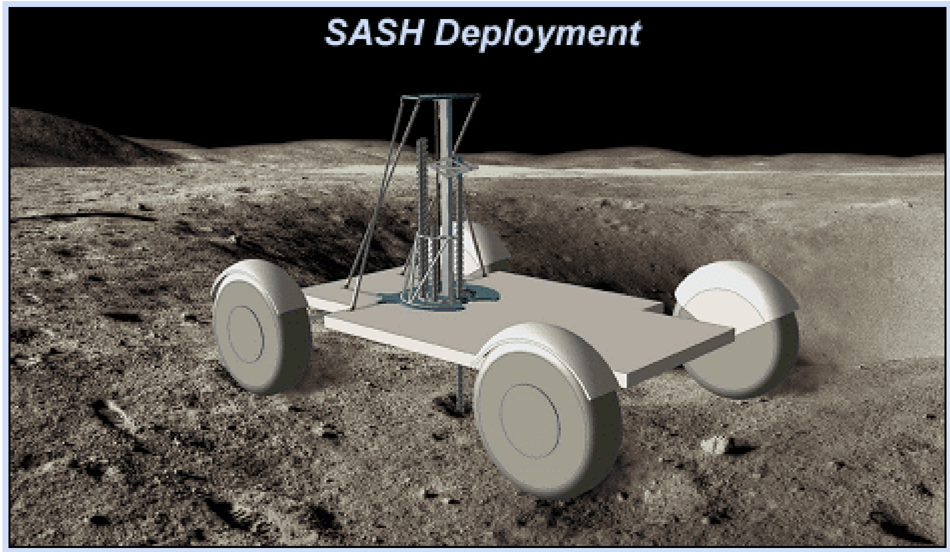
Distribution of temperatures inside a large flat-floored crater in a lunar polar region were calculated by Ashwin Vasavada (UCLA), an expert in thermal modeling of planetary surfaces. During the long lunar night the surface everywhere cools to less that 80 Kelvin, with some areas less than 50 Kelvin. But even during the hottest part of the lunar day, some portions of a crater like this remain very cold, reaching no more than 80 Kelvin. These regions can trap volatiles like H_2O, CO, and CO_2, and might be important sources for propellant to drive commerce throughout the inner solar system. Courtesy of Ash Vasavada, Univ. of California, Los Angeles.

Permanently dark areas could collect volatile materials otherwise scarce on the Moon. The most important of these is water. The neutron detector onboard the Lunar Prospector mission showed clearly that there is an enrichment of hydrogen (H) in polar regions, but could not determine whether it was in the form of H_2O, molecular hydrogen (H_2), elemental hydrogen, or some other form. The Clementine mission rigged an innovative radar experiment that suggested the presence of water ice, but observations of portions of the south pole using the huge radio telescope in Arecibo, Puerto Rico did not detect ice. The issue remains highly controversial, but leaves the rest of us lots of room to speculate on the nature of the hydrogen in polar regions.

If the hydrogen is in the form of H_2O ice, it could be an enormously important resource that could drive commercial development of the Moon, as Brad Blair and his colleagues discussed at the Roundtable. Before any commercialization can take place, however, cosmochemical prospectors have a lot of work to do. As I noted in my talk at the meeting, we know very little about the nature of the surface in the permanently shadowed areas of the Moon. The ground up rock might be finer grained than the regolith (fragmental surface materials on the Moon) we sampled at the Apollo landing sites, including that at the Apollo 16 site in the ancient highlands.

More important, if water condensed onto silicate grains at the cold temperatures in the shadows it would not be in the form of the familiar crystalline ice. It would be amorphous, lacking any long-range order to the H and O atoms--sort of an icy glass. In contrast to crystalline ice, this structure is quite accommodating to gases such as those in comets (carbon dioxide, carbon monoxide, methane). When amorphous ice (also called amorphous solid water) is heated above about 120 Kelvin, it changes to the crystalline form, releasing the trapped gases. This is one of the reasons why comets spew gas and dust. Thus, if we tried to mine the ice to make hydrogen and oxygen for propellant, heating the icy regolith might cause rapid loss of the water we were trying to mine. Heat is also released as amorphous ice transforms to crystalline ice, which could cause a runaway effect-catastrophic loss of a precious resource, at least locally.

But all that is speculation at present. We need to conduct experiments on regolith with ice in it, with and without other gases. This needs to include understanding what happens when the regolith is gardened by the rain of tiny meteorites that continuously strike the Moon. Most important, we need to characterize the permanently shadowed places thoroughly from orbit and with robotic landers equipped with sophisticated analytical instruments. NASA is planning such missions during the next five years. A talk by James Powderly and colleagues at Honeybee Robotics (in collaboration with scientists at the Johnson Space Center, Ames Research Center, Jet Propulsion Laboratory, Boeing, the Army Corps of Engineers, and Los Alamos National Laboratories) highlighted one well-tested concept for sampling the icy, cryogenic regolith in polar regions. Called the Subsurface Analyzer and Sample Handler (SASH) it is basically a drill equipped with instruments to measure physical properties, and the concentration and distribution of water ice (or hydrogen) in the regolith, using a rover as the drilling platform.

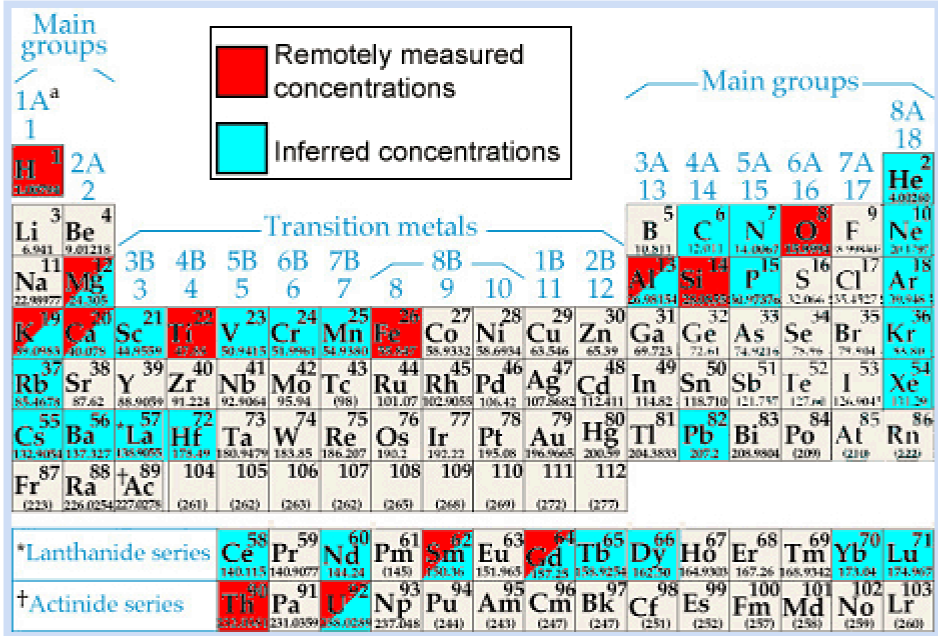


(Courtesy of James Powderly, Honeybee Robotics, Ltd., New York, NY)

Concept of SASH (Subsurface Analyzer and Sample Handler) operating from a rover on the lunar surface. The device can acquire cores and powdered samples from beneath the surface and deploy instruments down the holes to characterize the regolith, including detecting ice and hydrogen.

Exploring for Resources

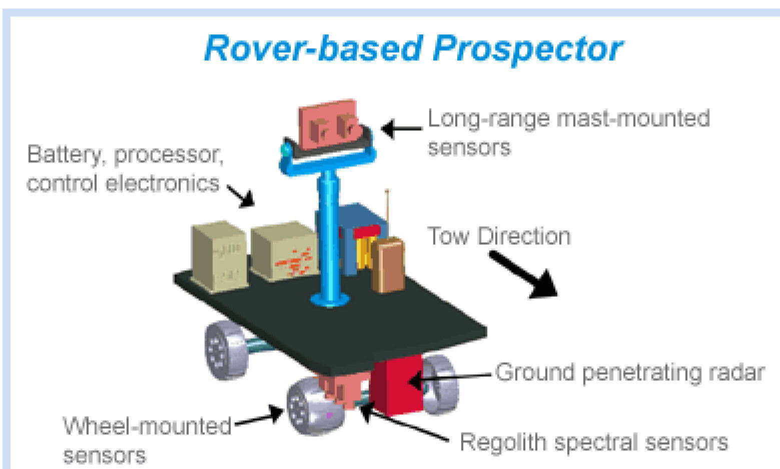
My colleague at the University of Hawai'i, Jeff Gillis, discussed the general problem of exploring for resources using orbital remote sensing. He explained that an important step in exploration is to understand what you need and to search for those substances. Quoting Dr. Phil, Gillis noted, "In order to get what you want you have to know what it is you want." In lunar exploration terms this means that we must develop strategies for resource exploration and efficient methods of extraction. Remote sensing surveys (orbiting and roving spacecraft) will provide the ability to select a site for the first lunar base. Gillis showed the value of remote sensing measurements to determine the locations of numerous resources. Although only a few elements can be measured remotely, others can be inferred from the concentrations of just one element. A prominent example is the concentration of thorium, which has been measured by the Lunar Prospector mission. High thorium concentrations are correlated in lunar samples with the concentrations of potassium, rare earth elements, zirconium, phosphates, and others. Thorium is a tracer for a host of other potentially valuable resources.



(Courtesy of J. Gillis, Univ. of Hawaii.)

A large number of elements can be measured directly by remote sensing techniques or inferred from the concentrations of tracer elements or other properties. These correlations were established by cosmochemists in their analyses of lunar samples.

Richard Dissly (Ball Aerospace and Technologies Corp.) and colleagues from several university and government laboratories discussed the idea of prospecting for resources using an autonomous rover equipped with an array of sensors. The sensors would be mounted in the wheels, on the front of the rover, and on a mast on the rover. All would work in consort to identify resource targets, such as concentrations of ilmenite or volcanic glasses. The virtue of autonomy is that it increases the speed of mapping, lowers operational costs, and is safer than doing it all with humans exposed to the space environment. It is also applicable for exploration on both the Moon and Mars.



(Courtesy of Richard Dissly, Ball Aerospace and Technologies Corp.)

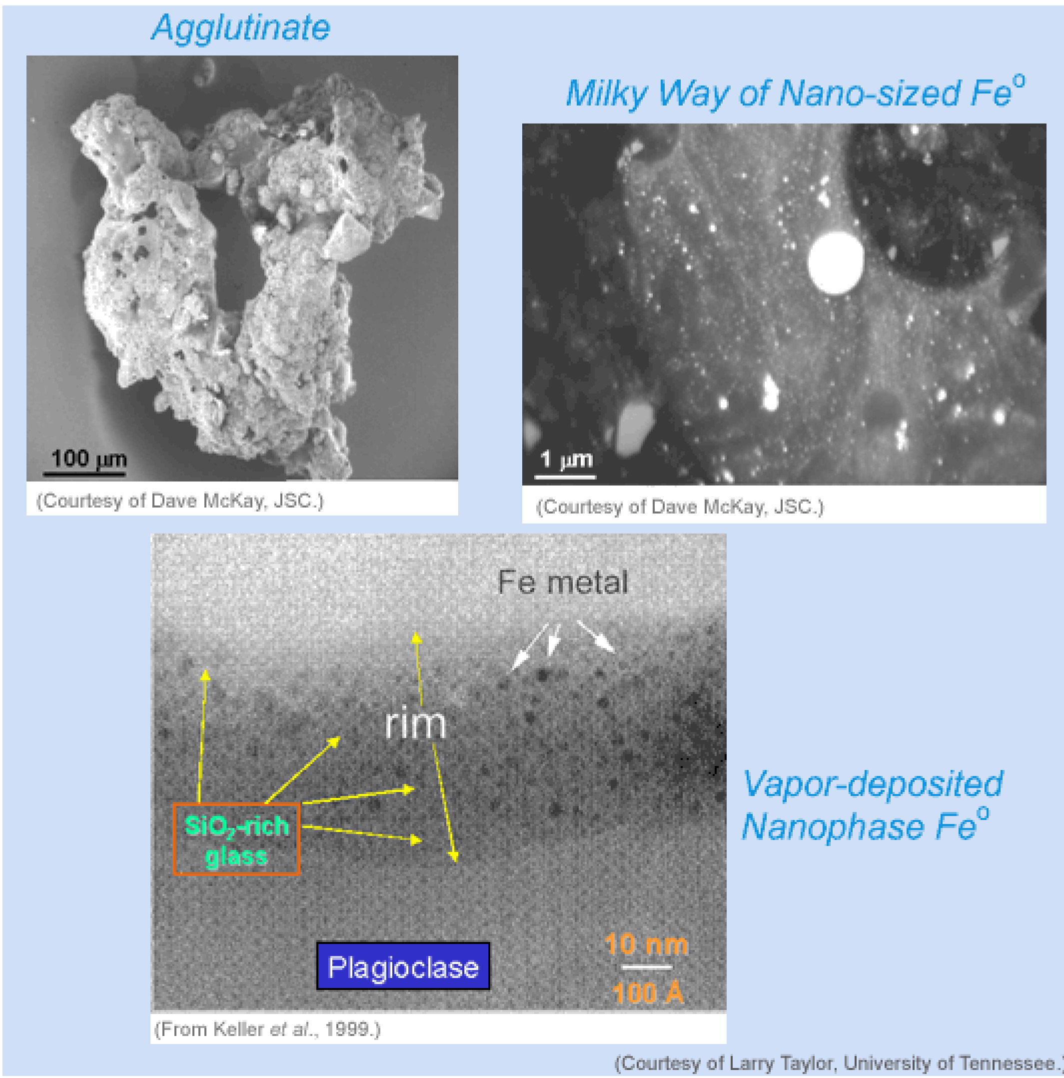
Rich Dissly's concept for an autonomous prospecting rover for use on the Moon and Mars.

Making Fake Moon Dirt

As mentioned above, permanent habitation and industrial use of the Moon and Mars will require that we live off the land-ISRU is essential. Developing techniques to excavate regolith, move it, separate its components, heat it, melt it, dissolve it, or even just pile it up will require a lot of experiments. Although Apollo astronauts returned 382 kilograms (840 pounds) of rock and regolith, the material is much too valuable to use for extensive experimentation. We need simulated lunar regolith-and lots of it. Seven participants at the Roundtable meeting indicated they would need more than

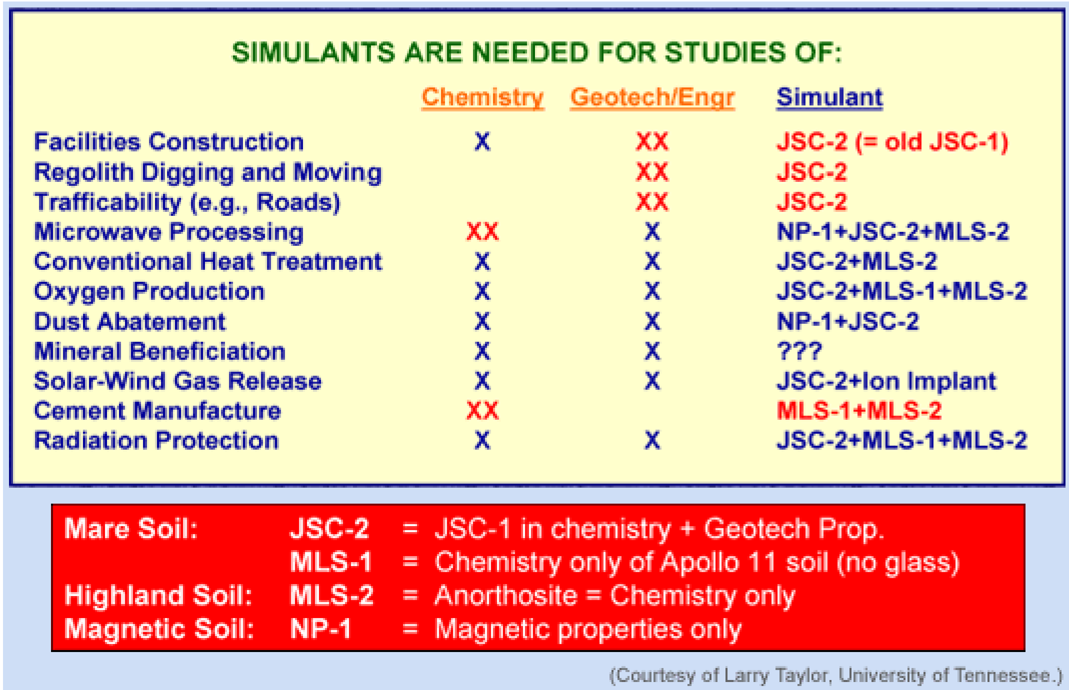
10 tons, and two indicated that they would need more than 100 tons. Larry Taylor (University of Tennessee) reports that he knows of one company that expects to use 600 tons. From this somewhat limited sampling, it is apparent that there will be a near-term need for a quantity that could approach 1000 tons of lunar soil simulant.

That's a lot of fake moon dirt. And it is not ordinary dirt. Larry Taylor reviewed the nature of the lunar regolith. It has some unique properties. Chief among them is the presence of glassy agglutinates, twisted, bubbly, swirly aggregations of rock and mineral fragments bound together by impact-produced glass. The glassy portions are decorated by a Milky Way, as Larry Taylor put it, of microscopic grains of metallic iron. The tiny metal grains are probably produced when hydrogen, implanted into the surface by the solar wind, reacts with iron oxide when the glass forms by micrometeorite impacts. Microscopic metal grains also form when impacts cause vaporization of surface materials. The environment is reducing, so extremely small metallic iron grains condense on the surfaces of mineral grains. This makes them magnetic.



Some of the unique properties of lunar regolith are shown here. Clockwise from the upper left: Agglutinates are glass-bonded aggregates of other regolith components. They contain countless microscopic grains of metallic iron (shown in the second image) formed by reduction of iron oxide present in the glass. The surfaces of mineral grains, even minerals that contain no iron, are coated with a mixture of silicon-rich glass and nanometer-sized grains of metallic iron (bottom image). It will not be easy to duplicate these properties.

The regolith has a distinctive distribution of grain sizes, high quantities of gases implanted by the solar wind (such as hydrogen and helium), crystals damaged by impact and radiation, and variable chemical composition. Some of these properties can be readily duplicated. Others will be difficult. Some might be impossible. Nevertheless, standardized simulants are needed so experiments in different laboratories can be compared readily to one another. Nevertheless, as Larry Taylor pointed out, one stimulant does not fit all. The chart below shows the types of uses of regolith simulants, what general type of property needs to be simulated, and a list of simulants that have been used. The **"Xs"** refer to the extent to which the property was successfully simulated--the greater the number the more accurately the property is matched by a stimulant.


SIMULANTS ARE NEEDED FOR STUDIES OF:

	Chemistry	Geotech/Engr	Simulant
Facilities Construction	X	XX	JSC-2 (= old JSC-1)
Regolith Digging and Moving		XX	JSC-2
Trafficability (e.g., Roads)		XX	JSC-2
Microwave Processing	XX	X	NP-1+JSC-2+MLS-2
Conventional Heat Treatment	X	X	JSC-2+MLS-2
Oxygen Production	X	X	JSC-2+MLS-1+MLS-2
Dust Abatement	X	X	NP-1+JSC-2
Mineral Beneficiation	X	X	???
Solar-Wind Gas Release	X	X	JSC-2+Ion Implant
Cement Manufacture	XX		MLS-1+MLS-2
Radiation Protection	X	X	JSC-2+MLS-1+MLS-2

Mare Soil:	JSC-2	= JSC-1 in chemistry + Geotech Prop.
	MLS-1	= Chemistry only of Apollo 11 soil (no glass)
Highland Soil:	MLS-2	= Anorthosite = Chemistry only
Magnetic Soil:	NP-1	= Magnetic properties only

(Courtesy of Larry Taylor, University of Tennessee.)

James Carter (University of Texas, Dallas) discussed the manufacturing of the widely used, but now used up, lunar stimulant JSC-1 (commissioned by the Johnson Space Center, JSC). He explained the value of simulants, the need for a standardized set of simulants, and described what properties of the regolith JSC-1 matched and did not match. It simulated the chemical composition of some Apollo soils, the types of minerals and glass present in the regolith, and the grain size distribution of the typical regolith. JSC-1 did not match the spectral properties in visible and near-infrared wavelengths, magnetic properties and the presence of microscopic metallic iron, the shapes of agglutinates, and the high contents of solar wind gases.

(Courtesy of James Carter, University of Texas, Dallas.)

Lunar simulant JSC-1 was produced from a volcanic deposit located near Flagstaff, Arizona under the supervision of James Carter. Twenty-five tons of it were produced and distributed by the astromaterials curatorial laboratory at the Johnson Space Center, but none is available now. Industry will need up to 1000 tons of stimulant to develop the technology for ISRU leading to permanent habitation and industrialization of the Moon.

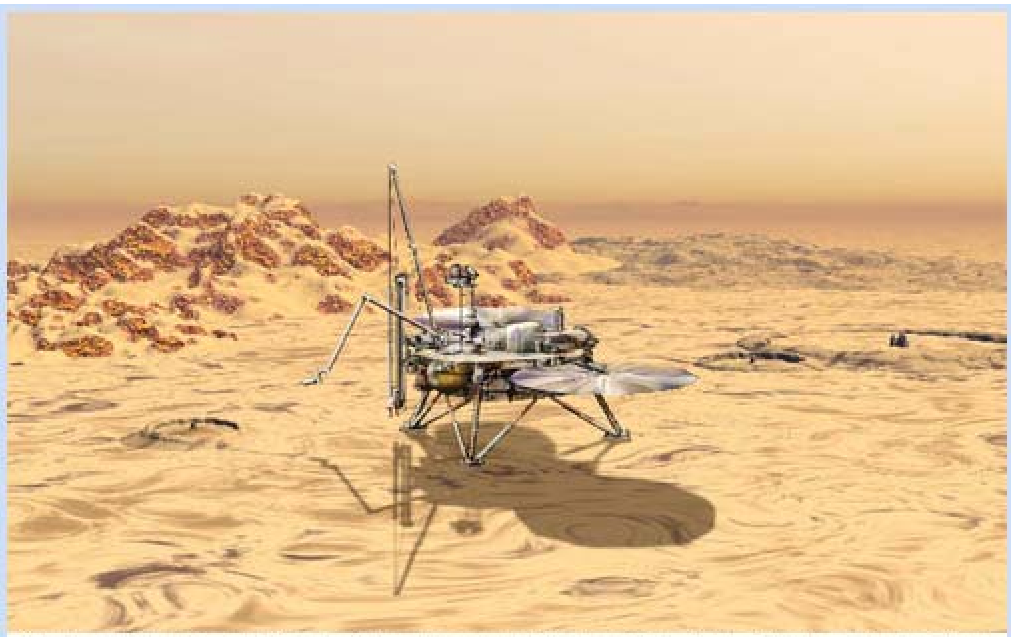
Most important, Carter introduced the concept of a "root stimulant," a basic mixture of minerals, rock fragments, and glassy objects. At least two of these are needed for the Moon: one with a chemical composition of a typical lunar maria and a second with a highlands composition. These basic root stimulants will be useful for many purposes, and specialized simulants (branches from the root) can be made from them. These might contain solar wind implanted gases, partly reduced iron, soil-ice mixtures (for the dark areas at the poles), vapor-coated grains, and many other features.

Marshall Space Flight Center is organizing a workshop on lunar simulants January 24 -26, 2005 to discuss in detail the problem of making simulants, how much to make, what properties should be simulated by a root simulant, and many other issues.

ISRU on Mars

Partly because less work has been done on ISRU processes for Mars and partly because President Bush's Exploration Vision calls for going to the Moon first, there was not much discussion of ISRU on Mars. However, one particularly important issue was addressed in separate presentations given by Carol Stoker (NASA Ames Research Center) and Humbolt Mandell (Center for Space Research, University of Texas, Austin): the need for deep drilling on Mars. This is essential for scientific exploration and for resource extraction. Stoker made a compelling case for being able to drill a few hundred meters in places where liquid water might reside beneath the surface because of over pressurization of ground ice. There are hundreds of places where gullies emerge from the sides of craters. The existence of liquid water only a few hundred meters below the surrounding plains is an enticing target for human bases and for the search for existent life on Mars. We only have to drill.

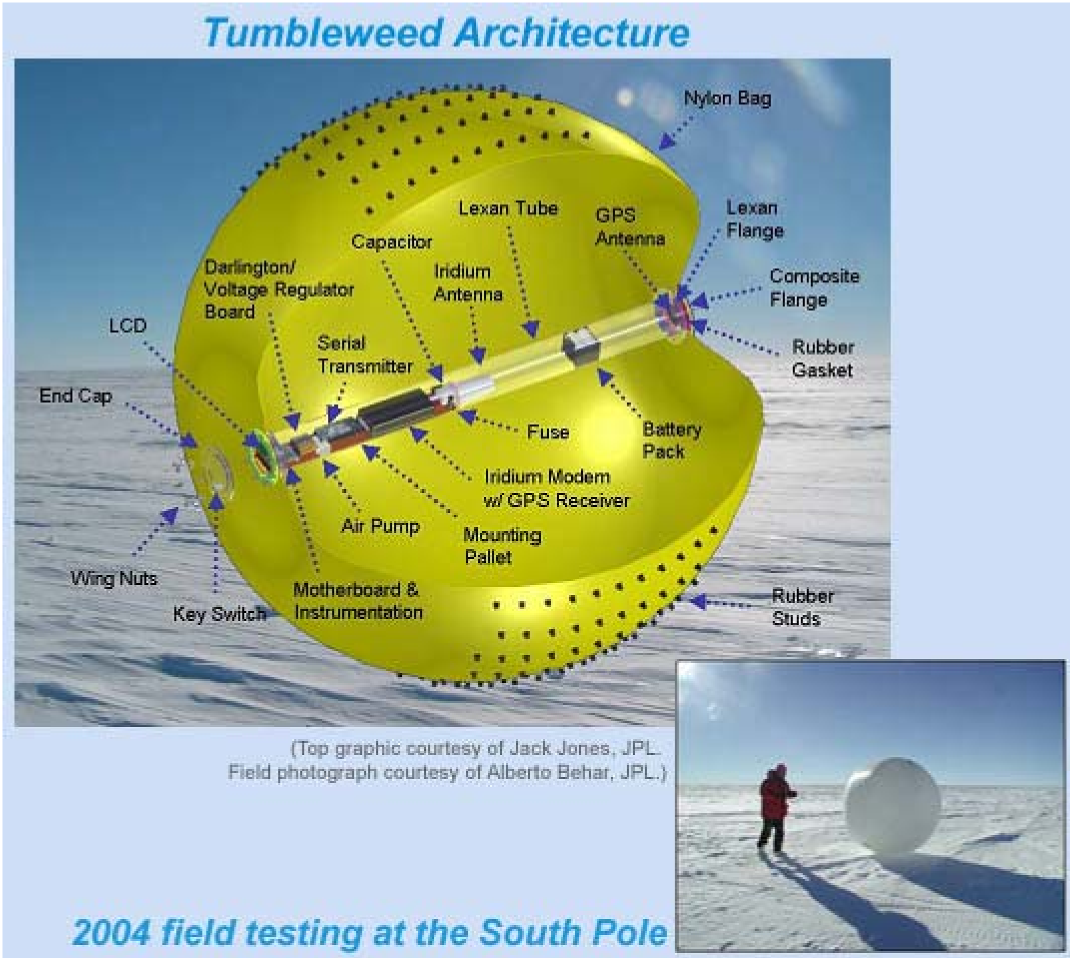
But drilling is not as simple as you might think, particularly if we do not use traditional lubricants, essential to prevent contamination that could compromise our search for life on Mars. The presentations by Stoker, Mandell, and Powerly (discussed above) all show that deep drilling is feasible, though some development is still necessary. The designs of drilling equipment are surprisingly similar, whether from Honeybee or from a design based on drilling technology developed by Baker Hughes, one of the foremost terrestrial drilling equipment companies. There was a strong consensus that deep drilling is an essential part of resource exploration and the search for life on Mars.



(Courtesy of Hum Mandell, Center for Space Research, University of Texas, Austin. Graphic by Kandis Elliott.)

Painting of a concept for a Mars lander equipped with a drill.

Two talks centered on the exploration for other resources on Mars. A presentation by Chris Woodworth-Lynas and his colleagues at Guigné Space Systems Inc. (Golden, Colorado) focused on rover-based instruments to search for resources on Mars. This included apparatus to make seismic measurements, with the geophones (seismic receivers) made from Micro-Electro-Mechanical Systems (MEMS) and mounted in the wheels of the rover. Kim Kuhlman (Jet Propulsion Laboratory) and colleagues from JPL and NASA Langley Research Center described an updated version of a fascinating concept called Tumbleweed proposed in the late 1970s by Jacques Blamont (JPL and the University of Paris). The idea is to make inflatable, light-weight balls that would travel with the winds of Mars to sample a wide area and map the distribution of potential resources on the surface. Each Tumbleweed would carry a suite of instruments that would measure soil properties, water vapor, mineralogy, and chemical composition. Kuhlman's JPL colleagues, Alberto Behar and Jack Jones, have tested the concept in Greenland and Antarctica. Tumbleweeds would fill a gap between orbiters and rovers. They would go wherever the wind took them, searching for answers about Martian geology and resources--the answer, my friend, is blow'in in the wind.



Model of Tumbleweed, showing components inside the light-weight spherical prospector. It has been tested in Antarctica (inset photo) and Greenland.

Other Great Ideas

PSRD concentrates on discoveries in cosmochemistry and planetary geosciences, so this report highlights mostly those areas. However, readers will find a wealth of fascinating ideas in the abstracts and the presentations given at the Roundtable meeting. You'll find out about the mysteries of granular flow, the production of metallic parts by carbonyl vapor deposition, automated mining techniques, and more.

Next Steps

The assembled cosmochemists, remote sensing specialists, engineers, construction experts, business men and women, entrepreneurs, and other technical experts and dreamers at the Roundtable meeting discussed the need to include ISRU right from the start in planning human activities on the Moon. All of the needed materials and energy to create a self-sufficient lunar outpost are available there and their use is essential to attain self-sufficiency and prepare the way for affordable travel to Mars. At some level of development, if we plan well, a lunar outpost can achieve economic "takeoff," from which it then becomes possible to cut the umbilical from Earth and provide products to Earth and to ventures in cislunar space in free-market exchanges. When that stage of development has been reached, the ingenuity of humans on the Earth and in space will provide new businesses and products to improve standards of living on Earth. In the meantime, it will be a role of the Exploration Vision to blaze the technology trail and of NASA to investigate the mechanisms by which new private investment in space can be encouraged.

In a white paper (pdf) written on behalf of the Space Resources Roundtable and based on the clear consensus at the meeting, Michael Duke (Colorado School of Mines) and I concluded:

> "We encourage NASA to establish a Space Resources Council that would be responsible for evaluating the political and economic framework in which space resources are developed and encouraging the development of the needed technology. Industry should play a role in the decision-making that must go into the integration of these important new technologies into NASA's exploration programs. Fulfilling the Exploration Vision requires that we invest immediately in the tools and techniques required to use space resources."

Additional Resources

David, L. (2004) Mining the Moon, the Gateway to Mars, *space.com*. http://space.com/businesstechnology/technology/moon_mining_041110.html

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Space Resources Roundtable VI, LPI Contribution No. 1224, Lunar and Planetary Institute, Houston. Abstracts available online courtesy of the Lunar and Planetary Institute. Presentations available online courtesy of the Space Resources Roundtable. [Links open in new window.]

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Taylor, L. A. (2004) The Need for Lunar Soil Simulants for ISRU Studies. white paper (pdf).

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