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Headline Article
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Using the Resources of the Moon to Expand Earth's Economic Sphere

--- Lunar and material scientists, engineers, and entrepreneurs discussed using lunar resources to enable lunar settlement and utilization.

Written by G. Jeffrey Taylor
Hawai'i Institute of Geophysics and Planetology

The Moon beckons, as shown by the legion of recent and planned missions by the space agencies of the United States, Europe, Japan, India, China, Korea, and Russia, plus a mostly privately-funded mission from Israel. Permanent settlement of the Moon requires use of resources from the Moon. To take stock of where we are in using lunar resources, an international workshop (Lunar ISRU 2019) was held in Columbia, Maryland, USA, organized by the Lunar and Planetary Institute, the Universities Space Research Association, and the NASA Lunar Exploration Analysis Group. The full name of the workshop explains its broad scope, "Developing a New Space Economy Through Lunar Resources and Their Utilization: A Stepped Approach to Establishing Cislunar Commerce Through Science and Exploration." The workshop covered five interrelated topics: identification, characterization, extraction, processing of resources, and the indispensable marketing and commercialization of lunar resources.

References:

- Lunar ISRU 2019 Workshop **online program with presentations and abstracts**.
- Lunar ISRU 2019 **Post-workshop Report** (pdf).

Building on a Steady Stream of Space Resources Research

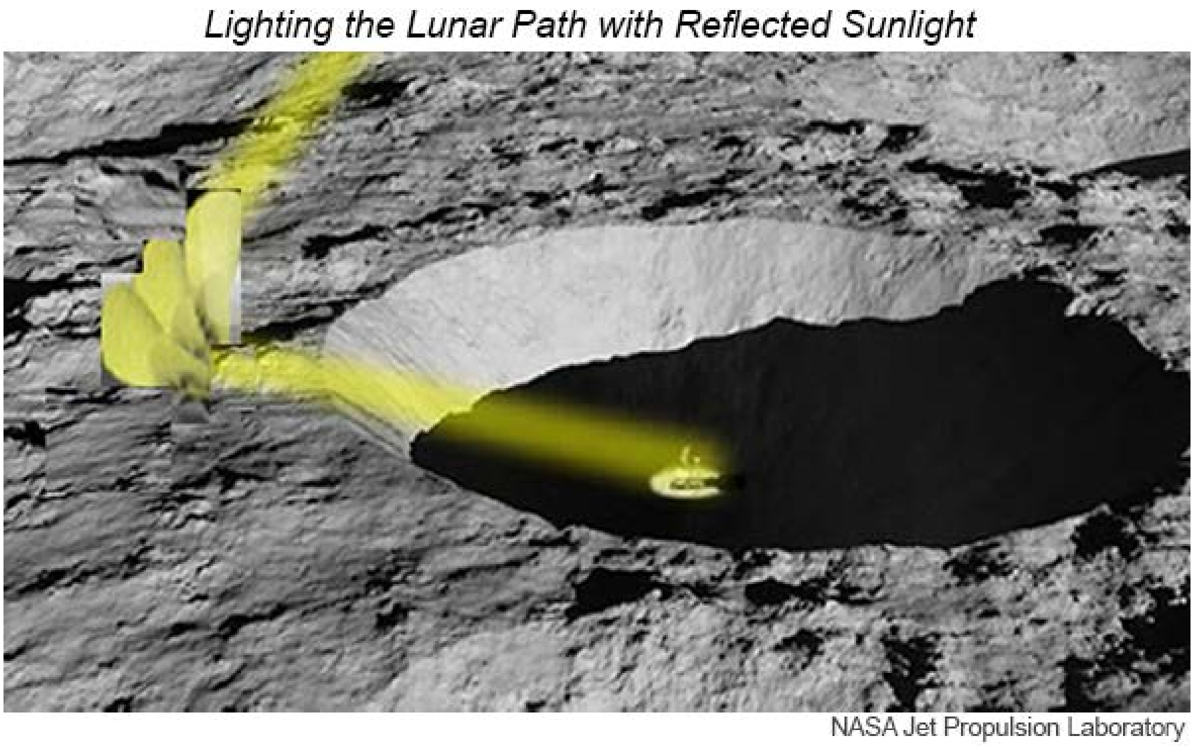
The signing by the President of the United States of Space Policy Directive-1 in December 2017 and creation of the Lunar Exploration and Discovery Program, has amplified interest in the use of lunar resources. This upsurge in activity, however, comes on top of a long-term, international research effort in identifying and using extraterrestrial resources. Many results have been reported at the annual meeting of the Space Resources Roundtable (**SRR**), which has held 20 annual conferences starting in 1999. The SRR joined forces in 2010 to hold joint meetings with the Planetary and Terrestrial Mining Science Symposium (PTMSS). Considering the success of these annual conferences and other meetings, it is no wonder that the

Lunar ISRU 2019 workshop was highly informative and stimulating. We report some highlights here to try to capture the essence of imaginative, futuristic (but not unrealistic) ideas for how we can use the resources of the Moon to establish permanent settlements and to expand Earth's economic sphere.

Energy

Extracting resources and maintaining safe habitats for humans is going to take a sizable amount of energy. The fragmental surface layer (**regolith**) has to be excavated (think backhoes and bulldozers), transported to a processing facility (dump trucks), its target ingredients extracted by heating, and the products (e.g., volatiles such as water, oxygen, or metals) transported to a site for further processing or to use to manufacture a useful item (e.g., solar cells, tools). Habitats need to be maintained with breathable air (produced on the Moon) and be temperature-controlled. Field vehicles (some pressurized) are needed to explore the Moon, both robotically and with humans, for scientific studies and resource prospecting. All these activities will require energy, a point made numerous times during Lunar ISRU 2019.

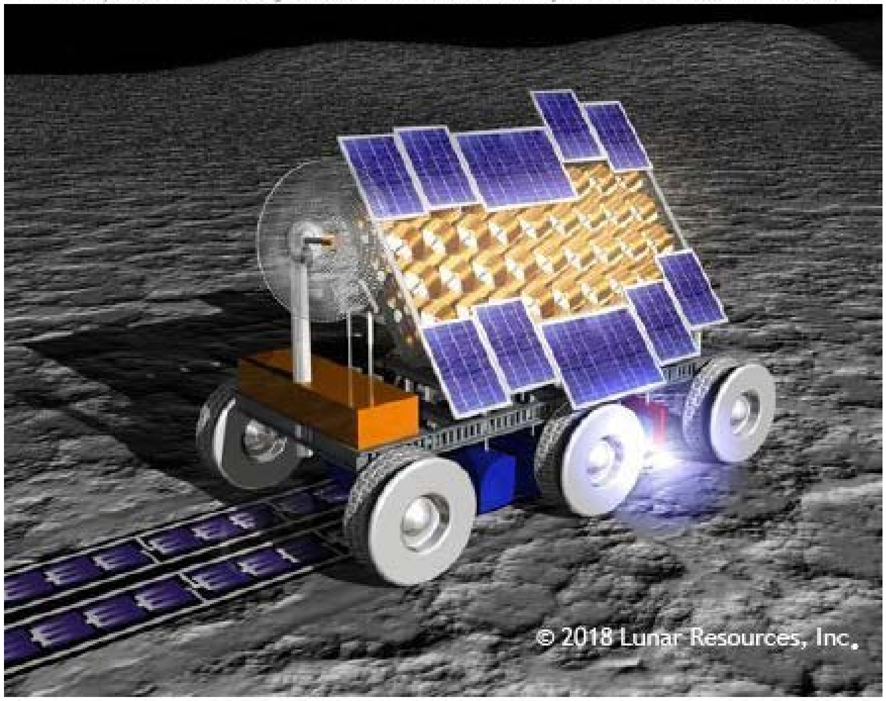
The most widely available energy on the lunar surface is sunlight, which delivers about 1360 watts per square meter (W/m^2). This means that even at 10% efficiency in converting sunlight to electricity, each square meter of photovoltaic cells could generate more electricity than needed to illuminate a 100-watt light bulb. The amount of solar energy varies with latitude. In polar regions the sunlight is never directly overhead. Instead, it grazes the surface at a low angle (only a few degrees above the horizon within about 5 degrees of the north or south pole). This has led to imaginative ways to harness the solar energy, such as using large reflectors called heliostats that redirect sunlight to where it is needed. For example, Adrian Stoica (NASA/Caltech Jet Propulsion Laboratory) suggested placing heliostats, which he calls TransFormers, around the rim of Shackleton Crater near the lunar South Pole. Heliostats turn as the sun appears to move in the sky, keeping the beam of light shining onto the target of interest, such as a rover in permanent shadow (see illustration below). He calculates that a TransFormer 40 meters in diameter could beam 300 W/m^2 to a rover 10 kilometers away, providing power to move, analyze, and extract H_2O in dark, permanent shadows. (The shadowed areas are very cold, even colder than the surface of distant Pluto.) The engineering challenge is to build 40-meter heliostats and then raise them onto towers a few hundred meters high that would be constructed on the rim of the crater. Tricky business, but several heliostats placed strategically around the crater could provide power to a rover in a permanent shadow 99% of the time.



Artistic depiction of solar collectors on the rim of Shackleton Crater, near the lunar South Pole, beaming energy to a mining and exploration rover on the floor of a large crater (21 kilometers in diameter), in permanent darkness. The heliostats, which Adrian Stoica calls TransFormers, redirect sunlight via mirrors, creating an oasis of sunlight and power for a hardworking robotic miner. Click for more details from **NASA/JPL News**.

Resources are available in places other than at the poles. For these regions solar power is also an option. Alex Ignatiev (Lunar Resources, Inc., Houston, Texas) and colleagues presented the latest ideas for how to make solar cells directly on the lunar surface. A rover with a wheelbase on the order of 1–2 meter and weighing about 200 kilograms could be equipped to produce a glassy substrate a few millimeters thick on which silicon and aluminum vapors are deposited to make thin film solar cells (see illustration below). The photovoltaic (PV) cell production rover would be powered by solar power (using conventional PV systems made on Earth) and would have an array of solar concentrators that would focus sunlight onto the powdery lunar regolith. The concentrated sunlight would melt the regolith, which when cooled would form glass. An evaporation system would deposit silicon and appropriate dopants (coatings) to make solar cells directly onto the glassy substrate. A separate system would deposit the conducting metal (e.g., aluminum, abundant in the lunar crust) for carrying the generated electricity to a central transmission facility. Ignatiev pointed out that these cells would be inefficient (5–7% of the sunlight to electricity), but that is compensated by the large size of the arrays and by the lack of an atmosphere to attenuate the sunlight.

Concept for Making Solar Cells Directly on the Lunar Surface



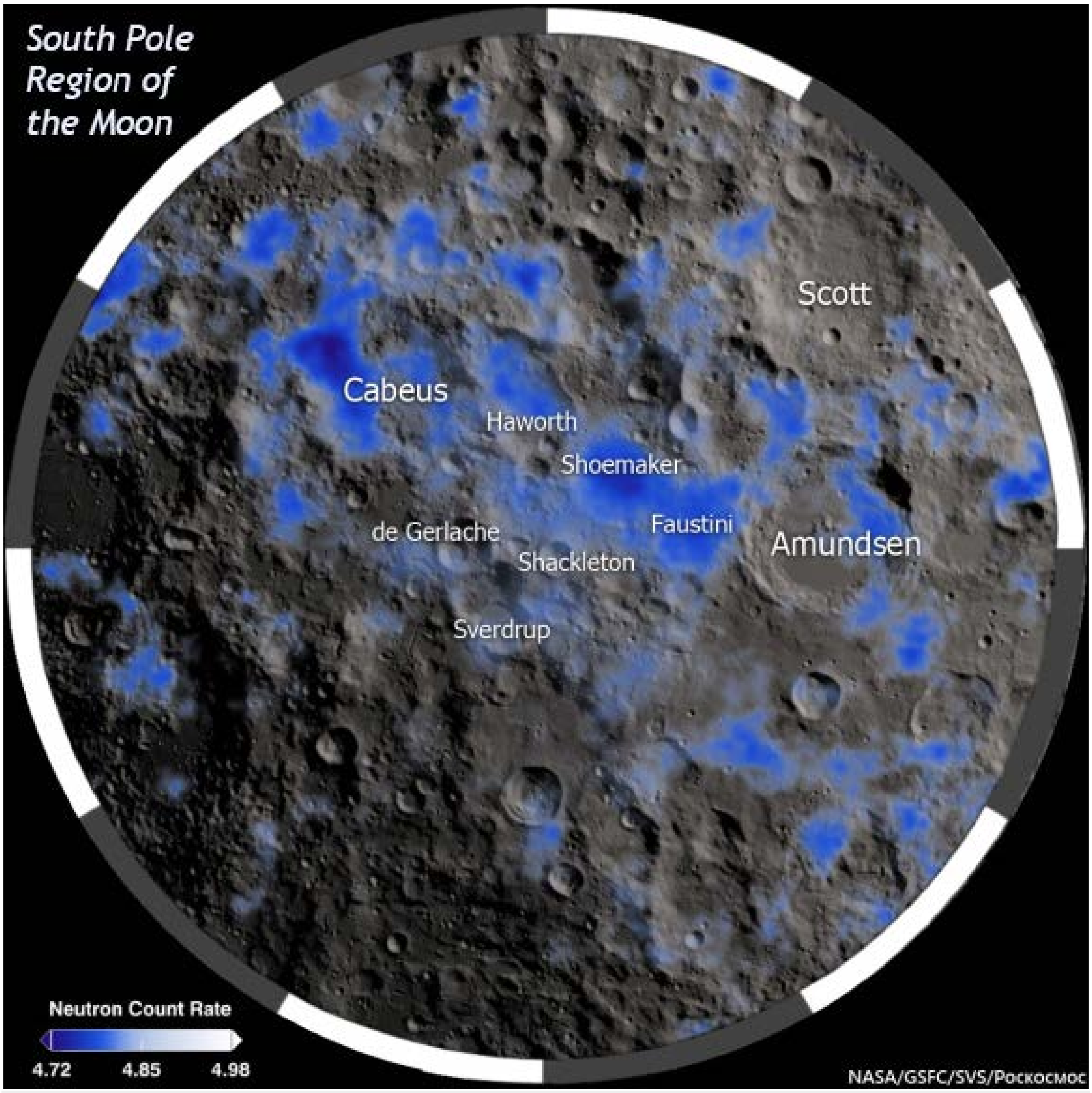
(Concept by Ignatiev *et al.*, Lunar Resources, Inc., Houston, TX.)

Artistic depiction of an autonomous rover frabricating photovoltaic cells on the lunar surface. Traditional solar photovoltaics power the rover, solar concentrators (yellowish in center of panel) focus sunlight onto the lunar regolith to melt it, and devices on the underside vapor-deposit silicon and minor elements for electrical production and aluminum for carrying off the power.

Icy Propellant in Dark, Frigid Craters

Permanently-shadowed regions at the lunar poles may hold the key to extensive human exploration and settlement of our inner Solar System: Lots of H_2O ice. Ice is useful, of course, especially to cool beverages during hot summer (or lunar!) days. But that is a trivial use of ice. It can be split into its constituent hydrogen and oxygen to make propellant, the central ingredient to overcoming gravity and enabling space travel. So it is not surprising that considerable time was spent at the workshop assessing polar water and how to extract it efficiently.

How much water is trapped in polar regions? **PSRD** summarized what is presently known about the water abundance at the poles in the article, **Recipe for Making H_2O in the Lunar Regolith: Implant Solar Wind Hydrogen and Heat with Micrometeorite Impacts**. The best guess is that the total amount of H_2O ice in the polar regions is between 100 million and a billion metric tons. (A billion metric tons of water is about twice the amount of water in Lake Erie.) Discussion at Lunar ISRU 2019 focused more on the distribution of water ice, not the total amount. The decision to mine a specific resource is based on numerous factors, including knowing where the concentration and extent of the potential ore deposit are highest. How deep are ice deposits? How does the concentration of water ice vary with depth and laterally across a region in permanent shadow? The deposits could be patchy, water-rich in one 100-square-meter area and bone dry in another 100-square-meter patch. This lack of knowledge was highlighted at the workshop, accompanied by descriptions of new approaches to assessing resources, lists of the data needed, and descriptions of potential missions to the permanent shadows to shine light into the shadows and into our knowledge base.



Map showing permanently shadowed areas in the South Polar region of the Moon. Neutron absorption data gathered by the LEND (Lunar Exploration Neutron Detector) instrument on NASA's Lunar Reconnaissance Orbiter (LRO) shows enrichment in hydrogen in these areas (colored blue). Estimates of the global **abundance of water ice** suggest that there could be between 100 million and a billion metric tons of H_2O ice in the polar regions.

Ingenious ways were described to extract volatiles from frozen regolith. They involve heating to make the volatiles mobile and creating pathways for them to move towards the surface. There is no lack of good ideas for extracting water vapor from the regolith. However, as Kris Zacny (Honeybee Robotics) pointed out, the difficult task is capturing the liberated gas. A coring device with internal heating and a cold trap developed by investigators at Honeybee and NASA Johnson Space Center did well in initial tests, capturing an average of 65% of the water in a simulated regolith, with some runs recovering up to 87% of the water.

In the Regolith of Opportunity, It's Plowing Time Again

The lunar regolith, that impact-generated dusty sand and rock pile on the lunar surface, is where almost all the ISRU action will take place. It will be raw material for building and shielding habitats, a source of metals and other useful materials, a source of volatiles, a substrate for solar photovoltaic arrays, and an amazing rock collection that holds the key to the Sun's history and the origin of the Moon. To get the most out of this important scientific, exploration, and commercial resource, we need to be able to efficiently dig it, move it, smooth it, and pile it up.

The regolith is unconsolidated, but still difficult to excavate. As pointed out by a team from the **Swamp Works** at NASA's Kennedy Space Center, a lunar excavator will need to have relatively low mass in order to get it to the Moon. In addition, gravity at the lunar surface is only one sixth that on Earth. These two factors make a lunar excavator something of a weakling when it comes to digging up Moon dirt. The Swamp Works crew came up with a **solution**: RASSOR—Regolith Advanced Surface Systems Operations Robot (see image below). The device uses bucket drums with scoops that deliver regolith to the drums. Two sets of drums are used, each operating in opposite directions, which keeps the reaction force strong enough to excavate regolith effectively. Equipped with arms to position the drums, RASSOR is capable of climbing obstacles and righting itself if it flips over. You can see it and the Swamp Works inventors in action in this **two-minute video**.

Photograph of RASSOR (Regolith Advanced Surface Systems Operations Robot) digging a trench in simulated lunar soil.

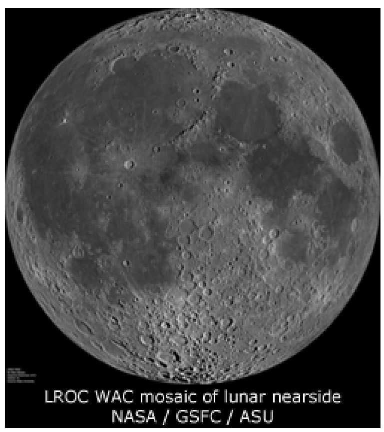
Sintering and 3-D Printing Using Regolith

Except for the simplest cases, using the regolith for construction material requires that it be stronger than a pile of loose dusty sand. Studies were done in the 1990s and during the past few years on sintering lunar regolith into assorted useful shapes (e.g., bricks, tools). Sintering involves heating the regolith hot enough to melt, at least partially, which takes a lot of energy. This can be accomplished by concentrating sunlight as described above or by heating with microwaves. The use of microwave heating has received a lot of attention over the years because **space weathering** processes produce nanometer-sized particles of metallic iron on grains in the lunar regolith (see **PSRD** article: **New Mineral Proves an Old Idea about Space Weathering**). These micro-minuscule iron blebs couple with microwaves very efficiently, causing regolith to heat rapidly.

With the advent of additive manufacturing (known colloquially as 3-D printing), experiments are now being done with simulated lunar and martian regoliths. This has great potential for construction on the Moon, and initial experiments reported at Lunar ISRU 2019 are promising. One troubling feature of the experiments so far is that to achieve reasonable strengths in 3-D printed structures using simulated regolith, a polymer of some sort needs to be included as a binder. A particularly popular one is PETG, which stands for polyethylene terephthalate with a glycol modification. It is the stuff we use for plastic water bottles. Brad Buckles (Bionetics Corporation) and Rob Mueller and Nathan Gelino from NASA's Kennedy Space Center have been experimenting with a mixture of 70% glass fiber made from basalt and 30% PETG. In principle, at an advanced lunar base, polymers could be made in agricultural facilities. It is still early days for experiments in using regolith to make structures by additive manufacturing techniques.

Commercialization of Lunar Resources

We cannot immediately begin to use and sell lunar resources, but it was clear from discussions at Lunar ISRU 2019 that it is not too early to start making business plans. The prospects for using water sequestered in lunar polar regions received a lot of attention. This might be the most advanced business case, as shown by the comprehensive review published recently (see **PSRD** report: **Refueling Space Exploration**). There was general agreement at the workshop that the commercialization of hydrogen-oxygen propellant from the poles would be aided significantly by using liquid hydrogen/liquid oxygen as propellants for all travel and transport in the space between Earth and the Moon. This would foster new businesses in refueling and repairing Earth-orbiting satellites—there are over a thousand operating satellites orbiting Earth today.



The future is bright for using the resources of the Moon to enhance space exploration and settlement. Interest in using lunar resources in ambitious space ventures is widespread among all space-faring nations. It will be fascinating and inspiring to see it happen!

Additional Resources

Links open in a new window.

- Buckles, B., Mueller, R. P., and Gelino, N. (2019) Additive construction Technology for Lunar Infrastructure, *Lunar ISRU 2019 Workshop*, **abstract #5077 pdf**.

- Ignatiev, A., Curreri, P., Sadoway, D., and Carol, E. (2019) The Use of Lunar Resources for Energy Generation on the Moon, *Lunar ISRU 2019 Workshop*, **abstract #5013 pdf**.

Lunar Exploration Analysis Group.

- Lunar ISRU 2019 Workshop **online program with presentations and abstracts**.
- Lunar ISRU 2019 **Post-workshop Report** (pdf).
- Morrison, P. D., Zacny, K. A., Vendiola, V. R., and Paz, A. (2019) Results and Lessons Learned from Testing of the Planetary Volatiles Extractor (PVEx) and Related ISRU Concepts, *Lunar ISRU 2019 Workshop,* **abstract #5076 pdf**.
- New Space Policy Directive Calls for Human Expansion Across Solar System, **NASA Press Release**, Dec. 11, 2017.
- Schuler, J. M., Smith, J. D., Mueller, R. P., and Nick, A. J. (2019) RASSOR, The Reduced Gravity Excavator, *Lunar ISRU 2019 Workshop,* **abstract #5061 pdf**.
- Stoica, A. (2019) A Solar Power Infrastructure Around Shackleton Crater, *Lunar ISRU 2019 Workshop,* **abstract #5096 pdf**.
- **The Space Resources Roundtable**.