Lunar ISRU 2019: Developing a New Space Economy Through Lunar Resources and Their Utilization

Workshop Report

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Introduction

The 2019 Lunar In Situ Resource Utilization (ISRU) Workshop was held at USRA HQ in Columbia, Maryland, on 15-17 July. An international group of approximately 200 people from the United States Europe, Australia, Canada, Korea, and Japan participated in this workshop, and represented government, commercial, and academic institutions.

The workshop brought together several broad communities not accustomed to working together: Policy, legislation, law, and regulation; marketing, valuation, and finance; mineral exploration (characterization); mining (extraction); mineral processing; and planetary science. Each community has its own levels of history and terminology. A common observation among the workshop attendees was that moving forward would be faster and more effective with better communication and coordination. In addition to speeding information dispersal, better communication would help replace disconnected efforts with more nuanced, broadly based cooperative work. To that end, a glossary or dictionary focused on Space Resources should be developed in 2020 and maintained indefinitely in an easy-to-find location.

The workshop was set up to investigate the five phases of resource utilization – Identification, Characterization, Extraction, Processing, and Markets. The first morning was devoted to introducing the workshop and community updates from space agencies and commercial entities.

MAJOR FINDINGS

Lunar ISRU will project US presence and permanent capability in space, and has the potential for commercial development.

Background: Developing ISRU technologies will enhance human spaceflight beyond low Earth orbit. The discussions throughout the workshop indicated that this development would achieve something that has been heretofore restricted to powerpoint charts. The LEAG Lunar Exploration Roadmap (https://www.lpi.usra.edu/leag/roadmap/) uses resources to highlight "commercial on-ramps" that will facilitate a new era of economic growth.

Space exploration architectures should be designed to utilize propellants that can be derived from lunar resources even if initially these need to be brought from Earth.

Background: The United States has an ambitious plan to get humans to the Moon to stay and to get humans to Mars. Technologies to extract and process lunar resources still need to be demonstrated but architectures that make use of these resources will lead to eventual sustainability, even if initially the "resources" need to be brought from Earth. Care must be taken to **not** accept architectures that preclude future use of ISRU resources in order to meet early mission goals.

Lunar resources will initially be used to sustain humans on the Moon and also have the potential to be exported to cislunar space.

Background: The idea of "survive and thrive" shows that the initial focus of using local resources is to allow the humans to survive on the lunar surface. As capabilities evolve and risks are reduced, production could be increased above and beyond what is needed for human survival, thus developing the export economy that allows humans to thrive off-planet. Indeed, lunar-derived propellant exported to cislunar space could be the initial driver for scaled-up surface operations of volatile deposits.

Terrestrial mining companies will engage in lunar ISRU if they can see the profit potential and a net benefit to their terrestrial operations.

Background: At present, the mining, oil & gas, mineral extraction, and equipment manufacturing industries appear to be interested on developing similar advanced technologies to the ones that will be needed for extreme space and lunar applications. They are willing to remain engaged in discussions and even collaborating on specific technology development projects of their interest. However, their direct participation in this endeavor at this time is unlikely for two reasons:

- The market for products from lunar geologic assets at this time is just emerging, and
- The lack of resource exploration (prospecting) data from surface assets prevents quantification of lunar reserves.

Acquisition and integration of global datasets for resources on the Moon will go a long way towards establishing the business case for commercialization of space resources and attracting the attention of the terrestrial mining industry.

In order to get terrestrial mining companies involved, a market potential needs to be evident for products derived from space resources. A commitment to human permanence on the Moon and Mars is enabling for the commercial aspects of lunar ISRU and would foster creation of markets such products.

Background: Discussion at the workshop showed that lunar ISRU is at a very preliminary stage. Critical steps in order to put ISRU in the critical path of human space exploration are understanding if resources are actually reserves (the need for resource exploration/prospecting data) and to establish markets for resource products. Human permanence on the Moon would go a long way to generating markets, but the initial critical step is gathering resource exploration data.

The model of the government supplying basic information on potential availability of resources should be extended to the Moon and beyond to reduce the risk perceived by commercial entities for involvement in ISRU activities off-planet.

Background: An important step NASA can take to promote lunar ISRU is to reduce the perceived risk by the publication of formal resource assessments, preferably in partnership with a historically reliable source of resource assessments such as the U.S Geological Survey (USGS). At this time, such an assessment would be most appropriate for lunar regolith used as bulk aggregate and/or oxygen production. The required data sets are in hand and the modest modifications to the standard USGS methodology for resource assessments used on the Earth are understood. While key *in situ* data are currently lacking for a formal assessment of lunar ice deposits, the assembly and statistical analysis of relevant remote sensing data will (a) support selection of landing sites for ground truth observations, (b) accelerate the publication of a lunar ice assessment once the *in situ* data are in hand and (c) provide insights on which new remote sensing observations will most improve future assessments. It is important that these efforts begin soon to ensure that the publication of these formal assessments dovetail with NASA's planned sequence of missions to establish a sustained human presence on the Moon by 2028.

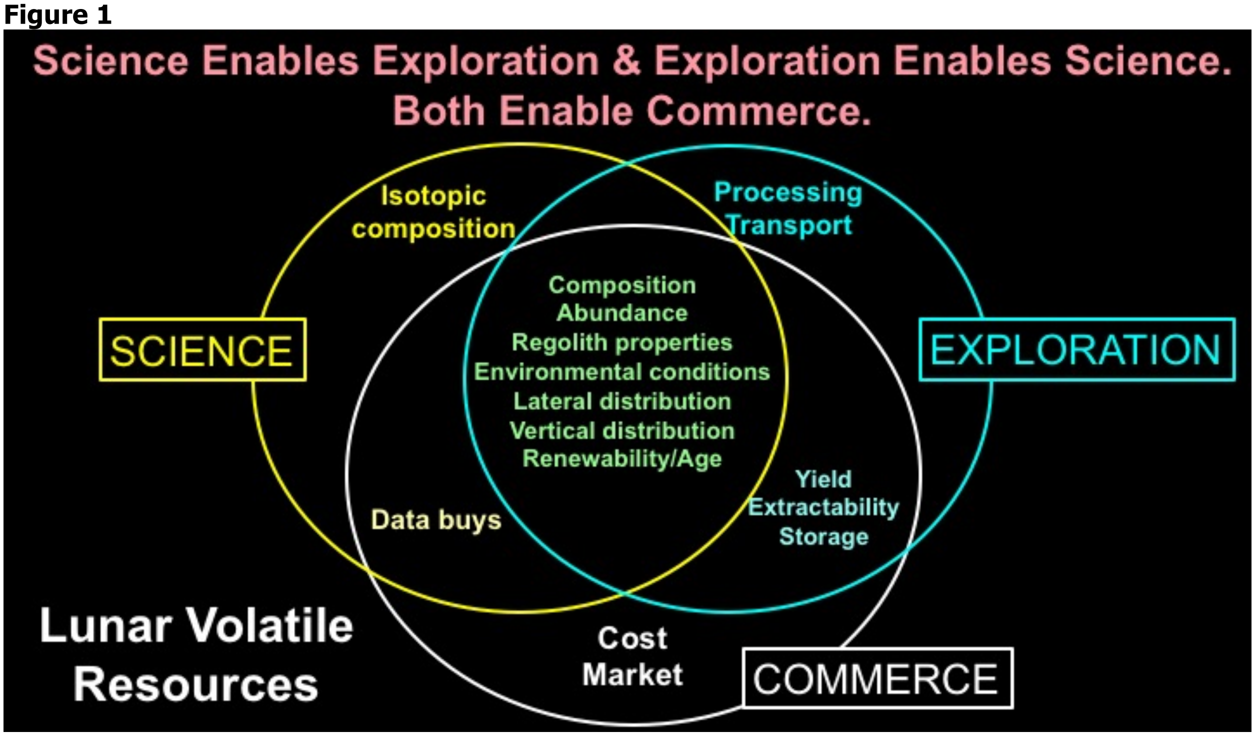
Important data are missing that are critical to quantify the reserve potential of various lunar resources. These data are critically needed at several locations. A prospecting or resource exploration campaign is needed as data from such a campaign could invigorate public-private partnerships.

Background: The prospecting/resource exploration campaign is the next important step in learning to live of the land. The data collected from such a campaign will be necessary for commercial participation in lunar ISRU.

The critically needed data for ISRU resource understanding and extraction are similar to those needed for science. Therefore, CLPS missions dedicated to understanding lunar resources would address SMD science goals as well as ISRU needs and give an early indication of resource production viability on the lunar surface.

Background: During the workshop, the following slide was used to illustrate that the data needs for the different stakeholders (i.e., exploration, commerce, and science) in the investigation of lunar water deposits are very similar (Fig. 1). Therefore, the prospecting campaign for these deposits and other lunar resources crosscuts NASA's mission directorates.

Figure 1



If utilization of lunar resources is possible, a review of power requirements for scaled up operations on the surface of the Moon will be required.

Background: Mining and processing operations are power hungry and kilowatt power may not be sufficient. If lunar resources are to be developed to allow humans to survive and thrive on the surface of the Moon, detailed analyses of power requirements for full production need to be undertaken now in order to develop the power systems needed for full ISRU operations on the lunar surface.

Lunar ISRU is multi-dimensional involving a variety of potential source deposits

Background: While polar water ice could have important implications for fueling the space economy and sustaining humans off-planet, they form just one part of what the Moon has to offer. The Moon also contains important resources in non-polar locations (e.g., volcanic deposits, regolith, etc.). Processing of these non-polar resources would also yield significant quantities of water, oxygen, and rare earth and other metals. Therefore, pursuit of regolith processing for oxygen, metals, and other mission consumables and products was also recommended.

Operation and maintenance of an off-world, full-scale ISRU plant is a major logistical issue that requires urgent attention.

Background: Representatives of terrestrial mining companies considered that the much of lunar ISRU community had potentially underestimated what it would take to set up and maintain a resource mining and processing facility on the lunar surface. Learning from the terrestrial experience is critical for the development of lunar and other space resources.

Development of lunar ISRU could speed development of martian ISRU as there is significant feed-forward potential.

Background: For example, excavation and processing of lunar resources from the polar ice deposits and regolith will inform us and reduce the risk of developing martian ISRU capabilities. Several studies have shown the use of lunar propellant can reduce the propellant required to be launched from Earth in support of a Mars mission (e.g., Plate, 2019, http://wgm.ca/en/2019/08/12/wgm-issues-conceptual-economic-lunar-water-mining-study/). However, other studies indicate that lunar propellant may not be economic (e.g., Jones et al., 2019, AIAA ScTech Forum http://arc.aiaa.org | DOI: 10.2514/6.2019-1372). More data are needed regarding the reserve potential of lunar water ice and its extractability.

NASA should work with interested space agencies and commercial entities to develop a coordinated nomenclature, strategy, and roadmap for obtaining the necessary prospecting/resource exploration data. As part of the strategy, they can discuss leveraging CLPS and other missions for lunar ISRU technology demonstrations.

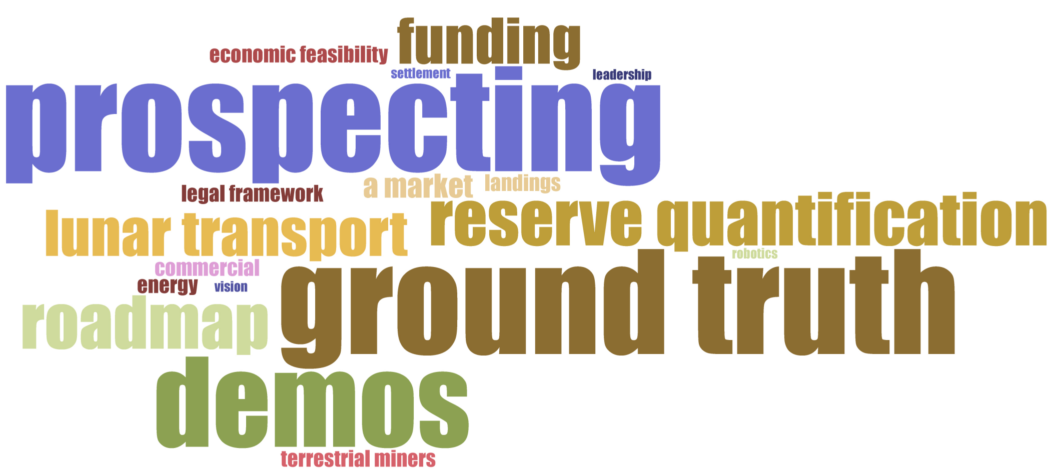
Background: The mineral industry and the lunar ISRU community use different nomenclature, and have different perspectives on design, operations and maintenance of production plants. Both communities will work to shrink those differences. For example, the mining industry plans the development of a mine site from high level requirements similar to level one mission requirements as a technology agnostic process. This conference seems to demonstrate a reverse process wherein technology is trying to drive the mine planning.

Audience Participation through Mentimeter (see **www.mentimeter.com**)
During the Lunar ISRU Workshop, the attendees were polled on fourteen questions and statements using *Mentimeter* to get a sense of where the majority opinion was regarding lunar ISRU. These questions, listed below, were distributed throughout the sessions to encourage audience participation. At any one time, about 50% of the attendees in a given session participated. A total of fourteen questions and statements were used to get a sense of where the majority opinion was regarding lunar ISRU. These are listed below and were interspersed throughout the workshop.

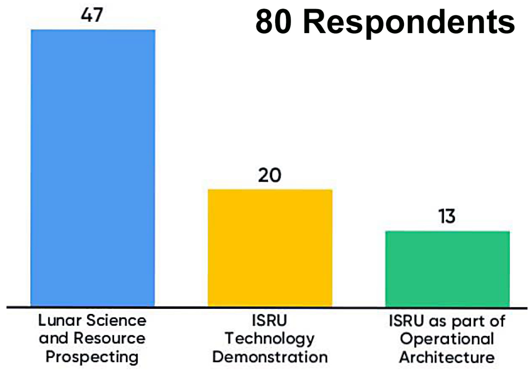
1. What is the next critical step that needs to be taken in order to make ISRU a reality on the Moon?
2. What should be the priority objective related to Lunar ISRU for Artemis?
3. When will lunar-derived propellants be cost competitive with Earth-derived propellants for missions to Mars?
4. Rank these challenges (Political Will, Geological Knowledge, Power Systems, Cryogenic Operations) for PSR-sourced propellant.
5. In short answers, what are the lunar resource markets you're most excited about?
6. What elements of strategic ISRU-related advice would you like to provide to NASA and the community as we embark on the Artemis program?
7. Do we REALLY need more orbital remote sensing data before we go to the surface to identify lunar ground resources?
8. What is the best way to explore a large PSR (e.g., Shackleton) to define the reserve potential?
9. What are the biggest characterization impediments to ISRU at scale?
10. Which characteristics are most critical to ISRU excavation and processing at scale?
11. What are the most understudied major problems we will encounter when producing feedstock for manufacturing fuels and propellants on the Moon?
12. What is the biggest hurdle for ISRU commercial development?
13. What area/technology for ISRU has the 'best' spin-in/spin-off potential for terrestrial industry?
14. In 1 or 2 words, what are the three takeaway messages you have learned at this workshop?

In order to get the audience comfortable with the process the first two questions were asked and the results are presented here.

- *What is the next critical step that needs to be taken in order to make ISRU a reality on the Moon*?
  [Note: the larger the words, the greater the number people who entered these terms]



- *What should be the priority objective related to Lunar ISRU for Artemis*?



The remaining questions are addressed in each of the session summaries below. However, please note that due to a difference in terminologies between the various participants of the workshop, "**resource exploration**" is equivalent to "**prospecting**" throughout the report and are used interchangeably.

Session Summary: Introduction and Updates.

The workshop was opened by an impassioned talk by NASA Deputy Administrator James Morhard, who emphasized the importance of lunar resources in NASA's plans for the Artemis program. He also talked about the Viper rover (being developed at NASA Ames and that this could be the first of a series of rovers to be used in surface exploration), as well as the Commercial Lunar Payload Service (CLPS) program and its importance for defining and understanding resources.

Dr. Martin Picard gave an update from the Canadian Space Agency and introduced us to the Lunar Exploration Accelerator Program (LEAP), which has the objectives of:

- Enabling Canadian businesses and academic institutions to develop and conduct science experiments designed for lunar conditions;
- Advancing and demonstrate innovative technologies on or around the Moon;
- Evaluating potential deep-space health technologies that will also provide direct benefits here on Earth.

This talk also highlighted near-term barriers for ISRU. These were the cost of the initial investment, advancement of technology, access to space for non-traditional companies (e.g., mining), inputs and implementation of the Canadian Minerals and Metals Plan. The International Traffic in Arms (ITAR) regulations continue to be a problem for forming international partnerships.

Dr. James Carpenter from the European Space Agency indicated that ISRU was an enabler for space exploration, and ISRU starts at the Moon. He cautioned that exploration of lunar polar resources was risky as a first prospecting effort and that maybe non-polar volatiles resources should be explored first. Dr. Carpenter also made the following observations regarding lunar resources:

- Primary benefits will come from new intellectual property & innovation in terrestrial industrial sectors.
- But there is no international consensus regarding the legal framework of space resources.
- Poor availability/quality/consistency for lunar simulants is a limiting factor for technology development.
- Demonstrations of in situ production and utilization are critical in order to show the validity of ISRU.
- Standard nomenclature is needed.

ISRU has traditionally not been in the critical path for human space exploration architectures because it is unproven. We must break the paradigm through in situ technical demostrations early on as we go to the Moon**.**

Bob Lamboray of the Luxembourg Space Agency gave a compelling talk regarding LSRU and the development of a commercial space ecosystem. The Luxembourg approach is not a mission or a program, but rather it facilitates policy and funding mechanisms. It is evident that one measurement by LCROSS is insufficient to convince a mining company to start operating on the Moon. Prospecting at several locations with groundtruth data acquisition should be the top priority. During the Q&A, input from terrestrial mining experts was that this industry would not be interested in lunar ISRU at this time because we still don't know if the resources are reserves and they don't see a customer base for the products from lunar resources. However, collaboration with commercial mining interests will be essential.

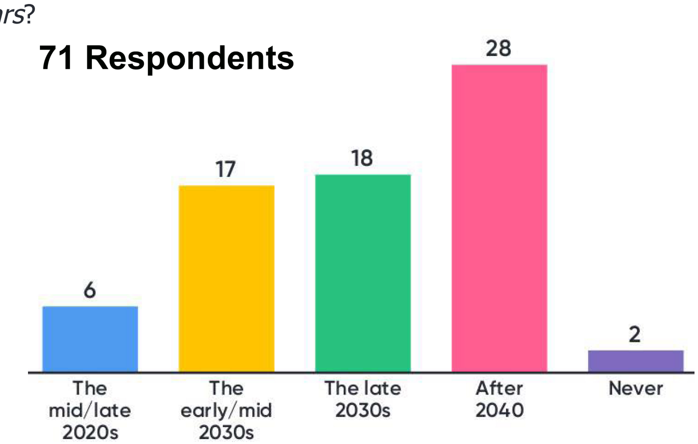
The NASA update reported on the VIPER lunar rover being developed at NASA Ames, with the goal of having one on the lunar surface in FY 2022. This could be delivered as part of the Lunar Commercial Payload Services program. This will be used for resource prospecting. During the Q&A, the subject of "speaking the same language" between different stakeholders in lunar ISRU development was broached. This is an issue that needs to be resolved – internationally. There was also discussion about how ISRU should be incorporated into human space exploration architectures. This would have important implications for power requirements. NASA is, at present, pursuing oxygen from the lunar regolith and water ice. ISRU has to be demonstrated on the Moon before it can be in the critical path.

The final talk of the first session was from Kyle Acierno of iSpace. He spoke about their first lunar mission being in 2021 that would be a lunar lander with a 30 kg payload and a rover with a 2.5 kg payload that includes a small drill able to get ~30 cm into the lunar regolith, and a mass spectrometer from the Open University, UK. iSpace thinks that rare earth element resources on the Moon could be an important target for future resource opportunities.

Commercial Lunar Propellant Panel (Panelists: Philipp Tewes from Paragon, Gary Barnhard from XISP, Brad Blair from PlanetMiner. Moderator = George Sowers, Colorado School of Mines). George Sowers introduced the idea of thermal mining ice deposits in permanently shadowed regions by heating the regolith and capturing the sublimates. Deeper deposits can be obtained through driving heat pipes into the subsurface. It was evident that full-scale production may require more than kilo-power. There are sustainable power solutions that already exist for ISRU, but scalable technology demonstrations are needed to prove viability. Paragon Space Development Corp is developing a processing plant for water ice. States that purified water should be split immediately otherwise it adds complexity. Impurities could be resources (e.g., ammonia for fertilizer). Uses customized ionomer membrane water processing module – vapor phase scrubbing. Storage of propellant was discussed in terms of loss of H_2, but why not store H_2O and split it as needed? Another issue that came up during discussion was the maintenance of the production plant and how this was to be handled. One other thing to remember in resource extraction is that there is a measured ore body grade and an extracted grade, which is usually lower – this adds another emphasis on technology demonstrations for resource extraction.

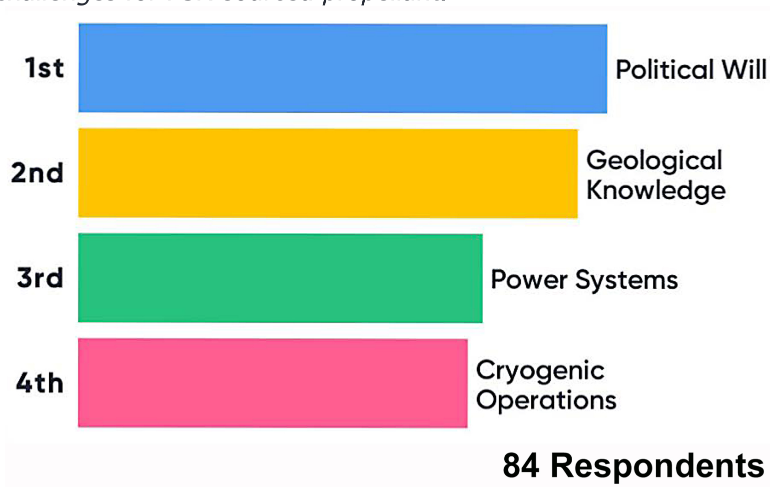
The audience was tasked to answer one question and complete one task at the end of the panel discussion:

- *When will lunar-derived propellants be cost competitive with Earth-derived propellants for missions to Mars*?



If the Moon is to enable Mars exploration, the timeline for making lunar resources competitive with resupply from Earth needs to be shortened. This can be done through methodical exploration and targeted technological investments.

- *Rank these challenges for PSR-sourced propellant.*



This is now the third time the United States has pivoted to the Moon since Apollo was cancelled. Therefore, political will is a major issue for creating a multi-decadal human space exploration program. However, all four issues noted here will be critical for enabling lunar resources to be used to allow humans to "survive and thrive" off Earth.

Session Summary: Identification of Lunar Resources

The "identification" session started off with two overview talks focused on lunar volatile reservoirs and polar ice deposits. We now know there is a volatile cycle on the Moon, with sources and sinks, that are both current (micrometeorites, diurnal variations) and ancient (lunar volcanic atmosphere). It was proposed that science and engineering synergy was required to truly understand these deposits.

One key result out of these talks was that 2000 kg of water-containing pyroclastic deposits, identified from the sample collection and from orbit in 2016, would need to be processed to get 1 liter of water. There could be 10's to 100's of millions of tonnes of water ice at the poles, but the result from the LCROSS impactor showed that polar water ice is not pure and would need to be refined after extraction. It was evident that better resolution of the resources (volatile and non-volatile) was needed and surface exploration as well as orbital concepts were presented to accomplish this. There is still a place for orbital measurements for locating lunar resources – better spatial resolution could, in some cases, optimize the deployment of surface assets. Groundtruth to all orbital measurements is vital to understand the distribution of lunar resources (LCROSS gave us one point for composition, but more surface data are needed).

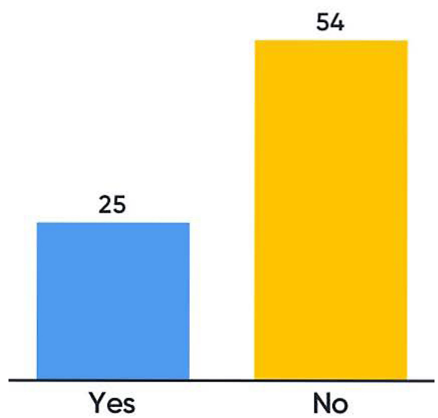
Several unknowns were highlighted in this session:

- Thickness of the ice deposits in the PSRs is not well constrained
- How do we define yield in an ISRU process?
- What lies below the surface to ~1m in a PSR?
- Power is a constraint on production of products from lunar resources.
- We don't know what is needed to explore a PSR – ice is stable (theoretically) 1-2 meters below the surface *around* a PSR.

From the panel discussion there was a debate regarding commercial involvement in resource identification, characterization, extraction, etc. On Earth the government usually supplies geologic maps that companies use to explore potential prospects (i.e., prospecting) – concentrations of minerals or potential geologic terranes. There are only coarse resolution maps available for the Moon. This, coupled with the lack of markets for any products from lunar resources, means the terrestrial mining industry will not be participating at the scale needed to commercially develop such resources on the Moon. However, another point that came out of this session was that if the volatile science and ISRU communities work closely we can learn a lot about the Earth-Moon system.

Two questions were given to the audience to get their feedback regarding the identification of lunar resources:

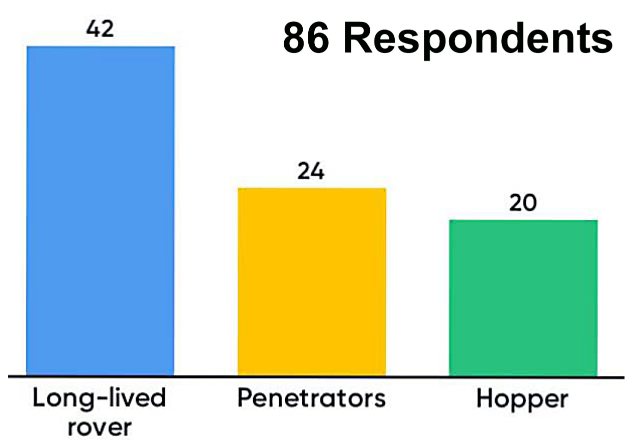
- *Do we REALLY need more orbital remote sensing data before we go to the surface to identify lunar ground resources*?



79 Respondents

The sentiment of the participants was that targeted orbital observations, especially over the lunar polar regions, can be useful in better deploying surface prospecting assets. However, these can be done in tandem with deployment of prospecting rovers (for example) on the lunar surface.

- *What is the best way to explore a large PSR (e.g., Shackleton) to define the reserve potential*?



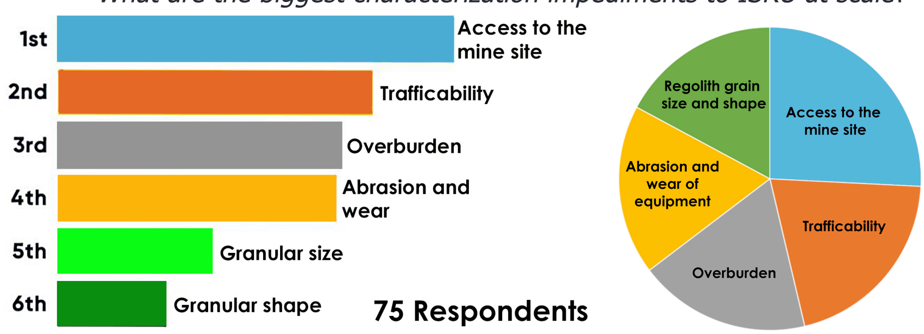
Having surface mobility will be critical for mapping out resource deposits, especially in the subsurface, to fully understand if these resources are, in fact, reserves.

Session Summary: Characterization

The Characterization session on Tuesday afternoon had a primary focus on the bulk characteristics expected of lunar regolith. The talks and presentations focused on the capabilities for testing in dirty thermal vacuum chambers, the need for appropriate simulants, the impact of regolith on various processes and machines and the need to better define the characteristics of the lunar regolith in and around any potential ISRU site that intends to operate at scale. Characterization extends from micro to macro and includes the form of a resource, how it may be bound to surrounding materials, its location and position in a field and issues such as access and overburden that must be addressed in scaled up ISRU operations. Simulants to be used for testing of systems must exhibit the appropriate characteristics that would have the greatest impact on success of a system in actual operation. Testing of systems must proceed in appropriate representative environments and larger dirty thermal vacuum chambers are being prepared to answer this need. It is advisable to begin a campaign soon to develop appropriate maps and filters such as those employed by USGS and CGS in preparing maps for mineral exploitation on Earth, as a means by which commercial and national agencies could begin to determine, on an increasingly finer scale, logical and viable sites for scaled up ISRU operations.

One question was given to the audience to get their feedback regarding the characterization of lunar resources:

- *What are the biggest characterization impediments to ISRU at scale*?



Results presented in two forms [Granular Size and Granular Shape are combined in the pie chart]. "At Scale" refers to operation *in situ*, on the Moon, at pilot- or full-size throughputs and industrially useful batch or continuous operational schedules. Many promising mineral extraction processes tested extensively in virtual or laboratory settings have not retained their promise when applied to more realistic situations. This supports the workshop finding that: *Operation and maintenance of an off-world, full-scale ISRU plant is a major issue that requires urgent attention*. No single impediment to characterization of full-scale lunar ISRU stood out to the participants. Site access was the most selected, but not by a wide margin. This implies that research funding and logistical support should not be too narrowly restricted, but spread out more evenly among these areas for the greatest effect.

Session Summary: Extraction

Extraction is the next general step in the mineral production sequence after identification and characterization. It consists of getting what we want – the target material, whether bulk regolith for radiation protection or water ice for fuel manufacture – while minimizing handling of what we don't want – waste or barren material, including overburden. We've learned to take advantage of accessible locations where natural processes have concentrated the target material to some degree. Whatever separation from waste has already happened makes the target material easier for us to acquire.

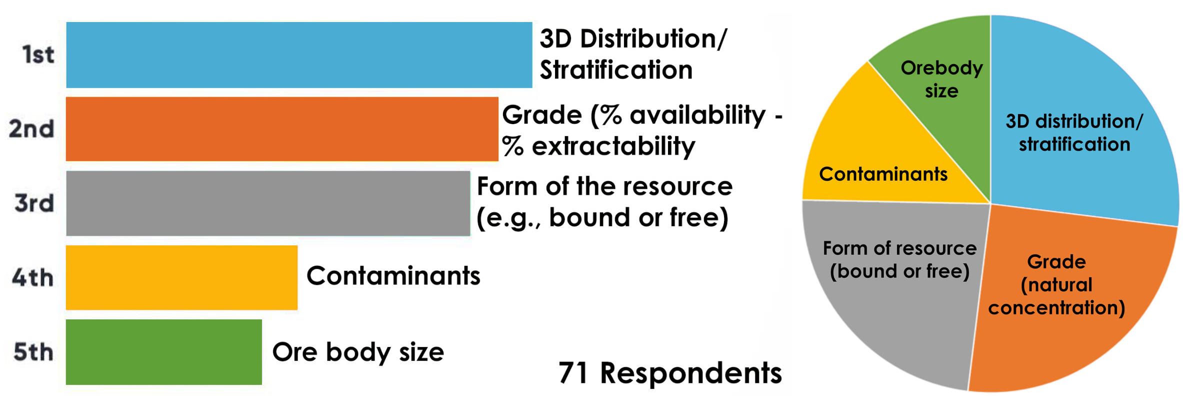
A mining method is an engineered sequence of activities in time and space designed for primary separation of target material from waste *in situ*. Beneficiation and processing continue the extraction to finer levels, with output designed to meet the needs of the next phase. Over millennia on Earth we have developed mining methods that rely on gravity as motive force, thick nitrogen atmosphere as thermal and geotechnical buffer, water as working liquid, and human bodies as engines. Lunar boundary conditions are very different, forcing mining methods to adapt, but the ultimate goal remains the same. Mining methods drive mine design and planning, informed by available extractive capabilities. Effective development of technologies to provide those capabilities considers the mining methods they would be used to support.

The morning's presentations started with a look ahead at some likely target materials, based on a comparison of what's available on the Moon, what products will be needed, and some popular methods to link the two. This was followed by a review of current regolith excavation concepts and prototypes with a focus on lunar mining applications. Excavation technology has become a pipeline for new professionals to enter ISRU.

Colorado School of Mines, Michigan Technological University, and the University of Central Florida followed with reviews of some of the research underway and planned at their campuses. These include development and testing of testbeds, technologies, and models for extracting lunar target materials. Nuclear and solar power generation were then discussed as methods to provide the necessary energy. Most of the remaining talks presented select examples of technologies for the ISRU toolkit, including updates on specific surface excavators, rover subsystems, material transport concepts, borehole volatiles extractors, and some preliminary thoughts on how they might fit into generic mining methods. Creating a successful operation on the lunar surface requires incorporating all these disparate aspects – and more – into a cohesive, sustainable multi-dimensional system. The final talks in this session addressed some approaches to this, through integrated systems modeling and geometallurgy.

The session wrapped up with a panel discussion on what holes remain in the current march forward. At the end of the panel discussion the audience was polled via two questions:

- *Which characteristics are most critical to ISRU excavation and processing at scale*?

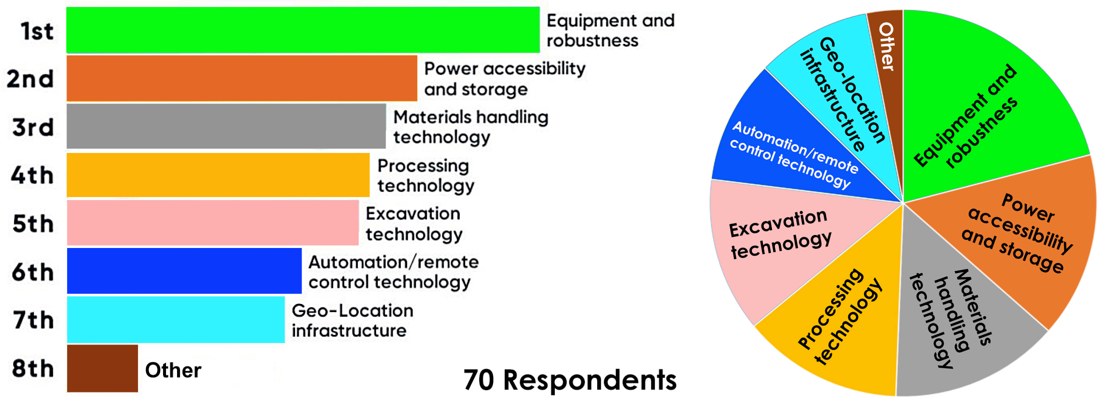


The three-dimensional distribution, grade, and form of the target material were deemed more critical to excavation and processing than orebody size or the presence of contaminants with downstream effects. This strongly supports these workshop findings: *Important data are missing that are critical in defining the reserve potential of lunar resources of interest*; and, *The model of the government supplying basic information on potential availability of resources (e.g., the United States Geological Survey) should be extended to the Moon and beyond to reduce the risk perceived by commercial entities for involvement in ISRU activities off-planet*.

Session Summary: Processing of Resources (MM 11, 12)

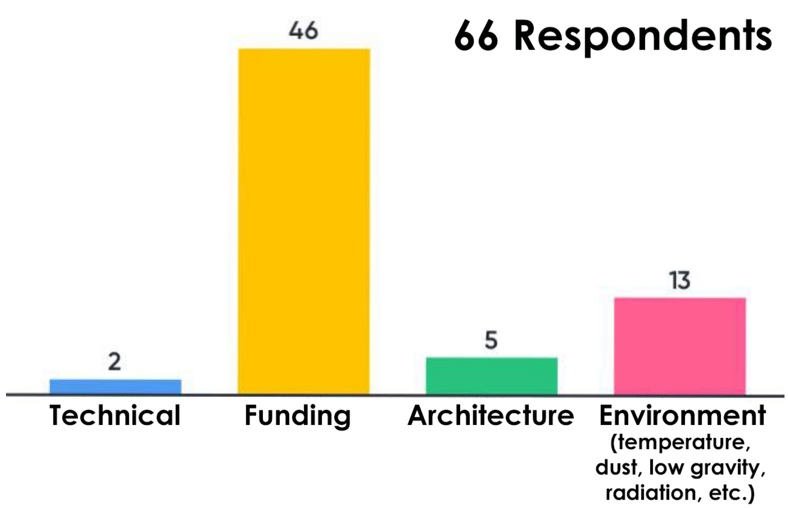
The session started with brief summaries from NASA and ESA on ISRU technology development activities at the respective agencies. After an informative primer on the mineralogical make-up of the regolith in the lunar south pole region and the implications for processing options, there were a half-dozen technical presentations on beneficiation of raw regolith and processing to extract oxygen from the mineral oxides, including use of microwaves, plasma pyrolysis, and molten regolith electrolysis. The second half of the session focused more on regolith processing for manufacturing and construction purposes. The session concluded with a panel session discussing some of the topics just presented. One key point raised during the panel session is that the data needed for ISRU are similar to those of interest to the science community, so that a CLPS mission dedicated to demonstrating the production of resources from regolith on the lunar surface will also provide significant scientific data about the nature of the regolith. Open discussions and answers from the Mentimeter exercise highlighted that equipment robustness, regolith handling, and access to large amounts of power (electrical and thermal) are critical for producing propellants and manufacturing/construction feedstock, and that autonomy and robotics may be the most important spin-in/spin-off for ISRU.

- *What are the most understudied major problems we will encounter when producing feedstock for manufacturing fuels and propellants on the Moon*?



The workshop participants considered that technology research and development of all kinds is under-supported, especially its ability to operate in the unfamiliar lunar working environment for useful lifetimes (this includes the extremely low temperatures of permanently shadowed regions, though not specifically called out here). The concern is spread more-or-less equally among power, materials handling, processing, and excavation technologies. Automation and remote-control advancements were felt to be proceeding at a more appropriate pace. Infrastructure to locate characterization and operations data on the lunar surface was not considered so crucial at this time.

- *What is the biggest hurdle for ISRU commercial development*?



Session Summary: Lunar Resource Markets

The lunar markets session outlined a number of the challenges and opportunities related to lunar resources. Given that markets are systems of exchanges for goods and services between parties, the questions related to markets for lunar resources focus on what those goods and services might be, and what types of exchanges between different parties might be possible. The overarching question at the moment is when and how ISRU can meaningfully contribute to economic sustainability at the Moon. There are lots of ideas related to this, but also no real-world examples of lunar ISRU that we can reference and learn from at this time.

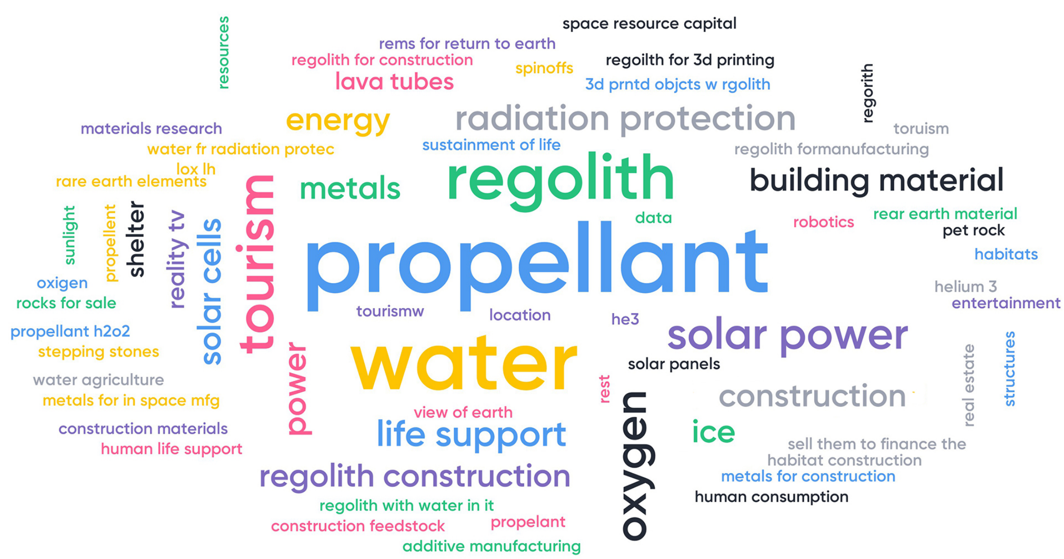
Currently, all significant contracts related to lunar missions are governmental in one form or another. In order to receive these government contracts, ~$200M has been invested from the private-sector into lunar-related companies, which is a positive sign. From a technology advancement perspective, it doesn't matter where the demand comes from as long as there is investment that advances the relevant spheres of knowledge and technology development.

One of the primary challenges related to developing markets for space resources is that ISRU is primarily relevant at scale, which means that it becomes challenging to justify the expense of ISRU development as part of near-term exploration architectures. This is because it is expected to be more expensive to produce large-scale consumables (such as propellant) in situ than to deliver those consumables from Earth until the architectures require very large scales of use for those consumables. Correspondingly, there is no strong incentive to build ISRU systems until we arrive at those scales. From an architectural trade perspective, lunar ISRU does not seem to be likely to trade well with propellant provision from Earth for any likely near-term Mars mission.

As a result, lunar ISRU is primarily beneficial when there is continuous human presence at Moon. At this time, therefore, it is important to be realistic, to focus on supply-side ISRU technology push efforts in the near-term, and for the community to rally around near-term missions that contribute significantly to evaluating the market potential for ISRU, and to advancing the social narrative for lunar resources, such as the VIPER mission.

The audience was invited to participate by responding to two questions:

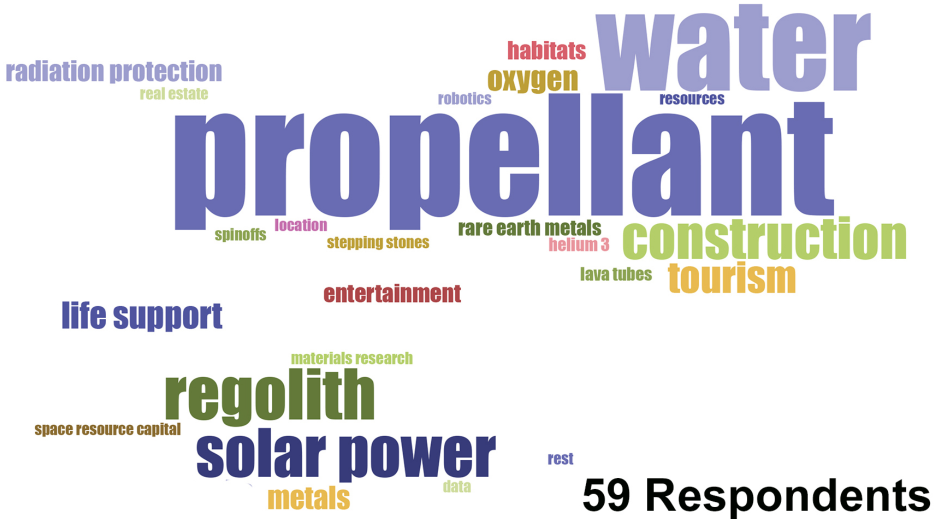
- *What are the lunar resource markets you're most excited about*?



79 Respondents

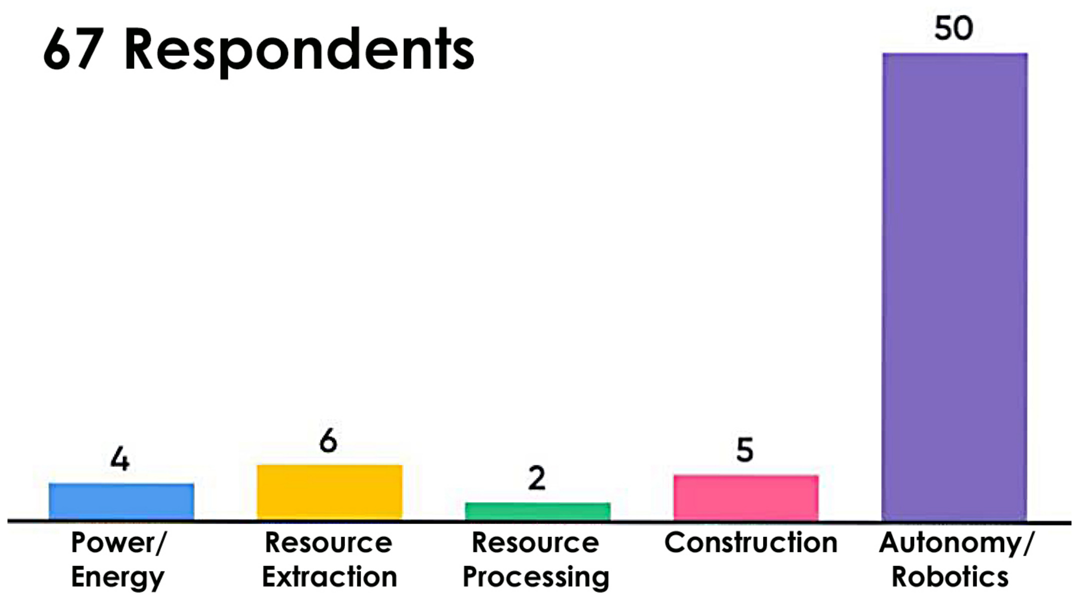
As noted above, the larger the word, the more popular was the response. The audience was most excited about markets developed for propellant, water, and regolith products.

- *What elements of strategic ISRU-related advice would you like to provide to NASA and the community as we embark on the Artemis program*?

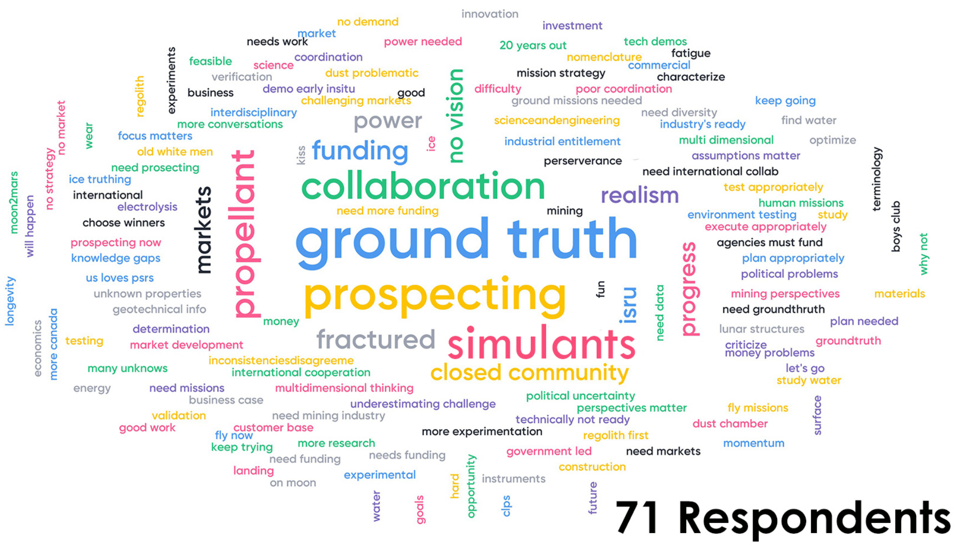


Session Summary: Workshop Wrap Up.
In the wrap up portion of the workshop, a synopsis of the findings was given and two more questions were asked of the audience.

- *What area/technology for ISRU has the 'best' spin-in/spin-off potential for terrestrial industry*?



- *What are the three takeaway messages you have learned at this workshop*?



Conclusions and Next Steps

The major conclusions from this workshop are as follows:

- Development and use of lunar resources is essential for sustainability.
- Resource exploration (prospecting) on the lunar surface with mobility assets is the critical next step to demonstrate that lunar resources are actually reserves and this has to be a campaign that explores several regions that have potential resources. For example, the ground truth about lunar polar water ice deposits, mapping these deposits and determining the viability of other lunar resources like regolith, oxygen, metals, etc., would be in line with current US space policy.
- Lunar resources will underpin the growth of the cislunar economy:
    - Lunar-derived propellant has the potential to lower the cost of all transportation beyond LEO by significant factors.
- The power and maintenance requirements for developing lunar resources if they prove to be reserves need to be quantitatively examined ASAP.
- Development of ISRU technologies for the Moon should, as far as possible, be applicable for use on Mars and beyond.
- The terrestrial extractive industries, in partnership with aerospace companies, have the expertise to develop lunar resources. However, the lack of a clear near-term market for lunar-derived ISRU products, as well as the lack of the necessary mapping of resource reserves, results in industry not yet being ready/willing to take leadership of this field. While there is significant interest from industry in the *potential* of ISRU, and some willingness to contribute private funds, further technology development and resource mapping is needed.
- A vital role exists for government to reduce risk through resource exploration, technology demonstration and being a customer for resources.
- Note that science data will enable exploration and exploration data will enable science. Both will enable commercial participation.

The next steps for this Lunar Resources initiative are currently being considered. These include development of public-private partnerships for resource prospecting/resource exploration and continued dialogue regarding the creation of markets for ISRU products. Also under consideration is developing an international lunar/space resources workshop in 2020. This is based upon the strong interest outside the United States for developing such resources. As such, we have an opportunity to create international as well as commercial partnerships to make ISRU a reality.