PRIORITIES FOR DEMONSTRATING LUNAR ISRU CAPABILITIES. L. S. Gertsch, Space Resources Roundtable, Inc. (www.ISRUinfo.com, 1006 Kingshighway, Rolla, MO 65409-0660, GertschL@umr.edu).

Introduction: The exploration of space will be easier when local (*in situ*) resources are used to produce items and consumables that otherwise would have to be shipped up from the deep gravity well of Earth. But nothing has ever been produced from raw materials collected anywhere other than Earth. Can it be done reliably? How must terrestrial processes be changed to be viable on the Moon, or on Mars? And how much can utilization of *in situ* resources (ISRU) contribute to the Vision for Space Exploration (VSE) and its potential evolution into the colonization of space?

Mission planners need to know such things. Capabilities and their limitations are most effectively confirmed or denied through demonstrations on-site, so precursor missions should include opportunities to demonstrate ISRU processes. The results must be returned in time for follow-up missions. However, the size, number, and duration of precursor missions are constrained by cost and timing, so hard choices must be made: Which capabilities are so important they must be demonstrated first?

Several assumptions about the generic architecture of the VSE make the ranking of potential ISRU-related demonstrations tractable:

- Human missions will rely upon some ISRU process(es) by 2022+.
  - The process is mission-enhancing, but not necessarily critical-path.
- Robotic landers will go to the moon on 2- to 3-year intervals, beginning in the next decade.
  - Robotic landers may be mobile or stationary.
  - Landed payload mass about 500 kg, including the power system.
  - Payload mass and power not dedicated totally to ISRU on most missions.
  - Power is solar for missions to sunlit regions, and fuel cell for shadowed regions (lifespan about 2 weeks). Nuclear power is assumed not available.

Given these constraints, the Space Resources Roundtable makes the following recommendations for which ISRU-related technologies should be demonstrated during the lead-up to, and the early stages of, the return to the Moon. After that, ISRU is expected to be an integral part of human and robotic presence on the Moon and in the push onward to Mars.

ISRU Demonstration Priorities: Mission-based demonstrations must satisfy certain criteria:

- Demonstrate sooner rather than later.
- Engage mission architects, whether NASA or industrial.
- Engage the public.
- Meet program needs for launch mass and cost.
- Demonstrate appropriate technology, at appropriate scales.
- Serve dual uses:
  - Show mission planners what to expect from ISRU, and
  - Prove the technology.
- Require in situ lunar demonstration; in other words, cannot be performed on Earth.

ISRU will generate the most "bang for the buck" (or the ton) when it is applied to:

Regolith excavation and transport.	For radiation/micro-meteorite shielding and thermal moderation.
Water production.	From regolith for life support and radiation shielding.
Oxygen production.	From regolith for life support and propulsion.
Fuel production.	From regolith for Earth return, lunar surface/orbital science expeditions, etc.
Energy production, transport, storage, and distribution.	For outpost use.
Structural and **building material** fabrication.	For outpost use.
Spare part, machine, and **tool** production.	For outpost use.
Construction and **site preparation**.	Using *in situ* materials and *in situ* energy.

These capabilities are demonstrable as single steps, as subsystems, and ultimately as end-to-end systems. The sub-capabilities can be divided roughly into the categories of *excavation and materials handling*, *materials processing*, and *manufacturing*. Unrelated technologies, or demonstrations of multiple approaches to the same end, can share the same mission, especially in the proof-of-concept stages where scales are small.

The logistics, planning, autonomy, and overall operations aspects of the necessary demonstrations (especially the integrated ones) require discussions outside the scope of this presentation.

Excavation and Materials Handling: The first stage in using any local material is gathering it (aside from resource characterization, which ISRU shares with scientific studies). Various samples have been collected, holes drilled, and trenches dug, but that is not enough for mission planning. Can these tasks be done repeatedly and autonomously? For how long, before equipment needs repair? How hard will it be to fix? What production rates can be expected? Can they provide feedstocks of the properties desired?

Several classes of excavation and materials handling capabilities should be demonstrated, in increasing order of complexity:

- Robotic precursor – excavate 10 kg of regolith.
  - Prove concepts for lunar surface excavation and material transport.
  - Validate analytical models.
  - Measure soil mechanics properties pertinent to later needs.
- Excavate regolith for oxygen production.
  - Demonstrate equipment performance.
  - Leverage terrestrial deep mining and small-scale mining technologies.
  - Test systems-level design.
- Excavate regolith for site preparation.
  - Large scale manipulation of regolith – berms, habitats, shielding, roads.
  - Test multiple, teamed excavation units for flexible capabilities.
- Excavate polar regolith for water extraction.
  - Mobility methodologies into and out of shadowed craters.
  - Different techniques required for regolith-ice mixes than for dry surface regolith than for compacted regolith.

Materials Processing and Manufacturing: The materials processing and manufacturing categories are grouped at this stage, but as ISRU concepts are proven, these categories must be broken apart for appropriate incorporation into mission architectures. In order of performance, early demonstrations should:

- Produce life support consumables.
  - Oxygen, water, nitrogen.
  - Increase safety margin.
- Produce propulsion consumables.
  - Oxygen, water, nitrogen.
  - Different product specifications than for life support.
  - Increase access to space, and safety margin.
- Generate power on-site.
- Manufacturing on-site.
  - Metals, ceramics, spare parts.
  - Demonstrate at later stages of planning the return to the Moon.
- Produce surface construction materials and capabilities.
  - Demonstrate at later stages of planning the return to the Moon.

Conclusion: "Living off the land" is a compelling strategy for the VSE. But it has never been done anywhere other than Earth. The ISRU demonstration missions outlined here will give mission architects knowledge they need to incorporate ISRU in their planning.

The time lag between missions using each other's results prompts parallel mission tracks, especially in the early stages of the VSE. Later missions take advantage of earlier mission findings.

- <u>Mission 1a – equator</u>
  - Scaleable oxygen production
  - Scaleable digging for feedstock
  - Characterize waste products
  - Study in situ volatiles
- <u>Mission 1b – shadowed polar crater</u>
  - Scaleable oxygen production
  - Scaleable digging for feedstock
  - Characterize waste products
  - Study in situ volatiles
- <u>Mission 2</u>
  - Longer-duration digging for feedstock
  - Extract volatiles
  - Produce power
- <u>Mission 3</u>
  - Integrated oxygen production at larger scale, including utilization of byproducts
  - And/or extract water (same complexity as Mission 1)
- <u>Mission 4</u>
  - Expanded power production
- <u>Mission 5</u>
  - Pilot/sub-pilot scale extraction or production, driven by results of Missions 3 and/or 4

These missions are doable within current time and cost constraints – indeed, they may already be planned for other purposes – and they can generate critical data for mission planners.

Background: These ISRU demonstration priorities were developed during Space Resources Roundtable VIII, the eighth annual meeting of the Space Resources Roundtable, Inc. (SRR), 31 Oct-2 Nov 2006. Roundtable IX will be 25-27 Oct 2007 in Golden, CO. Our website is www.ISRUinfo.com.