THE STRATEGIC VALUE OF ROBOTIC PRECURSORS TO HUMAN LUNAR POLAR EXPLORATION

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"Beginning no later than 2008, we will send a series of robotic missions to the lunar surface to research and prepare for future human exploration" – President George W. Bush, January, 2004.

A key goal of The Vision for Space Exploration (VSE) is to learn how to use lunar resources to support the long-term presence of humans on the Moon and to enable further exploration. A stated VSE objective is extended presence at the lunar poles, including the development of In Situ Resource Utilization (ISRU). As a decision has been made on a lunar return plan - a polar lunar base - is a robotic precursor program needed?

There are a number of decisions that need to be made regarding lunar ISRU. For example, oxygen and water may only be required to make up for losses in a closed life support system. Alternatively, these resources may be harvested for the production of fuel for cislunar operations as well for journeys farther a field. The latter capability is a necessity to enable a pay-as-you-go, permanent presence on the Moon and advance exploration of the Solar System.

The first question to be answered is which resources will be used and how they will be extracted. Hydrogen and oxygen, two important resources, can be found virtually anywhere on the Moon. Over most of the Moon, hydrogen is found in very low abundance (less than 100 ppm) from solar wind implantation and oxygen is about 45% of the lunar soil by weight.

The following are key ISRU issues: 1) the energy required to extract the substance of interest; 2) the efficiency and complexity of the extraction process (e.g., batch vs. continuous processing); and 3) the infrastructure needed on the Moon to establish resource production (e.g., mass needed on the lunar surface). A number of processes have been identified to extract O_2 from bulk lunar regolith; they have varying feedstock requirements (e.g., mare vs. highlands regolith), energy requirements, production efficiencies, and required infrastructure. Most of these processes are inefficient (less than a few percent yield) and require significant amounts of energy (tens of kWh/kg) Demonstrations of various techniques can be done on robotic missions, but most would need significant infrastructure for industrial-scale production (e.g., tens of metric tons/year, as in the production of rocket propellant), suggesting deferral of ISRU investment until a lunar transportation system is developed which supports these levels of mass delivery to the lunar surface.

Energy costs for extracting both O_2 and H_2 from typical lunar soil are presented in Table 1. Even taking advantage of abundant "free" solar thermal energy, extracting H_2 from typical lunar soils is a very energy intensive exercise.

The poles of the Moon are both different and largely unknown. Permanently shadowed regions may hold significant quantities of water ice (and other volatiles) mixed with the regolith. Water ice present in significant amounts (greater than 1-2 wt. %) would be a valuable resource. Water derived from ice can be electrolyzed to produce both H_2 and O_2 in a relatively low energy process (Table 1). The energy savings for mining lunar polar ice as opposed to processing non-polar lunar soil for the same quantities is significant.

Table 1. Energies required for selected lunar resource processes

Operation	Specific Energy
Equatorial Moon	
Excavation of regolith	0.01 kWh/kg regolith (electric)
Reduction of SiO_2 to Si + O_2	10.4 kWh/kg O_2 (electric)
Extraction of hydrogen from dry regolith[1]	2250 kWh/kg H_2 (thermal)
Polar regions	
Excavation of regolith	0.01 kWh/kg regolith (electric)
Extraction of water from icy regolith[2]	2.8 kWh/kg H_2O (thermal)
Electrolysis of water	4.7 kWh/kg O_2 (electric)
Electrolysis of water	48 kWh/kg H_2 (electric)

1. Assumes 100 ppm H_2, heated 800°C above ambient 2. Assumes 1% ice, heated 100° C above ambient

We do not yet know whether water ice is actually present at the poles and if so, its form, distribution, physical state or concentration.

It is known from measurements collected by NASA's Lunar Prospector spacecraft that enhanced levels of hydrogen are present in the polar regions. Average polar hydrogen concentrations are ~200 ppm, more than a factor of two higher than the equatorial average. What is not known is the form and location of the hydrogen. Is this enhancement general over a large area or does it represent small zones (at scales to small to have been resolvable in the LP data) of very high hydrogen concentrations? The elevated hydrogen signal could be explained by ice deposits in the permanently shadowed craters. In addition to elevated hydrogen content, the lunar poles have areas of near-permanent sunlight, permitting extended presence on the Moon without having to survive the 14-day nighttime and the extremely low surface temperatures (-150ºC) of the non-polar regions. Lit areas near the poles have a near-constant surface temperature of ~ -50ºC.

One of the objectives of a robotic program is to provide the data necessary for the definition and decision on technology development required for the human return to the Moon (know before you go). In the case of lunar resources, robotic precursors can determine if water ice is present and the data needed to understand what would be required to process the regolith to extract it. A robotic mission to explore a permanently shadowed crater (e.g., Shackleton near the lunar south pole) would provide such data if suitably designed and instrumented. Exploration of a permanently dark, cold crater is challenging, but represents a step that must be taken because of the huge potential benefit polar water could provide. In addition to strategic knowledge, such a mission could provide technology qualification for human lunar surface systems.

Once a robotic mission has determined the presence, form, distribution and concentration of polar ice, a decision can be made as to which ore is the most viable and what technology development program is required to exploit it. The problem is more complicated than a simple comparison of the energy required for break the O-Si or H-O bonds. Equipment and energy will be required to mine and move the regolith to a processing location, extract the product and store it and dispose of waste material. The nature and magnitude of difficulty of these steps are dependant on the nature of the deposit and the distances involved. It is these considerations that determine the effectiveness of lunar ISRU.

Robotic missions could characterize the potential of polar resources, demonstrate technologies to collect, move and process regolith, conduct extraction experiments (processes, efficiencies, possible problems), and experiment with conversion and storage techniques and processes. These demonstrations would facilitate understanding of the advantages and problems of selected methods of resource extraction and allow informed decisions on the which techniques to pursue. It has been suggested that once the decision has been made to establish a base at a lunar pole there is no need for any additional robotic missions. Such a decision now, while avoiding near-term costs, would result in higher risk and possibly much higher overall cost to the implementation of ISRU in human lunar return over the program lifetime. A possible path may be to identify cost sharing amongst international partners.

Summary and Conclusions

1. Harvesting polar resources may provide huge leverage to lunar ISRU. If polar ice exists and can be accessed, both H_2 and O_2 could be obtained for comparable amounts of energy input that yield O_2 only at the equator.

2. Polar ice may be most suitable feedstock for continuous resource processing; although we don't know this, we DO know that equatorial soils are NOT amenable to it.

3. Early propellant production can leverage cislunar transport significantly. A program to manufacture propellant on the Moon potentially could pay for itself after a few years of operations (a small facility (few hundred kg) can produce ~ 50 mT/year, the typical payload mass of a cargo-based LSAM.)

4. There are significant consequences to NOT finding out about polar conditions; you are driven down a road of known difficulty (and it is *considerable*.) ISRU will remain experimental (rather than productive) for a much longer time.

We believe that a robust program of robotic precursors not only reduces risk to the human program, but also provides operational experience on the Moon and visible program milestones in the long interval before humans actually return to the lunar surface. As President Bush noted in his speech announcing the VSE, a series of robotic missions to the Moon will pave the way for humanity's future on other worlds.