

HYDROGEN: A STRATEGY FOR ASSESSING THE KEY ELEMENT FOR THE LUNAR OUTPOST . J.

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Introduction: The Vision for Space Exploration (VSE) calls for the permanent occupation of the Moon using robots and humans. A key objective of the VSE is to learn how to use lunar resources in support of that activity and to achieve the objective of sustained lunar occupation, local resources must be exploited to the greatest possible extent.

Using ISRU a necessity to fulfill the objectives of the VSE as articulated by the President and within the context of “*pay-as-you-go*”. To facilitate *pay-as-you-go*, prevent expenditures on technical blind alleys, and reduce programmatic and technical risk, one needs to “*know before you go*.”

Key decisions with respect to resource utilization include its choice, use, and production method(s). While it is possible now, using our current understanding of maria and highland chemistries, to make a decision regarding which ore to exploit, such a decision in the absence of an understanding of the resource potential of the Moon as a whole could be fiscally and programmatically unsound. Understanding the resource potential of the polar regions, about which we have little data, is required to make an informed decision.

ISRU Requirements: Hydrogen and oxygen are the most valuable elemental resources and can be found anywhere on the Moon. H₂ typically occurs in very low abundance (~50 ppm) whereas O₂ makes up ~45% of the regolith by mass. The issue of mining hydrogen and oxygen is not so much where to go as what is involved in obtaining those elements in different places and using different feedstocks.

The Known Moon: The Apollo and Luna missions provided a sufficient database for understanding the chemical and physical properties of the equatorial lunar regolith. Several processes have already been identified to extract oxygen from both mare and highlands regolith; each has different energy requirements, production efficiencies, and required infrastructure. Most processes are inefficient (less than a few percent yield) and require significant amounts of energy (10’s KWh/kg); some are feedstock-sensitive (e.g., ilmenite reduction requires high-Ti mare regolith).

The Unknown Moon: The lunar poles are both different and largely unknown compared with the front-side low latitude area. Permanently shadowed regions *may* hold significant water ice (and other volatiles) mixed with the regolith. While enhanced levels of hydrogen are certainly present, we do not know its

form (H₂ or H₂O) or the physical properties of the deposit. If present as H₂O, that water can be electrolyzed to produce both H₂ and O₂ at relatively low energy expenditure.

While the Lunar Prospector neutron data indicate enhanced hydrogen over the polar regions, those data have insufficient resolution to differentiate between regional enhancement at 100-150 ppm and local concentrations in shadowed areas of 1000 ppm. This distinction has important implications for harvesting the hydrogen. If it is uniformly distributed over the polar regions, it is probably largely of solar wind origin and could be extracted anywhere. If it is sequestered in permanently shadowed areas, then the challenges of harvesting the hydrogen would be much different.

Implementation Approaches: In order to determine which model is correct, surface exploration must be conducted and *in situ* analyses made. The form, concentration and distribution (both vertically and laterally) of the hydrogen must be understood. Studies conducted during RLEP and LPRP considered a variety of mission options to explore both the illuminated and permanently shadowed regions. Options were considered in which a rover/lander combination was landed in an illuminated region; the rover was then deployed to explore both the illuminated and shadowed regions. In other options, a static lander was deployed to the illuminated region and a second “sled” was landed in the shadowed area carrying the rover; the sled simply delivered the rover and the rover then proceeded independently. For the mission scenarios in which two vehicles were landed; architecture involving single and dual launches were considered. Because of their size, these missions all had the ability to definitively determine the hydrogen form, distribution and concentration in both the illuminated and shadowed regions as well as conduct a complete review of environmental assessments.

An alternative architecture involving a more focused set of experiments to assess the hydrogen content has also been considered. This involves the use of hard landers to deploy a highly focused payload, in this case to assess the hydrogen content. The methodology is similar to that envisioned for deployment of a hard-landing seismometer (“Tonto”) from the Ranger spacecraft as it approached the Moon.

A small package (e.g., a sphere) would be deployed from orbit. A retrorocket would be used to null out the orbital and most of the descent velocity. The package would hit the surface and be designed to withstand the shock and operate for a few hours. The payload could include: a neutron spectrometer, volatile analysis package, and an elemental analysis experiment (e.g., XRF, apx). Unlike the Japanese Lunar A mission, the package would remain on the surface rather than penetrating into the regolith. Multiple packages would need to be deployed to obtain coverage in both the illuminated and shadowed areas.

Assessments using small landed packages would provide some data, but would be unable to address the broad distribution and concentration of the hydrogen. A mobile platform with the ability to collect and analyze subsurface samples will still be required. But, the understanding gained from these packages would provide very explicit guidance for a more sophisticated future mission.

Energy / Technology Issues: The energy needed to produce O_2 and H_2 is a more complicated issue than a simple comparison of the energy required to break the Si-O / metal-O or H-O bonds. The total cost for such harvesting includes the energy to extract the ore; the energy to emplace the infrastructure, as well as the energy to break the molecular bonds. Previous ISRU studies have noted that the presence of polar water and other volatiles must be answered before an accurate ISRU cost/benefit analysis can be completed. Finding such high-grade deposits allows “bootstrapping” of capability from RLEP-scale infrastructure and provides high leverage on resource production early in a program of lunar return. Water electrolysis is a mature technology, used extensively at industrial scales (e.g., submarines). Extracting oxygen from silicates has been done at large scales only in the aluminum-smelting industry and is a very energy-intensive operation.

Consequences: Once the presence, form, distribution and concentration of polar ice are determined, an informed decision can be made as to which ore (mare regolith or polar ice) is the most relevant to the lunar return architecture. Cost savings and risk reduction might come from more than simply lower energy requirements; it may be possible to extract polar volatiles *in situ* without moving the regolith. But, that possibility is a function of the nature of the deposit and distances involved, which are unknown. It is certainly true that the poles are more benign from both power generation and thermal loading perspectives. There are locations near the poles of near-permanent sunlight and a near-continuous surface temperature of $-50^\circ \pm$

$10^\circ C$, compared with the two weeks of darkness and a $250^\circ C$ temperature span at lower latitudes.

RLEP missions could demonstrate regolith mining, conduct extraction demonstrations, and experiment with conversion and storage techniques and processes. These would allow an understanding of the advantages and problems of each method and allow informed decisions as to which technique to pursue.

Conclusions: We could choose to go to the equator today; we have sufficient knowledge of the Moon and its materials in equatorial regions to design a human outpost now. We have enough samples and surface information to design and implement an ISRU plan; we know the level of difficulty and the likely costs of producing a given amount of product per unit time. If such a choice is made, there is no need for *any* early, information-gathering robotic missions, including the LRO.

However, we believe that it is unwise to choose a lunar architecture now, without first characterizing the nature of the polar volatiles. The unique nature of those polar resources could significantly reduce costs and enhance both the speed and scope of capabilities on the lunar surface. Over the next six years (2006-2012), NASA will spend about \$100B. An early, premature decision (*go before you know*) may avoid near-term RLEP expenditures, but could result in higher risk and possibly a much higher overall cost to implement the VSE. An RLEP program of 1-2% of the total program cost is not unreasonable, considering that permanent, sustained human presence on the Moon is a prime objective of the VSE.