LUNAR POLAR EXPLORATION: QUESTIONS, ISSUES AND MISSIONS. Paul D. Spudis, Lunar and Planetary Institute, Houston TX 77058 (spudis@lpi.usra.edu)

The Vision for Space Exploration calls for a return to the Moon with both robots and humans [1]. On the Moon, we will learn the skills and techniques needed to live and work productively off-planet. A key objective is to learn how to use lunar resources to support the long-term presence of humans on the Moon and to enable further exploration, implying extended presence on the Moon, development of significant infrastructure, and the exploitation of local resources to the greatest extent possible. A critical decision in lunar return is what resources are most important and how they will be used [2]. For example, oxygen and water may only be required to make up for losses to a closed-loop life support system. Alternatively, these resources may be harvested for the production of fuel for operations in cislunar space as well for journeys farther afield. The latter option is a necessity to enable pay-as-you-go, permanent presence on the Moon and further Solar System exploration.

In the last decade, we've found that the lunar poles are unique and interesting environments and that our understanding of the processes and evolution of this region is incomplete. The discovery of quasi-permanent sunlit areas near the poles [3, 4] have been complemented by mapping of the permanently dark areas [5, 6] and thermal modeling of resulting cold traps near the poles [7]. Several studies have attempted to determine the nature of volatile deposits at the lunar poles, using a variety of techniques from radar [8] to neutron spectroscopy [6]. It is reasonably clear that enhanced amounts of hydrogen are present at both poles, but both the origin and physical state of this material is uncertain.

Knowledge Needs We are interested in both process and history. We have no direct exploratory experience with the polar environment and thus, most of our understanding derives from modeling and prediction. The dark areas are presumed to be very cold, but we do not know exactly how cold they are [7]. The unknown form of polar hydrogen is a clue to both source regions and lunar processes. Polar hydrogen consisting predominantly of implanted solar wind protons has one implication, water ice and other volatile substances found in cometary cores another. To resolve these and other scientific issues, we must determine the physical, chemical, and isotopic properties of polar deposits and characterize the polar environment and its temporal and spatial variations.

Learning to live off the land on the Moon is a primary task of the Vision [1]. Among the questions to be answered are the extent to which ISRU is viable, which resources will be used, and how they will be extracted. Hydrogen and oxygen, two important material resources, can be found virtually anywhere on the Moon. Over most of the Moon, hydrogen is present in very low abundance (less than 100 ppm) from solar wind implantation and oxygen (bound to rock-forming silicates) is about 45% of the lunar soil by weight [9].

Successful large-scale exploitation of lunar resources is dependent upon: 1) the energy required to extract the substance of interest; 2) the efficiency and complexity of the process of extraction (e.g., batch vs. continuous processing); and 3) the infrastructure needed on the Moon to establish resource production (e.g., mass needed on the Moon). A number of processes have been identified to extract O_2 from the both the mare and highlands regolith; they have varying energy requirements, production efficiencies, and infrastructure. Most processes are inefficient (less than a few percent yield) and require significant energy (tens of kWh/kg). Some are feedstock-sensitive (e.g., ilmenite reduction requires high-Ti mare regolith.) Understanding what the poles offer is critical to making intelligent resource utilization choices.

We need first to map polar topography in order understand the extent and locations of both high illumination areas and permanently dark cold traps. This information is complemented by imaging of the poles under different seasonal conditions. Because the sun angles at the poles are always less than 1.5°, subtle slopes undetected in relatively low resolution orbital data could significantly effect terrain illumination.

The physical properties of most lunar materials are well known [9], but the unusual lighting conditions of the poles may have result in unpredicted effects on regolith properties, particularly if volatile material is present in frozen form. We must understand how such material is physically situated within the lunar surface and whether is intimately mixed with fine regolith or heterogeneously distributed and found as "clean" isolated deposits of distinct properties. This information is needed not only to understand and plan ISRU extraction strategies, but also to provide clues to process and thus, has scientific implications as well.

The nature of the polar volatile material itself is almost completely unknown. We suspect hydrogen to be the principal light element, but we do not know its physical state or distribution. Although not definitive, neutron data suggest that the hydrogen enrichment is correlated with permanently dark areas (cold traps) near the south pole, but this relation is much less clear for the north pole [6]. If the hydrogen is present in the form of water ice, it must occur only in permanently dark areas. The species and abundance of volatile material is of prime importance. In addition to hydrogen, we could expect to find other light elements including helium, carbon, nitrogen and sulfur. If the volatile material is of cometary derivation, a variety of additional elements and compounds could be expected, including CO, CH_3, NH_4, and several types of organic substances.

A polar exploration strategy A variety of missions can be imagined that would not only fundamentally advance our understanding of the scientific issues of the lunar poles (process and history), but also obtain critical strategic information that enables architectural decisions to be made intelligently (e.g., outpost location, resource processing techniques, etc.). Indeed, a decision not to fly such missions means that such decisions will have to be made in ignorance, increasing time, cost, and risk.

Much about the environment of the lunar poles will be addressed through the current round of international lunar orbital missions. Each current lunar mission carries a laser altimeter; in addition, the Chandrayaan mission will collect stereo images at 5 m/pixel, controlled by laser profiles. This will enable the making of a digital elevation model for both poles at a resolution of 10 m. Combined with continuous, repeated and detailed imaging (at resolutions up to 50 cm/pixel from LRO [10]) and direct measurement of the temperatures of the polar cold traps [10], we will obtain detailed information of the shape, topography and surface properties of the polar regions and hence, detailed knowledge of the extent and location of lit and dark areas.

New mapping of the polar deposits will use two techniques. The Mini-RF radar imager will map the dark areas of the poles and search for materials of anomalous RF reflectivity, possibly indicative of water ice [11]. The neutron spectrometer on LRO – and possibly gamma-ray spectrometer on Kaguya – will detect hydrogen deposits near the poles [10], hopefully at resolutions that will allow us to directly correlate (or not) hydrogen concentrations with the dark areas. Such a correlation is an important clue to process and origin.

Following the current international fleet of orbiters, new robotic missions can acquire additional critical information to make our return to the Moon safer and more productive. New orbital missions, hard landing probes, soft landing spacecraft, surface rovers, networks and sample returns all can provide important information and gain operational experience in the lunar environment. In addition, data from robotic probes are important to prepare for the characterization and utilization of local resources, one of the principal objectives of lunar return.

After characterization from orbit, measurements need to be made on the surface of the Moon. Such data can be acquired in a variety of ways on different missions. Hard landers, in which instruments are emplaced on the surface via "rough" landings, could use penetrators or crushable microspacecraft. Penetrators have been studied for use on planetary missions for some time, but to date, have never flown. The most recent attempt was the Japanese mission "Lunar A", which was cancelled because of technical difficulties [12]. A "crushable" lander approach may be better; such a technique was planned during he Ranger program of the 1960's [13]. In the case of Ranger, a seismometer was landed on the Moon encased in a crushable, balsa-case, water-jacketed landing sphere. New materials such as crushable aluminum could carry instruments to document the polar volatiles (e.g., neutron and mass spectrometers; XRF). These measurements would make an analysis of a single point, but such information could yield valuable insight into the polar deposits. For example, if the lander was in a sunlit area, and found hydrogen concentrations similar to the orbital average, it would suggest that the hydrogen is uniformly distributed around the poles, making a cometary ice origin less likely. On the other hand, a low hydrogen content there would indicate that concentrations in the dark areas must be significantly higher (in order to make the higher average seen from orbit). This would suggest that concentrated deposits of hydrogen exist in at least some dark areas, making an occurrence as ice much more likely. Although this mission would not resolve the issue of polar ice, it would significantly improve our understanding of the nature and distribution of these deposits.

Ultimately, we need to soft-land sophisticated instruments on the Moon to analyze the physical and chemical nature of the polar deposits in detail. Soft landers can analyze a single site and deploy instruments or roving vehicles. Rovers can conduct traverses and explore a region, making measurements and images in route. Because such missions will operate for extended periods in the dark, cold regions, they will require long-lived power sources, such as an SRG (nuclear) or a rechargeable hydrogen-oxygen fuel cell. Because most sites of potential volatile enrichment are out of the line-of-sight of Earth, a communications relay satellite is needed to reliably control the rover and return the collected data.

It is not clear that all we need to know about the polar deposits can be learned solely from *in situ* measurements. Sample return missions can collect reconnaissance samples of sites in preparation for human study or of sites where people can't or won't go. Special sample collection and containment procedures are required to preserve the integrity of volatile samples from a polar cold trap; it is not clear that such preservation is easily accomplished and the requirements will be largely dictated by the nature of the polar deposits, information to be acquired through direct, *in situ* characterization.

After the nature and occurrence of polar deposits are mapped and understood, it is important to demonstrate extraction techniques for resources on the Moon, both as program milestones and to assure that the full range of processing difficulties are understood. ISRU demonstration missions can be quite small; the principal needs are reliable Earth communications, long-lived power, access to feedstocks, and production tests such that the level of effort (power, time, operational difficulties) as a function of product yields can be understood. This information is critical for the selection of resource processing techniques to be used when people arrive on the Moon. After an evaluation program, the resource production equipment for a human outpost could be landed on the Moon, prior to the arrival of people. Long-term operation of modest facilities can produce enough resources to completely supply water and air for the outpost and give important experience for subsequent larger production levels (e.g., rocket fuel.)

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