SCIENCE, HUMAN SETTLEMENT OF THE MOON, AND LUNAR RESOURCE EXPLORATION AND UTILIZATION.

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Introduction: The central goal of human space exploration is (or ought to be) the development and settlement of space. This ambitious venture will lead to new businesses and wealth for the benefit of all earthlings, new perspectives of our world and its problems, creation of new resources, expansion of our civilization and values, and the capability of protecting Earth from space hazards. The first settlements will be on the Moon. Sustained presence on the Moon will require aggressive use of *in-situ* lunar resources (ISRU), and emphasis should be placed on the exploration for and use of lunar resources (see [1] for a review of lunar resource potential). Although science is not the driving reason for human exploration, it will benefit greatly from ISRU and the entire infrastructure developed to support human settlement. Identification of potential resources has its roots in the fundamental science resulting from sample analysis, field work, and remote sensing of the Moon. Prospecting and extracting resources will create new capabilities and opportunities for the scientific exploration of the Moon. Science and applied science are two parts of the same coin. In this white paper, I outline the relation between ISRU and science, with emphasis on lunar science.

Science enables ISRU development: During development of ISRU systems, science is essential. It is important to find and characterize lunar resources (geology and geophysics), and to understand phenomena so engineers can design systems that work (physics, chemistry, materials science). Studying resource extraction and manufacturing processes in the unusual lunar environment will likely lead to new understanding of physical and chemical processes, such as surface science and granular flow. During the operational phases of ISRU systems, science will play a role in testing the validity of the solutions stemming from research during development.

The search for and characterization of resources on the Moon uses our current knowledge of lunar science and measurements by the same techniques used to do fundamental scientific studies of the Moon. It uses orbital datasets (Fig. 1) and local geological and geophysical surveys to map and characterize potential deposits. In addition, the feedstocks used for ISRU processing will be studied by the same scientific techniques used to study lunar samples for the past 38 years. ISRU development will require a lot of applied lunar science.

ISRU could not be developed without application of engineering and materials science, and from fundamental chemistry and physics. There will be technical obstacles to overcome, and these sciences provide the means to overcome them.

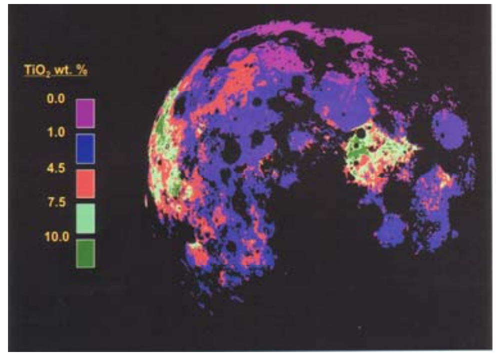

Fig. 1. Orbital measurements, such as Ti inferred from Clementine reflectance data, are good examples of how global prospecting for lunar resources is done using tools developed for the scientific study of the Moon.

ISRU enables science: ISRU boosts the scientific study of the Moon in two main ways: (1) The search for resources allows study of areas of scientific interest, such as lunar polar regions. (2) The development of a robust infrastructure allows for scientific investigations that would otherwise not be done, such as detailed studies of the composition and layering of the lunar regolith.

Searching for resources. The need for resources on the Moon adds strong rationale and often a pressing need for certain science investigations. A prime example is the search for volatiles in permanently-shadowed areas of the lunar poles, which appear to be enriched in H (Fig. 2). Such deposits contain the record of their sources and their chemical compositions. These might include the solar wind, comets, hydrous asteroids, and giant molecular clouds, which allows us to study water throughout the Solar System and in interstellar space. No matter how much H_2O and other volatiles are present, thorough study of the deposits will shed light on the nature of the mechanisms by which volatiles are transported to polar regions and then preserved in them. Preservation mechanisms may include burial, chemical and physical adsorption, and chemical reactions to form hydrous minerals. Perhaps most important, the deposits are natural laboratories in which to study interactions between fine dust and H and H_2O molecules—a natural laboratory for studying icy processes in space. Although these are compelling scientific reasons for exploring shadowed regions, the possibility that useful quantities of H_2O and other volatiles are present will drive our exploration of these fascinating, and currently barely explored, areas of the Moon.

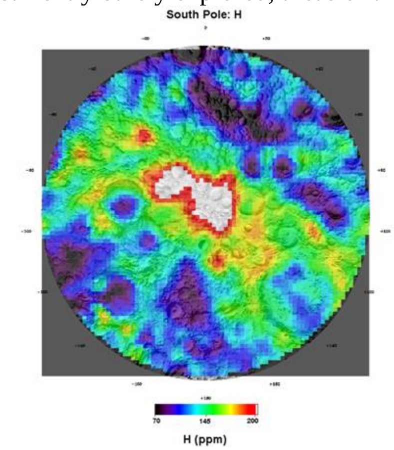

Fig. 2. H concentration at South Pole, measured by the Lunar Prospector neutron spectrometer. If H is greatly concentrated as H_2O in permanently-shadowed areas, it might average as much as 1.5 wt% [2].

Other scientifically-useful exploration targets are mafic igneous rocks, evolved igneous rocks, explosive volcanic deposits (pyroclastic deposits), meteoritic debris in the regolith and in impact melt sheets, and solar wind volatiles in the regolith [3].

Capable infrastructure and sustained presence. Once humans have settled the Moon and have routine access to the entire lunar surface and to cis-lunar space, lunar science will prosper. For example, there are several areas of lunar science that require detailed field observations and sample collection, or extensive excavation. These include detailed studies of the lunar regolith, such as understanding the nature of the boundary with underlying bedrock or the search for layers from specific impact events on the Moon or even on the Earth. The regolith is extremely complicated and understanding its formation will require detailed field studies of deep trenches in it, geophysical surveys, and sample analysis (on Earth or at the lunar base). It may be difficult to justify these time-consuming and long-duration studies on purely scientific grounds, but the studies are essential to understand how to process the regolith and to monitor feedstock for ISRU operations (e.g., oxygen or metals production). The necessary deep trenches may be a natural consequence of mining the regolith (Fig. 3).

Determining if there are variations in the rate of impact during the past billion years requires collecting samples from hundreds of impact craters. This huge task will take a long time and robust mobility. This mobility can be in the form of ballistic hoppers or teleoperated robots (Fig. 4) controlled from the lunar base [4,5]. These capabilities are essential for the exploration of Mars, too.

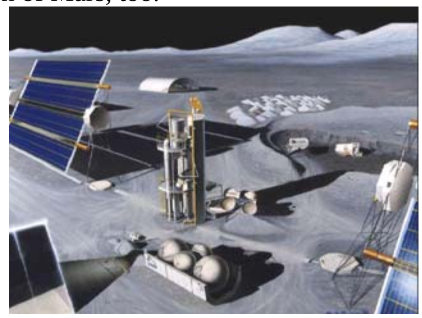

Fig. 3. Mining operations at a lunar settlement will reveal meters of the lunar regolith for scientific study. In fact, such studies might be essential to ISRU operations.

Fig. 4. Teleoperated robotic prospectors [4,5] will explore for resources and do geological field work.

Lunar environmental science. No matter how conservative our extraction systems will be (for everything mined in space is valuable), ISRU operations and extensive lunar settlement will affect the lunar environment, thereby creating the new field of lunar environmental science. This will entail installation of sensors at varying distances from an outpost or settlement. It provides an important opportunity to monitor the effects of human presence on biological and organic contamination, and to develop ways to mitigate them. This will help us prepare for human missions to Mars by helping minimize contamination and to understand the nature of such contamination.

References: [1] Duke, M. B. et al. (2006) *Rev. Min. & Geochem.* **60**, 597-655 [2] Feldman W. C. et al. (2001) *JGR-Planets*, ***106***, 23,231-23,251. [3] Taylor, G. J. and Martel, L. M. V. (2003) *Adv. Space Res.* **31**, 2403-2412. [4] Taylor, G.J. and Spudis, P.D. (1990) *Engineering, Construction, and Operations in Space II*, 246-255. ASCE, New York. [5] Spudis, P.D. and Taylor, G.J. (1992) *The Second Conference on Lunar Bases and Space Activities of the 21st Century*, NASA Conf. Pub. 3166, 307-313.