

In-Situ Resource Prospecting, Assaying and Mapping, K.R. Johnson and R. W. Easter, Jet Propulsion Laboratory, 4800 Oak Grove Drive, Pasadena, CA 91109, kenneth.r.johnson@jpl.nasa.gov, Robert.w.easter@jpl.nasa.gov

Introduction: Thar's gold in them thar hills!! We know it's there but we aren't quite sure where it is.

The Exploration Systems and Mission Division of NASA plans to develop In-Situ Resource Utilization (ISRU) technologies for the exploration of the Moon, Mars and beyond. It has been frequently suggested that in-situ resources might be beneficially used to provide consumables for astronaut survival (esp. oxygen and water), propellant for return vehicles (e.g., LOX, LCH₄, H₂), radiation shielding (using regolith covers and berms), and even to produce metals and ceramics for spare parts and solar photovoltaic cell substrates. These suggestions imply that if we can reduce the need to take all of the necessary supplies for a mission from Earth, there will be a net gain to a mission in terms of reduced Earth-launch mass, enhanced exploration duration, or the possibility of enabling long-term colonization. Initially, ESMD plans to focus on ISRU development for lunar applications.

Implementation of ISRU obviously requires in-situ resources of the type and composition that will be useful in satisfying an ISRU objective. The engineering design of equipment to gather and process in-situ resources requires some detailed knowledge of both the qualitative and quantitative analysis of the resources of interest. Analysis of the lunar samples returned by the Apollo and Luna exploration missions provided a wealth of qualitative and quantitative data about the mineralogy and the relative chemical composition of lunar surface regolith at different lunar locations. The Lunar Source Book provides a very detailed synopsis of the results of qualitative and quantitative analyses of those lunar samples. Table 7.15 in the Lunar Source Book lists the chemical compositions (wt%) of average soils at lunar landing sites. The soil is made up almost entirely of oxides of Silicon, Aluminum, Iron, Calcium, Titanium and Magnesium with small amounts of oxides of Sodium, Chromium, Manganese, Potassium and Phosphorus. Table 7.16 lists the major and minor element abundances (wt%) in bulk lunar soils as analyzed in five different particle size fractions (bulk, >90 μm, 20-90 μm, 10-20 μm, and <10 μm) to illustrate how the composition is distributed by particle size. Table 7.17 lists the trace element abundances (parts per million) in bulk soils separated into size fractions analogous to Table 7.16. Tables A8.1 through A8.6 provide statistical summaries of lunar chemistry including data showing the very small concentrations of solar-wind implanted elements (H, C, N, He, Ne, Ar, Kr, and Xe).

The major thrusts of the current NASA ISRU development program is to develop processes that can extract oxygen and volatiles from the lunar regolith. Various processes for extracting oxygen are under consideration but all of these processes face the daunting thermodynamic task of breaking the oxide bond by either electrolysis, hydrogen reduction or carbothermal reduction (with either CH₄ or CO). The volatiles of interest are primarily considered to be solar-wind

implanted gases hydrogen, helium and nitrogen which hypothetically can be released (desorbed) by heating the regolith up to 700°C. The products of these various processes are intended for use as propellants (O₂, H₂), consumables (O₂, N₂, H₂O), nuclear reactor fuels (He-3) or reactants for intermediate processing (primarily H₂ for reduction of oxides to form H₂O which is subsequently electrolyzed to form H₂ and O₂; secondarily H₂ to react with CO₂ to form CH₄ which is recycled in the carbothermal process).

Any lunar outpost that involves permanent or near-permanent human presence will require a significant amount of water for drinking and domestic use. Previous studies by JSC and others have estimated a water requirement of 10 kg/day per crew member for short term stays and 28 kg per day per crew member for long term stays. Assuming that it is possible to recycle up to 80% of the water (a fairly bold assumption), there would still be a water make-up requirement of about 6 kg/day per crew member. For a crew of four, for 365 days, the water make-up requirement would be at least 8760 kg, or nominally about 10 MT. If water recycle capability is limited or non-existent, about 40MT/yr would be needed. But the analyses of the lunar samples returned from the Apollo and Luna missions indicate that there is no trace of indigenous water in the lunar regolith. If water is not found on the moon, then the water requirement would need to be satisfied by deliveries from Earth at a cost that would clearly challenge the overall viability of a long-term manned base on the lunar surface. Therefore, it becomes clear that prospecting for and finding water on the moon are necessary precursor requirements for enabling a long-term manned lunar base.

The neutron spectrometer on the 1998 Lunar Prospector mission indicated that there was a higher concentration of elemental hydrogen in shadowed craters near the lunar poles than there was at other areas on the lunar surface. One would suspect that if the presence of hydrogen was due solely to solar-wind implantation then the concentration of hydrogen in the regolith would appear to be relatively uniform at all locations on the lunar surface. Since the Lunar Prospector neutron spectrometer data indicated that the hydrogen concentration was anything but uniform, it was then hypothesized that the permanently shadowed craters at the lunar poles were acting as 40 K cryotrap effectively freezing and containing any H₂O molecules that may have found their way to the poles by molecular motion. These H₂O molecules are thought to have originated from comet and meteor impacts on the lunar surface over millions of years. Because of the Lunar Prospector findings, it has been argued that it is important to send lunar landers and rovers to the shadowed lunar craters to collect "ground truth" data that can yield the unambiguous determination of the form of hydrogen (water ice, solar-wind implanted hydrogen, hydrates, organics, ammonia, etc.) that may exist in the permanently shadowed polar lunar craters and at what concentration and distribution (i.e., are there concentrated pockets of water ice,

or is the water ice resource uniformly distributed throughout the crater). We must prospect for the mere presence of water and then analytically assay the content of the water once/if it's found. We also must map the area that has been prospected to provide a qualitative and quantitative basis for making subsequent decisions regarding the suitability of a particular site for constructing a long-term lunar outpost based upon the presence and quantity of water that is available at each particular site surveyed. Therefore, collecting "ground truth" data primarily for establishing the presence and concentration of water ice and/or solar-wind implanted hydrogen should be an initial and primary focus of the lunar ISRU program.

What are the tools needed to provide the water/hydrogen prospecting, assaying and mapping function? First and foremost, a neutron spectrometer is needed to measure the presence and relative concentration of elemental hydrogen at a particular site. Ideally, the neutron spectrometer would reside on a lunar rover and would be used as the first mode of prospecting for locating relatively high concentrations of elemental hydrogen. At locations of high hydrogen concentration, microscopic images and Raman spectrographic analyses of core samples would provide data regarding the form of the hydrogen detected by the neutron spectrometer (water ice, solar-wind implanted hydrogen, hydrates, organics, ammonia, etc.), along with an indication of how these hydrogen-bearing materials are distributed as a function of depth from the lunar surface. It has been hypothesized that it could be possible that there might be subsurface layers of water ice that are continuous over relatively large areas. In locations where water ice is located, a ground-penetrating radar (GPR) system could be used to first characterize the signature at that location. By comparing GPR readings at contiguous sites, the uniformity of the subsurface structure can be mapped. This mapping can yield important information that can help establish the boundaries of subsurface water ice fields if they exist. Knowledge of these boundaries can be used where to delineate regolith excavation activities for optimum recovery of available water ice resources.

Resource prospecting is the act of methodically and qualitatively searching for a particular resource of interest. For ISRU purposes, we would first prospect for the presence of water ice and solar-wind implanted hydrogen. Resource assaying is the act of analytically determining the composition of the desired resource in the bulk material once a resource containing a relatively high concentration has been found. For ISRU purposes, we specifically want to know the wt% of water ice and solar-wind implanted hydrogen as a function of depth below the lunar surface. Resource mapping is the act of providing a data base of resource composition as a function of location and depth. With the resource maps we can determine the best and most viable potential location for situating a long-term lunar outpost. By structuring a program that combines prospecting, assaying and mapping into a cohesive effort, we will maximize our chances of

finding water and enabling the possibility of establishing a long-term manned outpost on the moon.