Lunar In-situ Resource Utilization

Gerald B. Sanders, *Johnson Space Center*
Tom Simon, *Johnson Space Center*
William E. Larson, *Kennedy Space Center*
Jackie Quinn, *Kennedy Space Center*
Robert P. Mueller, *Kennedy Space Center*
Kurt R. Sacksteder, *Glenn Research Center*
John Caruso, *Glenn Research Center*

A robust project is under way to develop the capabilities needed to produce most of the consumables required to sustain a lunar outpost from resources found on the moon. A key to fulfilling the goal of sustained and affordable human and robotic exploration is the ability to use resources that are available at the site of exploration (to "live off the land"), known as in-situ resource utilization (ISRU). Traditionally, these resources are the elements found in the soil or the atmosphere. However, ISRU can also include waste products that are the result of human presence. For example, the descent stage of the Altair lander contains residual propellants that can be scavenged. The tanks containing the propellants can be removed from the lander to provide storage tanks on the surface. Plastics from the astronauts' food containers can provide an important source of carbon at locations, such as the moon, that are carbon poor. By producing propellants, life support and fuel cell power consumables, and other items from in-situ resources and eliminating the need to launch everything from Earth, long-term launch and mission costs can be reduced while potentially increasing science and exploration capabilities as well as mission safety. The ability to modify the lunar landscape for safer landing, transfer payloads from the lander to an outpost, mitigate dust generation, and place and build up infrastructure is also extremely important for long-term lunar operations.

As ISRU hardware and systems for human robotic systems, energy storage and power systems, thermal control for surface systems, exploration life support, extravehicular activity (EVA), dust mitigation, cryogenic fluid management, and nontoxic propulsion have never been demonstrated before, NASA is hesitant to add these capabilities into mission designs and plans and make lunar mission success contingent on them. However, once demonstrated, these ISRU capabilities could be inserted into the lunar architecture. With this in mind, the NASA ISRU Project initiated development and testing of hardware and systems in three main focus areas: (1) regolith excavation, handling, and material transportation; (2) oxygen (O_2) extraction from regolith; and (3) ISRU concept evaluations. To minimize cost and ensure that ISRU technologies, systems, and functions are integrated properly into the outpost, technology development efforts are being coordinated with other lunar exploration development areas such as: human robotic systems, energy storage and power systems, thermal control for surface systems, exploration life support, EVA, dust mitigation, cryogenic fluid management, and nontoxic propulsion as well as outside government agencies, industry, academia, and International Partners. The goal is to maximize our ability to leverage funding and increase commonality of hardware at the outpost. Lastly, laboratory and field system-level tests and demonstrations are being performed as often as possible to demonstrate improvements in capabilities (e.g., digging deeper), performance (e.g., lower power), and duration (e.g., more autonomy or robustness) as well as to form the affiliations with industry and International Partners that will be needed once actual outpost flight hardware development and deployment begins.

The first step in the manufacture of lunar O_2 is to excavate the lunar regolith for delivery to the O_2 production system. Depending on the ultimate O_2 extraction efficiency achieved, the production of 1 mt (1.1 tons) of O_2 would, at worst, require the excavation of an area the size of a U.S. football field to a depth of perhaps 1 cm (0.39 in.) over a period of 9 months to 1 year. If more efficient O_2-production technologies are perfected, the excavation area could shrink to the size of a basketball court. Since this excavation is primarily a granular flow and physics issue, work focuses on three primary tasks: (1) modeling the granular behavior and flow of irregular-shaped, varied-size, and multiple mineral and glass particles and regolith-excavation implement interactions; (2) performing a controlled laboratory test with prepared soil bins; and (3) building and testing concept excavation and material transport hardware. A recent and significant accomplishment was re-creating and performing controlled testing of the Surveyor 3 bucket to compare to lunar flight data (figures 1(a) and 1(b)). Although not performed in either vacuum or 1/6g, the tests still provided confidence that our laboratory tests and modeling efforts are anchored by actual lunar measurement. Tests with the Cratos excavation concept vehicle have demonstrated that a small

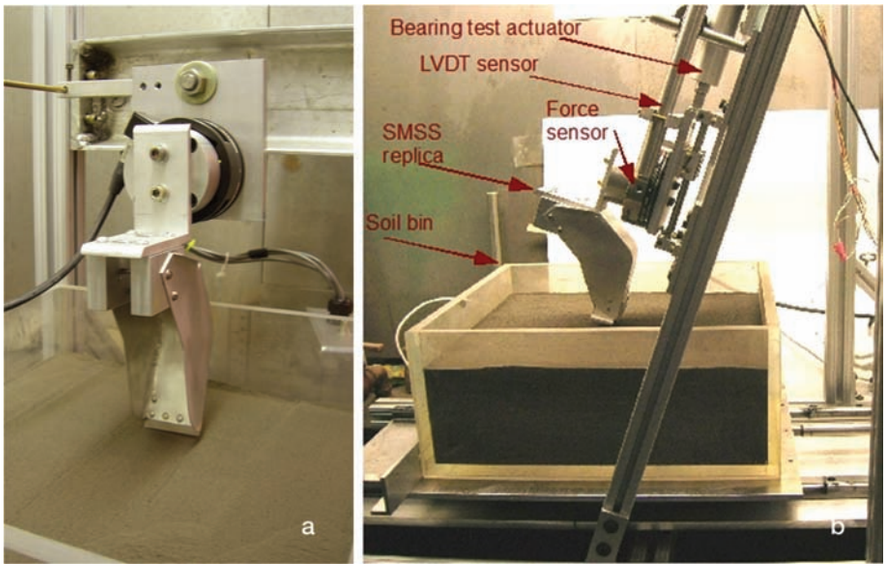

Fig. 1. *(a) Benchtop soil bin with blade. (b) Surveyor scoop replica tests.*

vehicle (~80 kg (176.4 lbs.)) can easily meet early O_2-extraction regolith delivery needs (figures 2(a) and 2(b)).

For O_2 production, we selected three processes that span the range of low risk/low yield to high risk/high yield. These processes under development are: hydrogen (H_2) reduction of regolith, carbothermal reduction from regolith, and molten electrolysis.

Hydrogen reduction is the simplest and least efficient of the three processes. When regolith is heated to around 1,000°C (1,832°F) and mixed with H_2 gas, iron-oxide (FeO)-bearing minerals and glasses in the lunar regolith (e.g., ilmenite ($FeO{\cdot}TiO_2$) are reduced to produce water vapor. This water vapor is condensed and electrolyzed to produce O_2 and to regenerate the reactant H_2 for subsequent processing. While this is not the most efficient process (the amount of FeO in lunar regolith is fairly low (5% to 15%)), it does have the advantage of lower temperatures that keep the lunar regolith in granular form, which greatly simplifies material handling. Both Lockheed Martin Astronautics (LMA, Denver, Colo.) and NASA are leading separate regolith processing reactor design efforts. LMA is designing and testing a rotating reactor with a single inlet/outlet port, and NASA is designing a fluidized bed with separate inlet/outlet ports. Both systems were fabricated, assembled, and tested (figures 3(a) and 3(b)). Before the full systems were built, subscale reactors were tested to determine temperature, H_2 flow rate, and reaction kinetic parameters.

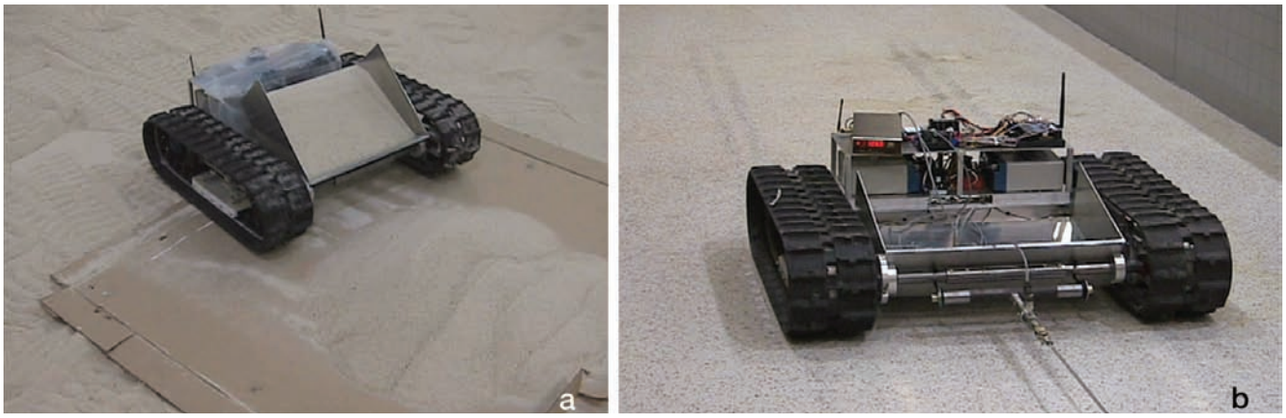

Fig. 2. *(a) Cratos excavation and delivery test. (b) Cratos drawbar pull and payload transit tests.*

Fig. 3. *(a) LMA PILOT system. (b) JSC ROxygen system.*

These first-generation systems thus verified performance and demonstrated operation feasibility at production rates scaled to outpost needs, so weight and volume were not minimized. The LMA precursor ISRU lunar oxygen test bed (PILOT) operated at one-fourth scale, and the NASA ROxygen system operated at two-third scale; both achieved the predicted 1% to 2% O_2 extraction (by mass).

The carbothermal reduction process is a more efficient O_2-production technique than the H_2-reduction process because not only will it reduce the FeO but also some of the silicates found abundantly in the lunar regolith. The process requires much higher temperatures (1,600°C (2,912°F)), however, so the regolith becomes molten. When methane (CH_4) is introduced into the melt chamber, it reacts with the molten regolith and carbon monoxide (CO) is produced. The CO is fed with H_2 into a methanation reactor where the CH_4 is regenerated and water is produced. The water is electrolyzed to recover the H_2 and produce O_2. This process can achieve efficiencies of 14% extraction of O_2 by mass or greater, but the main challenges of this approach are delivering the energy needed to form the melt and developing techniques to deal with molten materials. Orbital Technologies Corporation (ORBITEC), Madison, Wis., after performing successive tests of larger and larger melt/CH_4 reduction tests, designed and built a first-generation system. This system will combine with a solar concentrator system under development by Physical Sciences Inc. (PSI), Andover, Mass., through Small Business Innovative Research contracts (figures 4(a) and 4(b)) to produce O_2.

Through such cooperative development efforts, we plan to integrate ISRU technologies with lunar surface system architecture. In particular, the ability to produce and regenerate mission-critical consumables (e.g., O_2, water, and fuel for crew, power, and propulsion) can change surface element designs, technologies, and operations. Of course ISRU is only beneficial for exploration if other elements use the products and capabilities available. We coordinate with rovers, cryogenic oxygen storage, and thermal management to ensure that ISRU development is aligned with other lunar surface system development areas. The ISRU Project has also initiated

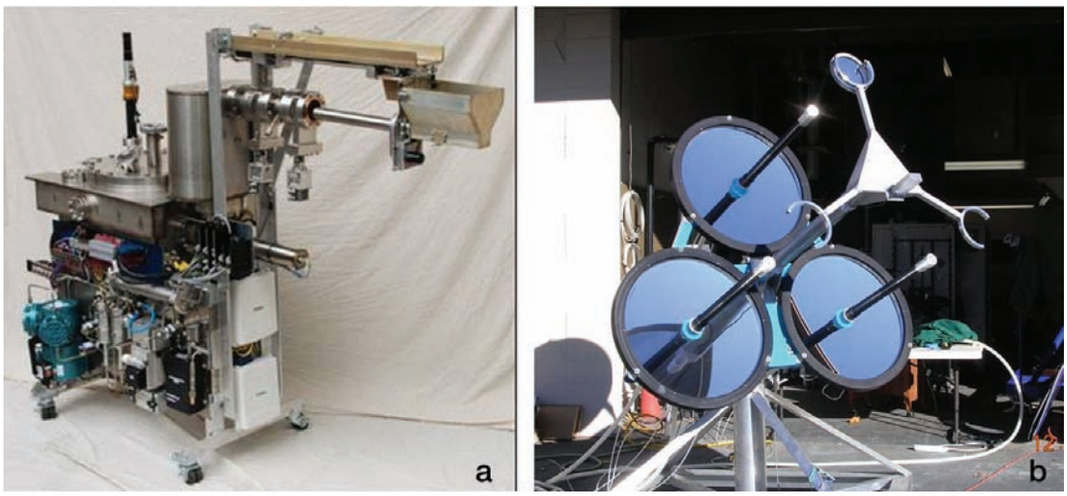

Fig. 4. *(a) ORBITEC carbothermal system. (b) PSI solar concentrator and fiber-optic cables.*

lunar analog field tests with other surface project areas using requirements and capabilities identified and defined in human lunar architecture studies.

Three capabilities of potential interest demonstrated in recent field tests are: (1) area clearing and berm building for landing and plume debris protection, (2) end-to-end O_2 extraction from regolith with excavation and O_2 storage, and (3) mobile resource characterization of permanently shadowed craters and subscale precursor O_2 extraction from regolith. The first capability was demonstrated both at the Johnson Space Center rockyard and at Moses Lake, Wash. The lunar attachment node for construction and excavation (LANCE), a blade for excavation, is 4.11 m (13.5 ft) wide by 0.52 m (1.7 ft) high and weighs about 143 kg (315 lbs.). This proof-of-concept composite blade was hard-mounted to the "Chariot" crew rover. In addition to clearing a large area, the LANCE-Chariot system also built a 1.2-m (3.94-ft) ramp berm (figure 5). The second and third tests occurred near the Mauna Kea, Hawaii, Visitor Center. To demonstrate the end-to-end hardware and operations associated with O_2 extraction of regolith, NASA built two separate and completely different systems.

Fig. 5. *LANCE blade on Chariot at Moses Lake, Wash.*

These systems had common requirements and common interfaces between the main units/modules for excavation, regolith processing, gas/water cleanup, water electrolysis, and O_2 storage such that the modules and excavators could be exchanged, if desired. The systems, based around the PILOT and ROxygen hydrogen reduction reactors (figures 6(a) and 6(b)), laid the cornerstone for creating a modular and expandable surface architecture. To demonstrate the mobile resource characterization applicable to a future lunar polar crater robotic precursor mission, NASA built the regolith and environment science and oxygen and lunar volatile extraction (RESOLVE) system. The RESOLVE system was mounted on the Carnegie Mellon University (Pittsburgh, Pa.) Scarab rover, with a NORCAT [Northern Centre for Advanced Technology Inc., Sudbury, Ontario Canada] drill and the Canadian Space Agency Neptec (Ottawa, Ontario Canada) TriDAR navigation vision system (figure 6(c)). All field tests verified that performance and operations as well as information will be used in future lunar surface system architecture studies.

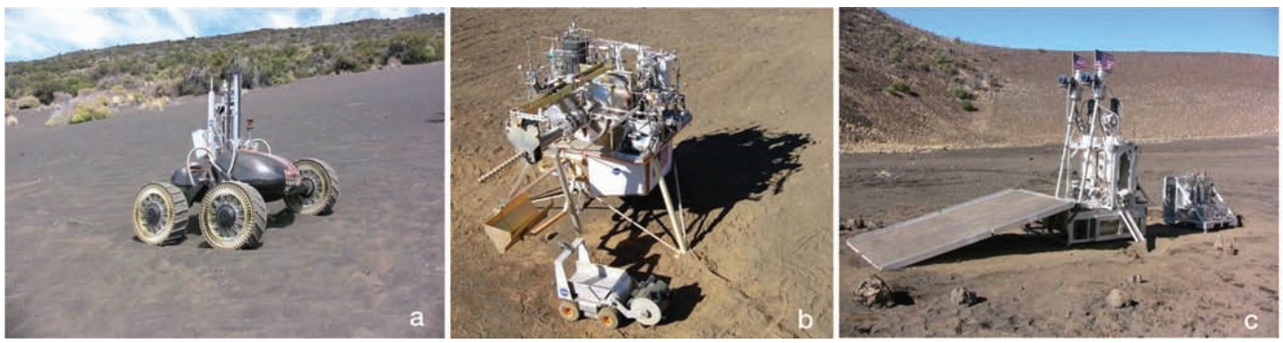

Fig. 6. *(a) NASA RESOLVE on Carnegie Mellon University Scarab rover. (b) LMA PILOT and Bucketdrum rover. (c) JSC ROxygen.*

Click here for next report