THE 2010 FIELD DEMONSTRATION OF THE SOLAR CARBOTHERMAL REDUCTION OF REGOLITH TO PRODUCE OXYGEN. R. J. Gustafson[1], B. C. White[1], M. J. Fidler[1] and A. C. Muscatello [2], [1]Orbital Technologies Corporation (ORBITEC™), 1212 Fourier Drive, Madison, WI 53717, gustafsonr@ORBITEC.com, [2]National Aeronautics and Space Administration, NE-S1, John F. Kennedy Space Center, FL 32899, anthony.c.muscatello@nasa.gov.

Introduction: The Moon and other space exploration destinations are comprised of a variety of oxygen-bearing minerals, providing a virtually unlimited quantity of raw material which can be processed to produce oxygen. One attractive method to extract oxygen from the regolith is the carbothermal reduction process, which is not sensitive to variations in the mineral composition of the regolith. It also creates other valuable resources within the processed regolith, such as iron and silicon metals. Using funding from NASA, ORBITEC recently built and tested the Carbothermal Regolith Reduction Module to process lunar regolith simulants using concentrated solar energy. This paper summarizes the experimental test results obtained during a demonstration of the system at a lunar analog test site on the Mauna Kea volcano on Hawaii in February 2010.

Description of the Carbothermal Regolith Reduction Module: The Carbothermal Regolith Reduction Module (Figure 1) which has been previously described in detail [1], consists of a receiving hopper, a loading auger, an internal storage hopper, a transfer auger, a reduction reactor with attached solar inlet port and rake/leveling device, and an exit valve. Methane is stored in a tank and pumped into the reactor as needed. Reaction gases are sent through a gas scrubber to remove contaminants before they are combined with recycled hydrogen in a Sabatier reactor. The resulting water is condensed and transferred to a separate electrolyzer to make the oxygen product. The methane produced is recycled back into the carbothermal reactor. Solidified melts are periodically released from the reactor.

Overview of the Field Demonstration: A joint Canadian Space Agency (CSA)/NASA team planned and executed the 2010 International Lunar Surface Operations (ILSO). As part of the ILSO, the ISRU field demonstration was an integrated end-to-end oxygen extraction, storage, and utilization process including: regolith excavation and delivery, heating and melting of the regolith with a solar concentrator, carbothermal reduction using methane, electrolysis of the water product, recycling and solid storage of the hydrogen, powering the carbothermal reduction reactor with a fuel cell using that hydrogen, and firing of a methane/oxygen thruster onto a simulated landing pad sintered using heaters and concentrated solar energy. Previously dried volcanic tephra from the demonstration site at the 9000 ft. level was used as the regolith feed to the reactor. Over the course of eight days, sixteen batches of tephra were processed with varying durations using single melts in the reactor. Note that the hardware was designed to contain up to seven melts and produce up to 1 MT of oxygen/yr on the lunar surface.

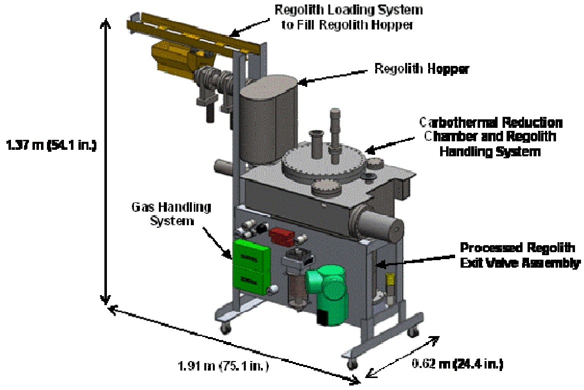

Figure 1. Solid Model of the Carbothermal Regolith Reduction Module

Major goals. The major goals established for the Carbothermal Regolith Reduction Module for the ILSO were: (1) operate for a minimum of 3 test days and a goal of 7 test days (each test day should include at least 4 hours of steady-state operation); (2) operate with a single melt size up to 130 g for each batch; (3) maximize the production of oxygen per day by finding the optimum combination of oxygen yield and processing batch time; (4) demonstrate a production of at least 16 g O_2/operating day; (5) process at least 159 g of tephra per operating day; (6) operate all the key systems together, including the Carbothermal Regolith Reduction Module, Solar Energy Module, Gas Clean-up Module, Methanation Reactor, NASA-supplied Water Clean-up Module and NASA-supplied Water Electrolysis Module; (7) demonstrate an average recovery of 99% of the carbon for all processing batches; (8) transfer of tephra delivered by the pneumatic feed system and/or CSA rover into the reactor; (9) carbon reduction of the tephra using concentrated solar energy and methane gas; (10) automated removal of the processed tephra and preparation for next processing batch; (11) continuous reformation of the methane and water using hydrogen from the Water Electrolysis Module; (12) condensation of the water and transfer to the Water Electrolysis Module; and (13) dumping of processed tephra to support removal by CSA.

Summary of the Results: Figure 2 shows a photograph of the integerated system operating during the 2010 ILSO. The Pneumatic Regolith Transfer System built by Honeybee Robotics and the NASA Kennedy Space Center is visible on the front left. The Solar Energy Module built by Physical Sciences Inc. is visible in the back. Figure 3 is an example of a processed tephra melt. Note that numerous metallic iron spheres are visible on the top surface of the melt.

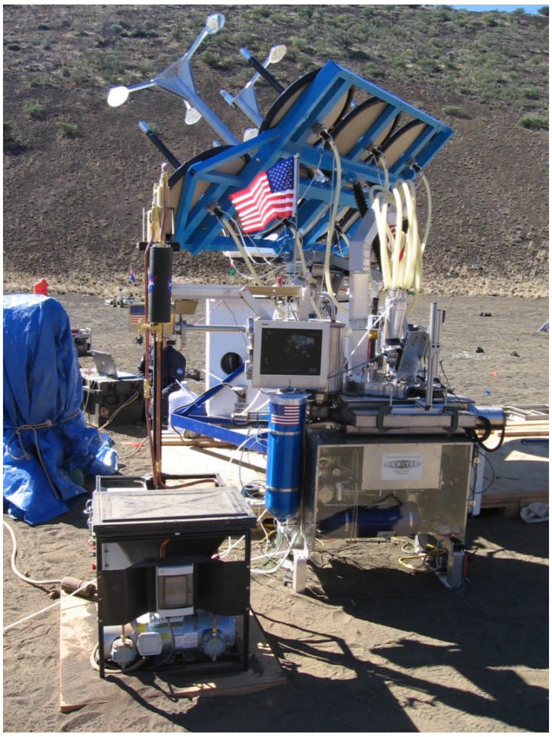

Figure 2. Photograph of the Integrated Carbothermal Regolith Processing System

Table 1 summarizes the results of the preliminary results of the testing campaign on Mauna Kea. Solar energy delivered to the tephra surface was around 500-600 W after accouting for transmission losses through the Solar Concentrator, quartz rod and windows, and additional losses due to dust buildup on the reflectors. Oxygen yields approached 10% based on the water collected. Although the tephra was baked to remove excess water before processing, the water collected includes up to 2% residual moisture. Gas chromatograph (GC) data is currently being analyzed to determine the oxygen yield based on the production of CO and CO_2. Preliminary results from the GC indicate oxygen yields up to 8.1% by mass were achieved.

Figure 3. Example of a Processed Tephra Melt

Table 1. Results of the Solar Carbothermal Reduction of Tephra on Mauna Kea

Tephra Melt Mass (g)	Processing Time (min.)	Equivalent O_2 (g)	O_2 Yield by Mass (%)
24.5	80	Checkout tests	Checkout tests
23	80		
10.0	80		
32.2	90		
27.9	120	10.2	9.6
24.5	80		
26.0	80		
17.9	80		
13.0	80	7.3	9.9
27.6	80		
14.1	80		
11.5	80		
15.9	120	10.5	10.0
27.9	120		
19.8	100		
30.8	160		

All thirteen major goals were fully met with the exception of (4) and (5), which were over 50% complete, and (7) which requires pending laboratory analyses to verify. In conclusion, the Field Demonstration was highly successful.

Reference:

[1] Robert J. Gustafson R. J. et al., AIAA 2010-1163, 48th ASM (2010).