THE 2010 FIELD DEMONSTRATION OF THE SOLAR CARBOTHERMAL REDUCTION OF REGOLITH TO PRODUCE OXYGEN

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Outline

• Introduction
• Background Information
• Results of the Field Demonstration
• Open Issues
• Future Plans
• Conclusions
Introduction

• The carbothermal reduction process is a mature terrestrial technology to produce high-purity silicon from silica (SiO$_2$)
• It can also be used to produce oxygen from the regolith through the carbon reduction of minerals that contain silicon, iron, and titanium oxides (such as ilmenite and silicates)
• Over 28% of the mass of JSC-1A lunar regolith simulant can potentially be extracted as oxygen, mostly from reduction of silicates
• Silicates are believed to be a significant component of the regolith on many extraterrestrial bodies
• Therefore, the carbothermal reduction process can be efficiently used with regolith from any location on the Moon, asteroids, Martian moons, or Mars with little or no beneficiation
**Carbothermal Reduction Background**

- Carbothermal reduction produces oxygen using the following reactions ($MO_x = FeO, Fe_2O_3, TiO_2$ [partial reduction], and $SiO_2$):

  1. $MO_x + x CH_4 \xrightarrow{1600\,^\circ C} M + x CO + 2x H_2$
  2. $x CO + 3x H_2 \rightarrow x CH_4 + x H_2O$
  3. $x H_2O \rightarrow x H_2 + 0.5x O_2$
  4. $MO_x \rightarrow M + 0.5x O_2$
Carbothermal Reduction Background

- The baseline carbothermal reduction process has three basic steps
  - Step 1. Carbon Reduction of Metallic Oxides
  - Step 2. Methane Reformation
  - Step 3. Water Electrolysis
Carbothermal Regolith Processing System

PSI

Solar Energy Module

Carbothermal Reduction Reactor

Gas Clean-Up Module

Hopper Reduction Reactor

Module

CO+H₂+CH₄+

HCl+HF+HS

Gas Clean-Up Module

CO+H₂+CH₄

Methanation Reactor

ORBITEC

H₂<sub>0</sub> (liquid)

Water Clean-Up Module

H₂O (liquid)

ORBITCE

Regolith Collection & Delivery Module

Regolith

ORBITEC

Slag

Eletral Energy

ORBITEC

Slag

Processed Regolith Exit Valves

NASA

NORCAT/CSA

Regolith

Oxygen Storage Module

OREO

NASA

John F. Kennedy Space Center

NASA
ORBITEC developed the Carbothermal Regolith Reduction Module to demonstrate the extraction of oxygen from lunar regolith simulant using concentrated solar energy:

- Automated filling of the regolith hopper and transfer to carbothermal reduction reactor
- Automated gas handling system, including gas clean-up beds and methanation reactor
- Automated removal of processed regolith
- Ability to operate remotely through an http interface

Hardware is sized to produce 1 MT O₂ per year.
Solar Energy Collection and Delivery Module

- Physical Sciences Inc. built a Solar Energy Collection and Delivery Module that provides concentrated solar energy to the Carbothermal Regolith Reduction Module.
- Seven solar concentrators are mounted on an array with two-axis tracking of the sun.
- The solar energy from each concentrator is delivered to the carbothermal reactor via a fiber optic cable.
- Each fiber optic cable delivers up to 100 W (total of 600 to 700 W) of concentrated solar energy.
Carbon Reduction with Solar Energy

- Testing at ORBITEC demonstrated oxygen yields up to 10.3%wt with processing times up to 80 minutes for JSC-1A lunar regolith simulant and Hawaiian tephra.
- The carbothermal reduction process produces silica fume as an intermediate product, so keeping the end of the quartz rod clean has been a challenge.
- ORBITEC has built and successfully tested a gas nozzle that keeps the end of the quartz rod clean during processing (aerodynamic window).
Methane Reformation Reactor

- A two-stage microchannel methanation reactor was built by Pacific Northwest National Laboratory
  - First stage operates at ~450 °C to increase kinetics followed by second stage at ~350 °C to achieve better CO conversion
  - Problems with internal coking limits incoming H₂:CO ratio to 3.7:1 or higher
  - Complete CO conversion with 4.4% CO₂ and 51.3% H₂ in exit stream
- The ORBITEC methanation reactor uses an industrial nickel-based catalyst
  - Operates at 250 °C = slower kinetics but better CO/CO₂ conversion
  - Can be operated with incoming H₂:CO ratio to 3:1 (stoichiometric) with no coking
  - Complete conversion of CO with 0.7% CO₂ and 13.6% H₂ in exit stream
Field Demonstration

- The NASA ISRU program is raising the TRL of various technologies through analog field demonstrations, e.g. Nov. 2008, Jan./Feb. 2010
- The Carbothermal Processing System (CT System) was selected to be demonstrated as part of the 2010 International Lunar Surface Operations and ISRU Analog Test
- The field demonstration was held January 24 - February 14, 2010 at an analog test site on Mauna Kea on the Big Island of Hawaii
- The analog test site is located at an elevation of ~9,000 feet (2,743 m) near the Visitor Center and Hale Pohaku which is the astronomer's dormitory
I came to Hawaii for this??????
Analog Test Site on Mauna Kea

ISRU/Science Operation Area

Outpost Oxygen Production Field Test Location

Flat, Open Area for Site Preparation & Oxygen Extraction Demos

Access Road

Staging Area

Lodging Infrastructure

Slide stolen from Jerry Sanders and Bill Larson
Lunar/Mars-Like Terrain on Mauna Kea
Summary Video of the Field Demonstration
Successful Results

The tephra melts processed in the CT System during the field demonstration.

Processed tephra melts from Day 5 - Experiments 1, 2 & 3

Liquid water collected in the water reservoir downstream of the condenser.

Processed tephra melt from day 6 - Experiment 1
## CT System Performance Data
(10% O₂ Total Yield & 2-8% Reduction Yield)

<table>
<thead>
<tr>
<th>Date</th>
<th>Batch #</th>
<th>Tephra Melt Mass (g)</th>
<th>Processing Time (min.)</th>
<th>Estimated Delivered Solar Power (W)</th>
<th>Water Collected (g)</th>
<th>O₂ Yield by Mass (%) [from water]</th>
<th>O₂ Yield by Mass (%) [from GC]</th>
<th>O₂ Produced (g) [from GC]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Day 5 (2-Feb-10)</td>
<td>1</td>
<td>24.5</td>
<td>80</td>
<td></td>
<td>450-500</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Day 5 (2-Feb-10)</td>
<td>2</td>
<td>23</td>
<td>80</td>
<td></td>
<td>550</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Day 5 (2-Feb-10)</td>
<td>3</td>
<td>10.0</td>
<td>80</td>
<td></td>
<td>510-360</td>
<td></td>
<td></td>
<td>4.0</td>
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<tr>
<td>Day 6 (3-Feb-10)</td>
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<td>32.2</td>
<td>90</td>
<td></td>
<td>555</td>
<td></td>
<td></td>
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<tr>
<td>Day 6 (3-Feb-10)</td>
<td>2</td>
<td>27.9</td>
<td>120</td>
<td></td>
<td>550-510</td>
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</tr>
<tr>
<td>Day 7 (4-Feb-10)</td>
<td>1</td>
<td>24.5</td>
<td>80</td>
<td></td>
<td>550</td>
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<td></td>
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<tr>
<td>Day 7 (4-Feb-10)</td>
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<td>26.0</td>
<td>80</td>
<td></td>
<td>560-580</td>
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<tr>
<td>Day 7 (4-Feb-10)</td>
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<td>17.9</td>
<td>80</td>
<td></td>
<td>570-540</td>
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<tr>
<td>Day 7 (4-Feb-10)</td>
<td>4</td>
<td>13.0</td>
<td>80</td>
<td></td>
<td>510-450</td>
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<td></td>
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<tr>
<td>Day 8 (5-Feb-10)</td>
<td>1</td>
<td>27.6</td>
<td>80</td>
<td></td>
<td>570</td>
<td></td>
<td></td>
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<tr>
<td>Day 8 (5-Feb-10)</td>
<td>2</td>
<td>14.1</td>
<td>80</td>
<td></td>
<td>530</td>
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<td></td>
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<tr>
<td>Day 8 (5-Feb-10)</td>
<td>3</td>
<td>11.5</td>
<td>80</td>
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<td>500</td>
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<tr>
<td>Day 9 (6-Feb-10)</td>
<td>1</td>
<td>15.9</td>
<td>120</td>
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<td>575</td>
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<td>Day 10 (8-Feb-10)</td>
<td>1</td>
<td>27.9</td>
<td>120</td>
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<td>500-530</td>
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<td></td>
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<tr>
<td>Day 10 (8-Feb-10)</td>
<td>2</td>
<td>19.8</td>
<td>100</td>
<td></td>
<td>590-300</td>
<td></td>
<td></td>
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<tr>
<td>Day 11 (9-Feb-10)</td>
<td>1 &amp; 2</td>
<td>30.8</td>
<td>160 (total)</td>
<td></td>
<td>570</td>
<td></td>
<td></td>
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</table>

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ORBITEC Methanation Reactor
(\sim 100\% \text{ CO Conversion})

<table>
<thead>
<tr>
<th>Feed Ratio ((\text{H}_2):(\text{CO}+\text{CO}_2))</th>
<th>Flow Rate ((\text{scem}))</th>
<th>Inlet Gas Stream Composition ((% \text{ mol}))</th>
<th>Outlet Gas Stream Composition ((% \text{ mol}))</th>
<th>Conversion Rate (%)</th>
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</thead>
<tbody>
<tr>
<td>Lab</td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>3:1</td>
<td>1480</td>
<td>19.9 0.0 5.8 0.81</td>
<td>1.3 5.7 0.00 0.10</td>
<td>100 58</td>
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<tr>
<td>3:1</td>
<td>1482</td>
<td>37.2 0.0 11.6 0.94</td>
<td>2.1 13.4 0.00 0.01</td>
<td>100 63</td>
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<tr>
<td>Field Demonstration</td>
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<tr>
<td>2.2:1</td>
<td>1050</td>
<td>7.1 4.1 2.6 0.66</td>
<td>0.51 7.9 0.00 0.84</td>
<td>100 -27</td>
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<tr>
<td>2.4:1</td>
<td>1050</td>
<td>8.5 5.5 3.1 0.44</td>
<td>0.85 9.6 0.00 0.46</td>
<td>100 -4</td>
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<td>2.8:1</td>
<td>1050</td>
<td>6.8 4.0 3.2 1.41</td>
<td>0.62 9.1 0.03 0.59</td>
<td>99 56</td>
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<tr>
<td>3:1</td>
<td>1050</td>
<td>9.6 4.0 2.8 0.43</td>
<td>0.68 8.8 0.00 0.24</td>
<td>100 43</td>
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<tr>
<td>5.4:1</td>
<td>1050</td>
<td>8.1 3.2 2.1 0.47</td>
<td>1.25 7.8 0.00 0.09</td>
<td>100 80</td>
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<tr>
<td>6.6:1</td>
<td>1050</td>
<td>7.3 4.2 1.5 0.48</td>
<td>1.27 7.2 0.00 0.02</td>
<td>100 97</td>
</tr>
<tr>
<td>7.0:1</td>
<td>1050</td>
<td>7.3 3.1 1.4 0.48</td>
<td>1.37 6.3 0.00 0.02</td>
<td>100 95</td>
</tr>
</tbody>
</table>
Excellent Gas Scrubber Performance

- NASA/KSC measured the concentrations of fluorine, chlorine, and sulfur compounds in the water produced in the CT System and predicted the concentrations that were present in the gas phase.
- Goal of reducing gas concentrations to less than 1 ppm was achieved.

<table>
<thead>
<tr>
<th>Sample Name</th>
<th>Water Concentration</th>
<th>Predicted Gas Concentration</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>mg/L</td>
<td>ppm</td>
</tr>
<tr>
<td></td>
<td>F</td>
<td>Cl</td>
</tr>
<tr>
<td></td>
<td>mg/L</td>
<td>mg/L</td>
</tr>
<tr>
<td>Carbothermal Sample 1</td>
<td>0.306</td>
<td>14.077</td>
</tr>
<tr>
<td>Carbothermal Sample 2 (deionized water)</td>
<td>0.365</td>
<td>0.085</td>
</tr>
<tr>
<td>Carbothermal Sample 3</td>
<td>0.374</td>
<td>16.429</td>
</tr>
</tbody>
</table>
CT Chamber Seals Worked Very Well

- The overall leak rate of the Carbothermal Reduction Chamber was measured throughout the field demonstration.
- The leak rate measurements verify that the regolith inlet valves and processed regolith exit valve maintained their sealing performance after multiple uses with the tephra.

<table>
<thead>
<tr>
<th>Date</th>
<th>Leak Rate (psi/min)</th>
<th>Leak Rate (sccm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Day 4</td>
<td>0.0048</td>
<td>31.5</td>
</tr>
<tr>
<td>Day 8</td>
<td>0.0025</td>
<td>16.4</td>
</tr>
<tr>
<td>Day 9</td>
<td>0.0024</td>
<td>15.7</td>
</tr>
<tr>
<td>Day 10</td>
<td>0.0018</td>
<td>11.8</td>
</tr>
</tbody>
</table>
Delivered Solar Power (8-Feb-2010 Exp. 2)

(Based on solar flux measurements)
Measured Melt Temperature (8-Feb-2010 Exp. 2)

Specular reflection

Time [min] vs. Temperature [°C] and Quartz Rod Position [cm]

Melt Temperature and Rod Height
Power vs. Temperature (8-Feb-2010 Exp. 2)