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 $SiO_2$):

\[
\begin{align*}
MO_x + x \text{CH}_4 & \xrightarrow{\text{>1600}^\circ C} M + x \text{CO} + 2x \text{H}_2 \\
x \text{CO} + 3x \text{H}_2 & \rightarrow x \text{CH}_4 + x \text{H}_2\text{O} \\
x \text{H}_2\text{O} & \rightarrow x \text{H}_2 + 0.5x \text{O}_2 \\
\hline
MO_x & \rightarrow M + 0.5x \text{O}_2
\end{align*}
\]

(1) (2) (3) (4)
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 Reduction Module

- 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 $O_2$ 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 H\(_2\):CO ratio to 3.7:1 or higher
  - Complete CO conversion with 4.4% CO\(_2\) and 51.3% H\(_2\) in exit stream

- The ORBITEC methanation reactor uses an industrial nickel-based catalyst
  - Operates at 250 C = slower kinetics but better CO/CO\(_2\) conversion
  - Can be operated with incoming H\(_2\):CO ratio to 3:1 (stoichiometric) with no coking
  - Complete conversion of CO with 0.7% CO\(_2\) and 13.6% H\(_2\) 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
Base

Flat, Open Area for Site Preparation & Oxygen Extraction Demos

Access Road

Slide stolen from Jerry Sanders and Bill Larson
Field Demonstration Overview

- **Solar Concentrator Array**
  - Sunlight
  - Electricity

- **Load-Haul-Dump Rover**
  - Tephra
  - Processed Tephra

- **Carbothermal Reduction Reactor**
  - Tephra

- **Fuel Cell**
  - \( \text{O}_2 \) (air)
  - \( \text{H}_2 \) (gas)
  - \( \text{H}_2 \) (liquid)

- **H}_2 \text{ Hydride Storage**

- **LO}_2/\text{CH}_4 \text{ Storage and Thruster**
  - \( \text{O}_2 \) (gas)

- **Water Electrolysis and GO}_2 \text{ Storage**
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

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## 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>-</td>
<td>-</td>
<td>4.0</td>
<td>3.7</td>
</tr>
<tr>
<td>Day 5 (2-Feb-10)</td>
<td>2</td>
<td>23</td>
<td>80</td>
<td></td>
<td>-</td>
<td>-</td>
<td>4.0</td>
<td>3.7</td>
</tr>
<tr>
<td>Day 5 (2-Feb-10)</td>
<td>3</td>
<td>10.0</td>
<td>80</td>
<td></td>
<td>-</td>
<td>-</td>
<td>4.0</td>
<td>3.7</td>
</tr>
<tr>
<td>Day 6 (3-Feb-10)</td>
<td>1</td>
<td>32.2</td>
<td>90</td>
<td></td>
<td>-</td>
<td>-</td>
<td>4.0</td>
<td>3.7</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>-</td>
<td>-</td>
<td>4.0</td>
<td>3.7</td>
</tr>
<tr>
<td>Day 7 (4-Feb-10)</td>
<td>1</td>
<td>24.5</td>
<td>80</td>
<td></td>
<td>-</td>
<td>-</td>
<td>4.0</td>
<td>3.7</td>
</tr>
<tr>
<td>Day 7 (4-Feb-10)</td>
<td>2</td>
<td>26.0</td>
<td>80</td>
<td></td>
<td>-</td>
<td>-</td>
<td>4.0</td>
<td>3.7</td>
</tr>
<tr>
<td>Day 7 (4-Feb-10)</td>
<td>3</td>
<td>17.9</td>
<td>80</td>
<td></td>
<td>-</td>
<td>-</td>
<td>4.0</td>
<td>3.7</td>
</tr>
<tr>
<td>Day 7 (4-Feb-10)</td>
<td>4</td>
<td>13.0</td>
<td>80</td>
<td></td>
<td>-</td>
<td>-</td>
<td>4.0</td>
<td>3.7</td>
</tr>
<tr>
<td>Day 8 (5-Feb-10)</td>
<td>1</td>
<td>27.6</td>
<td>80</td>
<td></td>
<td>-</td>
<td>-</td>
<td>4.0</td>
<td>3.7</td>
</tr>
<tr>
<td>Day 8 (5-Feb-10)</td>
<td>2</td>
<td>14.1</td>
<td>80</td>
<td></td>
<td>-</td>
<td>-</td>
<td>4.0</td>
<td>3.7</td>
</tr>
<tr>
<td>Day 8 (5-Feb-10)</td>
<td>3</td>
<td>11.5</td>
<td>80</td>
<td></td>
<td>-</td>
<td>-</td>
<td>4.0</td>
<td>3.7</td>
</tr>
<tr>
<td>Day 9 (6-Feb-10)</td>
<td>1</td>
<td>15.9</td>
<td>120</td>
<td></td>
<td>-</td>
<td>-</td>
<td>4.0</td>
<td>3.7</td>
</tr>
<tr>
<td>Day 10 (8-Feb-10)</td>
<td>1</td>
<td>27.9</td>
<td>120</td>
<td></td>
<td>-</td>
<td>-</td>
<td>4.0</td>
<td>3.7</td>
</tr>
<tr>
<td>Day 10 (8-Feb-10)</td>
<td>2</td>
<td>19.8</td>
<td>100</td>
<td></td>
<td>-</td>
<td>-</td>
<td>4.0</td>
<td>3.7</td>
</tr>
<tr>
<td>Day 11 (9-Feb-10)</td>
<td>1 &amp; 2</td>
<td>30.8</td>
<td>160 (total)</td>
<td></td>
<td>-</td>
<td>-</td>
<td>4.0</td>
<td>3.7</td>
</tr>
</tbody>
</table>

*Note: Data includes estimated O₂ yield by delivered water mass (%), O₂ yield by GC (from water and GC), and O₂ produced from GC.*
## ORBITEC Methanation Reactor

(\sim 100\% \text{ CO Conversion})

<table>
<thead>
<tr>
<th>Feed Ratio</th>
<th>Flow Rate (scem)</th>
<th>Inlet Gas Stream Composition (%mol)</th>
<th>Outlet Gas Stream Composition (%mol)</th>
<th>Conversion Rate (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(H_2):(CO+CO_2)</td>
<td></td>
<td>H_2  CH_4  CO  CO_2</td>
<td>H_2  CH_4  CO  CO_2</td>
<td>CO  CO_2</td>
</tr>
<tr>
<td>Lab</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<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>
</tr>
<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>
</tr>
<tr>
<td>Field Demonstration</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<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>
</tr>
<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>
</tr>
<tr>
<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>
</tr>
<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>
</tr>
<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>
</tr>
<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>F mg/L</td>
<td>Cl mg/L</td>
</tr>
<tr>
<td>Carbothermal Sample 1</td>
<td>0.306</td>
<td>14.077</td>
</tr>
<tr>
<td>Carbothermal Sample 2</td>
<td>0.365</td>
<td>0.085</td>
</tr>
<tr>
<td>Carbothermal Sample 2 (deionized water)</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

[Graph showing temperature changes over time with annotations for Melt Temperature and Rod Height]

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Power vs. Temperature (8-Feb-2010 Exp. 2)