Solar Thermal Power System for Lunar ISRU Applications: Result of ISRU Analog Test, Mauna Kea, HI

Prepared by:
T. Nakamura and B.K. Smith
Physical Sciences Inc.
6652 Owens Drive
Pleasanton, CA 94588

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Background

- Solar power is a readily available heat source for *in-situ* resource utilization (ISRU)

- During 1993-1996 Physical Sciences Inc. (PSI) developed a laboratory prototype of the optical waveguide (OW) solar power system for lunar material processing (SBIR Phases I & II by NASA/JSC)

- During 2007-2009, PSI developed the ground-based demonstration system (SBIR Phase III by NASA/GRC)

- The Phase III system was completed in March 2009 and has been tested at ORBITEC for the carbothermal oxygen production program
Solar Concentrator Array with Seven Reflectors

Noon Position

11’ x 11’ x 7’
~1400 lbs

Stowed Position
Solar Concentrator Tested at PSI: March 2009

Seven concentrators mounted on the tracking array

Back of the array with reactor interface
Solar Concentrator: Reactor Interface

The reactor interface with quartz rod

The quartz rod emitting solar radiation
**Solar Concentrator Power Output**

**Fiber Cable vs. Reactor Input Optics**

<table>
<thead>
<tr>
<th></th>
<th>Concentrator/Cable (3/20/09)</th>
<th>Quartz Rod (3/23/09)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ambient Solar Flux (W/m²)</td>
<td>880</td>
<td>880</td>
</tr>
<tr>
<td>Power (W)</td>
<td>795</td>
<td>703</td>
</tr>
<tr>
<td>System Efficiency (%)</td>
<td>37.8</td>
<td>33.3</td>
</tr>
</tbody>
</table>

- **Solar Flux:** ~880 W/m²
- **Date:** 3/20/09 for Concentrator/Cable, 3/23/09 for Quartz Rod
Solar Concentrator System Integrated with the ORBITEC Carbothermal Reactor
Physical Sciences Inc.

Solar Concentrator Array Preparing for Solar Sintering of Tephra
Afternoon Cloud Diminishing the Solar Power
**Measurement of Ambient Direct Solar Flux**

<table>
<thead>
<tr>
<th>Date</th>
<th>Ambient Solar Flux (W/m²)</th>
<th>Comment</th>
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</thead>
<tbody>
<tr>
<td>1/28/10</td>
<td>821</td>
<td>Clear but overcast</td>
</tr>
<tr>
<td>1/29/10</td>
<td>872 ~ 992</td>
<td>Thin high clouds</td>
</tr>
<tr>
<td>1/30/10</td>
<td>821 ~ 889</td>
<td>Partially cloudy</td>
</tr>
<tr>
<td>1/31/10</td>
<td>889 ~ 1006</td>
<td>Overcast with high cloud</td>
</tr>
<tr>
<td>2/1/10</td>
<td>434 ~ 650</td>
<td>Cloudy</td>
</tr>
<tr>
<td>2/2/10</td>
<td>684 ~ 1078</td>
<td>Clear at noon, high clouds late in the day</td>
</tr>
<tr>
<td>2/3/10</td>
<td>1000 ~ 1026</td>
<td>Clear</td>
</tr>
<tr>
<td>2/4/10</td>
<td>914 ~ 1034</td>
<td>Clear</td>
</tr>
<tr>
<td>2/5/10</td>
<td>995 ~ 1078</td>
<td>Clear</td>
</tr>
<tr>
<td>2/6/10</td>
<td>944 ~ 1060</td>
<td>Clear</td>
</tr>
<tr>
<td>2/8/10</td>
<td>981 ~ 1033</td>
<td>Clear</td>
</tr>
<tr>
<td>2/9/10</td>
<td>872 ~ 1051</td>
<td>Warm, Clear with thin high clouds</td>
</tr>
</tbody>
</table>
PSI Solar Concentrator Integrated with NORCAT Rastering System
Ray-Tracing for Sintering Rod

Note: Rod Length 15 cm is for ray-tracing, not actual hardware

For output power = 1 kW
One-Color Optical Pyrometer

- Raytek MMG5H
- 5 micron measurement
- Solar energy doesn’t interfere with the measurement
- Sensor was calibrated for emissivity at 550 ºC
Sintering Quartz Rod Assembly Photo
Melting Tephra
Process Optimization

- 500 W – 560 W power in full sun
- 2 in from tephra surface
- Temperatures reached more than 1300º C at steady state
- Multiple trials at different speeds and distances
- 2.35 mm/sec produced ~1100º C surface temperatures consistently
15” x 15” Sintered Test Patch
Sintered Patch After Thruster Firing
PSI Solar Concentrator Integrated with ORBITEC Carbothermal Reactor
Carbothermal (CT) Reactor Operation

CT reactor displaying the Tephra melt on screen

Tephra melt temperature (°C)
CT Reactor Melts
Power Output Measurement

Cable Output

Quartz Rod Output
# Performance of the Solar Concentrator System

## San Ramon, CA vs. Hawaii Analog Test 2010

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<tr>
<td><strong>Solar Flux (W/m²)</strong></td>
<td>880</td>
<td>924</td>
<td>1054</td>
<td>989</td>
<td>1023</td>
<td>1057</td>
<td>859</td>
</tr>
<tr>
<td><strong>Nominal Cable Power (W)</strong></td>
<td>619</td>
<td>646</td>
<td>614</td>
<td>625</td>
<td>707</td>
<td>707</td>
<td>557</td>
</tr>
<tr>
<td><strong>Figure of Merit</strong></td>
<td>0.282</td>
<td>0.256</td>
<td>0.259</td>
<td>0.2556</td>
<td>0.280</td>
<td>0.271</td>
<td></td>
</tr>
<tr>
<td><strong>True Cable Output (W)</strong></td>
<td>795</td>
<td>(865)**</td>
<td>(657)**</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>System Eff. (%)</strong></td>
<td>37.8</td>
<td>39.2*</td>
<td>32.0*</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Quartz Rod Output (W)</strong></td>
<td>703</td>
<td>607</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>System Eff. (%)</strong></td>
<td>33.4</td>
<td>24.0</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Comments</strong></td>
<td>Pre-ship test results. Silver coated S.S. Inlet Optics, New Fiber, Clean Mirrors</td>
<td>First test in Hawaii. Al deposited Al Inlet Optics</td>
<td>Mirror dusty</td>
<td>Mirror dusty</td>
<td>Mirror dusty</td>
<td>Dust cleaned from all mirrors</td>
<td>Low flux early in the morning, higher flux (~ 1050) later in the day</td>
</tr>
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</table>
Dust on the Primary Mirror

Dust Deposit on the Primary Concentrators

Seven Primary Concentrators Cleared of Dust Deposit
- 10% Power Increase by Cleaning
Effect on Cable Inlet

- Deterioration of cable inlet decreased performance by 6%
Summary

- PSI team deployed and operated the solar concentrator system in environments that are not encountered in laboratory test setting
  - Solar flux varied in a broad range (450~1050 W/m²)
  - Dust effects on primary reflector and cable inlet
  - Freezing temperature in the night

- PSI/NORCAT Team demonstrated solar sintering of Tephra
  - Lunar surface stabilization with solar thermal sintering of regolith
  - Sintered a 15 in x 15 in Pad
  - Single layer due to time constraint

- PSI/ORBITEC Team conducted a series of Carbothermal (CT) oxygen production experiments
  - Tephra melt at 1700~1800 C
  - 16 successful CT reaction tests
Remote Operation from NASA/JSC

PSI Solar Concentrator (middle), ORBITEC CT Reactor (right) and NASA/JSC Water Electrolizer (left) operated remotely from Houston, TX
Acknowledgements

- The PSI team would like to thank those who helped us in preparation, setup, deployment and operation of the solar concentrator.

- Collaborations with NORCAT and ORBITEC personnel have been very effective, stimulating and rewarding.

- Our participation in the ISRU Analog Test, Mauna Kea, HI was made possible by the Phase III SBIR contract administered at NASA/KSC (MNK10EA03P), Dr. Anthony Muscatello, the technical contact.

- The solar concentrator system deployed at Mauna Kea was developed under the SBIR Phase III program supported by NASA/GRC, Dr. Alloysius Hepp, the technical contact.
Questions?