Solar Thermal Power System for Oxygen Production from Lunar Regolith

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Multi-use Solar Thermal System: Schematic

- Transmission of high solar flux via flexible optical waveguide
- Scale up by incremental increase of concentrator units
- Transportable and deployable on the lunar surface
- Multi-use for a variety of oxygen production processes
Solar Energy for Lunar Material Processing: Previous Concept

- Difficult to achieve ideal heating of process materials
  - uneven heating
  - uncontrolled heat flux

- Difficult to modularize
  - limited scaling
  - non-ideal process configuration

Figure by NASA/JSC (ca. 1992)
The Optical Waveguide Solar Energy System Used for Hydrogen Reduction of JSC-1 and Ilmenite (1996)

SBIR Phases I and II supported by NASA/JSC:
Dr. Carlton Allen; Dr. David McKay; Dr. Wendell Mendell (COTR)
The OW Solar System Used for Recent Solar Power Experiment
Phase I Objectives

- Demonstrate the feasibility and evaluate the effectiveness of the solar thermal system for representative lunar oxygen production process(es)

- Develop conceptual designs for the lunar based solar thermal system for selected oxygen production process(es)

- Design the engineering prototype of the solar thermal system to be tested in Phase II
**Phase I Work Plan**

PSI will conduct the Phase I program with:
- Lockheed Martin Space Systems Company (LMSSC)
- Orbital Technologies Corporation (ORBITEC)

1) PSI will conduct laboratory experiments to evaluate feasibility of the solar thermal system for lunar oxygen production process(es)

2) PSI, with input from ORBITEC and LMSSC, will develop a conceptual design of the solar thermal system for selected oxygen production process(es)

3) PSI, with input from ORBITEC and LMSSC, will develop a design for the engineering prototype to be tested in Phase II
Cable Inlet Optics (Previous Technology)

Fill factor = 0.73 ~ 0.82
Cable Inlet Optics (New Technology)

Reflective Matrix
Secondary Concentrator
Testing of Cable with New Inlet Optics (5/7/07)

- Focus Flux Intensity: 167 ~ 182 W/cm²
- Power Input to S.C.: 31.40 W
- Power Output: 21.70 W
- Transmission Efficiency: 69.10% including Fresnel Loss (previous 52 ~ 55%)
Solar Test of Cable with New Inlet Optics

Cable Test with PSI Concentrate

Cable Transmission (3.14 m): 69%
Pathway for Component Efficiency Improvement

<table>
<thead>
<tr>
<th>Component</th>
<th>1996-2005</th>
<th>May 2007</th>
<th>Space-Based Operational System</th>
<th>Improvement Measures</th>
</tr>
</thead>
<tbody>
<tr>
<td>Concentrator</td>
<td></td>
<td></td>
<td></td>
<td>• Protected silver coating</td>
</tr>
<tr>
<td>Reflectivity</td>
<td>0.722</td>
<td>0.858*</td>
<td>0.936</td>
<td>• High slope accuracy and in the absence of atmospheric scattering</td>
</tr>
<tr>
<td>Intercept factor</td>
<td>0.82</td>
<td>0.975</td>
<td>0.975</td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.88</td>
<td>0.88</td>
<td>0.96</td>
<td></td>
</tr>
<tr>
<td>Optical Fiber Cable</td>
<td>0.526</td>
<td>0.69</td>
<td>0.812</td>
<td>• AR coating (650~1100 m)</td>
</tr>
<tr>
<td>Front Fresnel ref</td>
<td>0.965</td>
<td>0.965</td>
<td>0.983</td>
<td>• Improved inlet optics and high purity fiber</td>
</tr>
<tr>
<td>Fiber fill factor</td>
<td>0.734</td>
<td>1.0</td>
<td>1.0</td>
<td>• AR Coating (650~1100 m)</td>
</tr>
<tr>
<td>Integral fiber</td>
<td>0.77</td>
<td>0.74</td>
<td>0.84</td>
<td></td>
</tr>
<tr>
<td>transmission</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Back Fresnel ref</td>
<td>0.965</td>
<td>0.965</td>
<td>0.983</td>
<td></td>
</tr>
<tr>
<td>System Efficiency</td>
<td>0.38</td>
<td>0.592</td>
<td>0.760</td>
<td></td>
</tr>
</tbody>
</table>

* Plating silver coating on the PSI concentrator surface is assumed
Receiver Interface with Oxygen Production Process

- **Hydrogen reduction of lunar regolith (850-1000°C)**
  - Temperature easily attained
  - Thermochemical process demonstrated
- **Carbothermal lunar regolith processing (CLRP; 1600-1800°C)**
  - High temperature requirement
  - Main focus of Phase I work

![Diagram](image-url)
Melting JSC-1 with Xe-Arc Light Source

Imaging Optics

Non-imaging Optics
Melting JSC-1 with Xe-Arc Light Source: II

Optical Fiber Cable Heating JSC-1 with 60W of Power  
(T = 1450 C)

Vitrified JSC-1 Melt  
(dia. = 14mm; depth = 6mm)

Source: PSI/Orbitec project, “Solar Thermal System for  
Carbothermal Lunar Regolith Processing System (CLRPS)”
Melting JSC-1 with Solar Heat: I

Two Cables Focused On a Single Point

- Power: 104 W
- Peak Flux: 84.4 W/cm²
- Temperature: 1556°C
Melting JSC-1 with Solar Heat: II

Three Cables Focused
On a Single Point
Power = 145 W
Peak Flux = 117.4 W/cm²
Temperature = 1728~1800 C

Vitrified JSC-1 Melt: 14 mm dia
Surface Temperature of JSC-1 Melt

Temperature measured by Type C (W 5% Re - W 26% Re) thermocouples

- Orbitec CO₂ Laser
- PSI Solar
- PSI Solar (unsteady)
- PSI Xe Arc
Conceptual Design Basics

- 1 MT of oxygen/year at a lunar polar region

- Two oxygen production processes
  - Hydrogen reduction process (5.6 kW)
  - Carbothermal reduction process (5.6 kW)

- PILOT (Precursor In-Situ Lunar Oxygen Testbed) platform as the basis
Oxygen Production Process

Hydrogen Reduction Process (LMSSC)

Carbothermal Reduction Process (ORBITEC)
Hydrogen Reduction Process on PILOT
Solar Power Delivery to Rotating Reactor
Carbothermal Reduction Process
Solar Power Delivery to Carbothermal Reduction Reactor
Solar Thermal System: Stowage
# Summary of the System Component Weight

<table>
<thead>
<tr>
<th><strong>Concentrator System</strong></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Concentrator</strong></td>
<td>Cassegrain (parabolic primary + hyperbolic secondary)</td>
</tr>
<tr>
<td><strong>Diameter</strong></td>
<td>Primary Concentrator = 2 m, Secondary Reflector = 0.5 m</td>
</tr>
<tr>
<td><strong>Specific Weight</strong></td>
<td>3.567 kg/m² (RCAT: Rigid Concentrator and Tracking System, AFRL solar thermal propulsion data)</td>
</tr>
<tr>
<td><strong>Weight per Concentrator</strong></td>
<td>11.2 kg including support and tracking mechanisms</td>
</tr>
<tr>
<td><strong>Number of Unit</strong></td>
<td>2</td>
</tr>
<tr>
<td><strong>Conc. System Weight</strong></td>
<td>22.4 kg</td>
</tr>
</tbody>
</table>

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<thead>
<tr>
<th><strong>Optical Waveguide (OW) System</strong></th>
<th></th>
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<tbody>
<tr>
<td><strong>Optical Fiber</strong></td>
<td>Fused Silica Core (2 mm dia.), Fluorine Doped Silica Clad (2.2 mm dia.), Polyimide Jacket (2.5 mm dia.),</td>
</tr>
<tr>
<td><strong>Fiber Weight per meter</strong></td>
<td>9.95 gram/m</td>
</tr>
<tr>
<td><strong>Number of Fiber per Cable</strong></td>
<td>169</td>
</tr>
<tr>
<td><strong>Cable Diameter</strong></td>
<td>3.8 cm (1.5 inch)</td>
</tr>
<tr>
<td><strong>Cable Weight per meter</strong></td>
<td>1.68 kg/m</td>
</tr>
<tr>
<td><strong>Cable Length</strong></td>
<td>3.5 meter</td>
</tr>
<tr>
<td><strong>Cable Weight</strong></td>
<td>5.88 kg</td>
</tr>
<tr>
<td><strong>Number of Cable</strong></td>
<td>2</td>
</tr>
<tr>
<td><strong>OW System Weight</strong></td>
<td>11.76 kg</td>
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<tr>
<td><strong>OW System Weight</strong></td>
<td>11.76 kg</td>
</tr>
<tr>
<td><strong>Total System Weight</strong></td>
<td><strong>34.16 kg</strong></td>
</tr>
<tr>
<td><strong>Total Supplied Power</strong></td>
<td>5.905 kW</td>
</tr>
<tr>
<td><strong>Weight per kW</strong></td>
<td><strong>5.785 kg/kW</strong></td>
</tr>
</tbody>
</table>
Summary and Conclusions

• Solar thermal system based on the optical waveguide (OW) technology is viable and effective for oxygen production from lunar regolith

• In this Phase I program we demonstrated a significant and dramatic increase in system efficiency

• We conclusively demonstrated that solar thermal power is capable of heating the lunar regolith to the temperatures necessary for oxygen production

• The system will be light-weight and efficient when deployed on the lunar surface
Acknowledgement

This work was supported by NASA/JSC through Contract NNJ07JB26C, Mr. Aaron Paz (COTR).