Solar Thermal Power System for Oxygen Production from Lunar Regolith: Engineering System Development

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

* 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

\[
\Delta T = \Delta X \kappa \approx 300 \text{ K/mm}
\]
Melting JSC-1 with Xe-Arc Light Source

1. Imaging Optics
2. 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)

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
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)
Carbothermal Reduction Process
Solar Capture Sequence for the Polar Region
Solar Power Delivery to Carbothermal Reduction Reactor

- Radiation Reflector
- Processed Regolith Removal Rake
- Processed Regolith (Solid)
- Regolith Transfer Auger
- Quartz Rod
- Radiation Shield
- Regolith Surface

Dimensions:
- 4 cm
- 8 cm
# Summary of the System Component Weight

<table>
<thead>
<tr>
<th>Concentrator System</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Concentrator</td>
<td>Cassegrain (parabolic primary + hyperbolic secondary)</td>
</tr>
<tr>
<td>Diameter</td>
<td>Primary Concentrator = 2 m, Secondary Reflector = 0.5 m</td>
</tr>
<tr>
<td>Specific Weight</td>
<td>3.567 kg/m² (RCAT: Rigid Concentrator and Tracking System, AFRL solar thermal propulsion data)</td>
</tr>
<tr>
<td>Weight per Concentrator</td>
<td>11.2 kg including support and tracking mechanisms</td>
</tr>
<tr>
<td>Number of Unit</td>
<td>2</td>
</tr>
<tr>
<td>Conc. System Weight</td>
<td>22.4 kg</td>
</tr>
</tbody>
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<table>
<thead>
<tr>
<th>Optical Waveguide (OW) System</th>
<th></th>
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<tbody>
<tr>
<td>Optical Fiber</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>Fiber Weight per meter</td>
<td>9.95 gram/m</td>
</tr>
<tr>
<td>Number of Fiber per Cable</td>
<td>169</td>
</tr>
<tr>
<td>Cable Diameter</td>
<td>3.8 cm (1.5 inch)</td>
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<tr>
<td>Cable Weight per meter</td>
<td>1.68 kg/m</td>
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<tr>
<td>Cable Length</td>
<td>3.5 meter</td>
</tr>
<tr>
<td>Cable Weight</td>
<td>5.88 kg</td>
</tr>
<tr>
<td>Number of Cable</td>
<td>2</td>
</tr>
<tr>
<td>OW System Weight</td>
<td>11.76 kg</td>
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<td>OW System Weight</td>
<td>11.76 kg</td>
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<tr>
<td><strong>Total System Weight</strong></td>
<td><strong>34.16 kg</strong></td>
</tr>
<tr>
<td>Total Supplied Power</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

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