Solar Thermal Technology for In-Situ Resource Utilization

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Presented at
3rd International Energy Conversion Engineering Conference
San Francisco, California

15-18 August 2005
Lunar ISRU Processes

- **Oxygen**
  - propellant
  - fuel cell
  - life support system

- ** Metals**
  - structural materials
  - storage vessels
  - powdered metal for propulsion

- **Construction materials**
  - ceramics, glass concrete
  - radiation shielding
  - building blocks
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*
Optical Waveguide (OW) Solar Energy System
OW Solar Energy System: Features

- High concentration of solar flux (~10^-4 suns) can be transmitted via flexible OW lines directly into thermal reactor
- Solar intensity or spectra can be tailored to specific material processing steps
- Provide solar energy inside of enclosures
- The system can be modularized and can be easily transported to and deployed at the lunar base
- The system can be applied to many material production processes
The Ground Test Model of the OW Solar Thermal Power System
Thermal Reactor for Hydrogen Reduction of JSC-1
Thermal Reactor with Optical Fiber Cables
Inside of Thermal Reactor
Material Processing Container
Material Processing Experiment

Hydrogen reduction of iluminate:
\[ \text{FeTiO}_3 + \text{H}_2 \rightarrow \text{Fe} + \text{TiO}_2 + \text{H}_2\text{O} \]
@ 800 C ~ 1100 C

Material sample:
Lunar soil simulant (JSC-1) containing 3 wt% of iluminate

Reaction detection:
Absorption of a water line at 1.36 µm
Thermal Reactor Temperature versus Solar Power

![Graph showing the relationship between power input and temperature. The graph includes data points for specific dates and symbols that indicate when certain modifications were made to the reactor.]

- 3/18/96
- 3/19/96
- 3/26/96
- 3/23/96, moly rad shields added
- 4/13/96, moly sleeve insert added
- 4/27/96
- 4/29/96
- 5/9/96

Least square fit line for the data points.
Hydrogen Reduction of Ilmenite (FeTiO₃)

Reactant: Ar+5%H₂
Mass Flow Rate: 0.5-0.25 slpm at t=0
Sample Weight: 20 gram

Reactor Temperature: 697°C

Reactor Temperature: 775°C
Mass Flow Rate: 0.25 slpm at t=0
Sample Weight: 20 gram

Water Vapor (ppm) Thousands

Time (min)
Hydrogen Reduction of JSC-1

- Reactor Temperature: 832 C
- Reactant: Ar+5%H₂
- Sample Weight: 20 gram
- Mass Flow Rate: 0.25 slpm at t=0
- Dotted Line: Least Squares Curve Fit
## System Efficiency of the Engineering Model and the Future Space Based System

<table>
<thead>
<tr>
<th></th>
<th>Engineering Model Results</th>
<th>Space-Based Operational System</th>
<th>Improvement Measures</th>
</tr>
</thead>
<tbody>
<tr>
<td>Primary concentrator</td>
<td>0.722</td>
<td>0.864</td>
<td></td>
</tr>
<tr>
<td>Reflectivity Intercept factor</td>
<td>0.82 0.88</td>
<td>0.90 0.96</td>
<td>Reflectivity enhancing coating Intercept factor in space will be higher</td>
</tr>
<tr>
<td>Concentrator fiber coupling</td>
<td>0.708</td>
<td>0.965</td>
<td></td>
</tr>
<tr>
<td>Front-end Fresnel reflection</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fiber fill factor</td>
<td>0.965</td>
<td>0.965</td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.734</td>
<td>1.00</td>
<td>Improve fiber cable front termination design for higher fill factor</td>
</tr>
<tr>
<td>Optical fiber cable transmission (10 meter)</td>
<td>0.743</td>
<td>0.868</td>
<td></td>
</tr>
<tr>
<td>Fiber transmission</td>
<td>0.77 0.965</td>
<td>0.90 0.965</td>
<td>Use low-OH fiber for higher transmission efficiency</td>
</tr>
<tr>
<td>Back-end Fresnel reflection</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>System efficiency</td>
<td>~0.380</td>
<td>~0.724</td>
<td></td>
</tr>
</tbody>
</table>
Achievable Temperature versus Solar Flux Intensity

- Single Fiber Test Data (1999) - NA = 0.44
- Phase I Data (2003) - NA = 0.37
- Phase II Projection - NA = 0.37
- Solar Thermal Propulsion Program - NA = 0.48
- Phase I Data (2003)
- Material Processing Exp. Results (1996)

Effective AM0 Concentration Ratio
Optical Fiber Cables Emitting Solar Power
# High Temperature Processes for Lunar ISRU

## Chemical Process Recovery

<table>
<thead>
<tr>
<th>Class</th>
<th>Description</th>
<th>Examples</th>
<th>Temperature [K]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Pyrolysis</td>
<td>$O_2$ production at low to medium pressure</td>
<td>2000-2500</td>
</tr>
<tr>
<td>2</td>
<td>Gas-solid reactions</td>
<td>Reduction of regolith to produce $O_2$</td>
<td>1000-1200</td>
</tr>
<tr>
<td>3</td>
<td>Gas-liquid or three-phase reactions</td>
<td>Reduction of magma to produce $O_2$, silicates</td>
<td>1600-1800</td>
</tr>
<tr>
<td>4</td>
<td>Desorption of solids</td>
<td>Solar wind volatiles, drying</td>
<td>1000-1200</td>
</tr>
</tbody>
</table>

## Manufacturing

<table>
<thead>
<tr>
<th>Class</th>
<th>Description</th>
<th>Examples</th>
<th>Temperature [K]</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>Hot liquid processing</td>
<td>Metal/basalt casting, glass processing</td>
<td>1200-1800</td>
</tr>
<tr>
<td>6</td>
<td>Sinter forming</td>
<td>Powder metallurgy, refractory sintering</td>
<td>900-1800</td>
</tr>
<tr>
<td>7</td>
<td>Composite forming</td>
<td>Fibers, whiskers, flakes in matrix</td>
<td>900-1800</td>
</tr>
<tr>
<td>8</td>
<td>Welding/Glass blowing</td>
<td></td>
<td>1600-1800</td>
</tr>
</tbody>
</table>

## Power Operations

<table>
<thead>
<tr>
<th>Class</th>
<th>Description</th>
<th>Examples</th>
<th>Temperature [K]</th>
</tr>
</thead>
<tbody>
<tr>
<td>9</td>
<td>Thermal energy storage</td>
<td>In fused basalt</td>
<td>&lt; 1400</td>
</tr>
</tbody>
</table>
Pyrolysis of Regolith for Oxygen Recovery
Hydrogen Reduction of Ilminite
Solar Wind Volatile Recovery
Basalt Melting for Glass Production
Brick Sintering Oven
Brick Joining Oven

High Intensity Fiber Cable

Lower Intensity Radiation

Bricks

Section A-A

High Intensity Radiation
Lunar-Based Solar Material Processing Plant

Solar Radiation
Plan View of a 100 kW Process Plant
(2 m Concentrators)
Plan View of a 100 kW Process Plant
(4 m Concentrators)
Solar Power System Weight

Weight per kWth

<table>
<thead>
<tr>
<th>Thermal Size</th>
<th>1 ~ 10 kWth</th>
<th>10 ~ 100 kWth</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cable length</td>
<td>2 m</td>
<td>4 m</td>
</tr>
<tr>
<td>Cable</td>
<td>0.96 kg</td>
<td>1.9 kg</td>
</tr>
<tr>
<td>Conc. + Cable</td>
<td>2.2 kg</td>
<td>3.1 kg</td>
</tr>
</tbody>
</table>

Conc. eff = 0.86
Conc. sys. weight (with support and tracking) = 1.2 kg/m²
Optical fiber cable weight = 400 gram/kWth-m @ 5000 sun
Conclusions

- The optical waveguide system is capable of collection, concentration, and transmission of solar energy for in-situ resource utilization.
- The overall system efficiency for the engineering model was 38%. Much higher efficiency (~72%) can be achieved for a space-based operation system.
- The system can be applied to a variety of high temperature chemical processes, manufacturing processes, and power generation and storage.
- Technology issues for the future includes:
  - lightweight concentrator system
  - lightweight and efficient optical fiber cable
  - material processing solar reactor