High Operating Temperature Transfer & Storage (HOTTS) System for Light Metal Production

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Presented by Jim Occhialini
**High Operating Temperature Transfer & Storage (HOTTS) System for Light Metal Production**

<table>
<thead>
<tr>
<th>Global Non-Profit Institute with the mission to improve the human condition by turning knowledge into practice, recognized for solving critical social and scientific problems</th>
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<tbody>
<tr>
<td><strong>Project Summary</strong></td>
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<tr>
<td>- Technical milestones and deliverables have been met to date, but economics are challenging</td>
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<tr>
<td>- Renewable energy heat production from solar thermal integrated into a light metals plant is &gt;5 times the cost relative to burning natural gas</td>
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<td>- For heat integration, amount of available heat in world-class Titanium plant not enough to justify capital; float glass plants are most amenable</td>
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<td>- Longer term implementation into the CSP market (5-10 years) can reduce the power price by 15-20%; overall cost comparison with PV + energy storage to be evaluated</td>
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**High Temperature Coatings (MOC)**

**Fundamentals of Heat Transfer**

Enable the use of renewable energy generated thermal energy in light metal production processes and Concentrated Solar Power with early market demonstration for heat recovery in industrial applications
Market Selection for Heat Integration

HOTTS Heat Integration – Market Evaluation Matrix

- Cement
- Electric arc furnace
- Steel (blast oxygen furnace gas)
- Solid waste incinerators
- FCC regenerator cooler
- Non-ferrous metal refining (Ni, Al, Zn, Cu)
- Hydrogen (SMR; partial oxidation)
- Float glass with oxyfuel
- Titanium

Relative Market Size

HOTTS' Relative Competitiveness

Higher Need Markets
Heat Recovery Costs for Float Glass

<table>
<thead>
<tr>
<th></th>
<th>HOTTS Heat Integration – U.S. (10 MWₜ)</th>
<th>HOTTS Heat Integration – Japan (10 MWₜ)</th>
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<tbody>
<tr>
<td><strong>Levelized Cost Of Heat for HOTTS ($/kWh)</strong></td>
<td>$0.044ᵃ</td>
<td>$0.059ᵃ</td>
</tr>
<tr>
<td><strong>Natural Gas (with Oxyfuel) Combustion Cost ($/kWh)</strong></td>
<td>$0.021</td>
<td>$0.056</td>
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Cost estimates include the effects of US vs Japanese labor rates (1.25x US) and electricity rates (2x US)

- Cost of incumbent (natural gas combustion) sets baseline:
  - $0.013/kWh for US, $0.041/kWh for Japan ($4/MMBTU and $11/MMBTU)
- Marginal cost of O₂ is 0.75 to 1.5 cents/kWhᵇ
  - 0.75 cents/kWh for US, 1.5 cents/kWh international
- Carbon hurdle rate (CO₂ avoidance) in US is about $150/t CO₂ (~$0.024 extra per kWh)

HOTTS technology competitive in international markets (initial entry point)

(a) Assumes 17 year lifetime, 7.9% real discount rate
(b) Assumes 0.025 to 0.05 $/kg O₂ (0.1 to 0.2 $/100 scf)
Competitiveness for Float Glass

Natural Gas + Oxyfuel Combustion Cost (cents/kWh)

Natural Gas Price Variance in Int’l Market

HOTTS cost international operation

International Monetary Fund, 2021 Natural Gas Projection
Titanium waste heat recovery

Application Description
- Vacuum distillation process
- Stainless steel vessel
- 1040°C
- 3-4 days

Ability to compete:
Current approach is air cooling (which takes 3-4 days) with no heat recovery.

Market Size in 2020 14-28 MW_t
- Current global capacity: 330,000 t / year
- Expected growth: 5% / year
- Average plant size: 14,500 t / year
- New plants per year in 2020: 1-2 (global)
- Total market size: 14-28 MW_t

- Waste heat for Ti sponge limited by conductivity through diameter
- Amount of heat available is almost a factor of 20x less than a float glass plant!
- Technology will not scale down cost effectively

Photo 2 Titanium sponge mass with diameter of about 1.7 m and height of about 2.5 m (shown as placed on side)
Technical Concept

- Use particle HTFs that raise the upper operating temperature of solar thermal from 600 to >1100°C and are not limited by freezing
- Develop the ability to store high-quality, thermal energy with process integration capabilities for continuous operation
- Develop composite or coated metals that can withstand high temperatures and resist erosion

Table 1. HTFs and Their Primary Limitations

<table>
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<tr>
<th>Heat-Transfer Fluid</th>
<th>Major Limitations</th>
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<tbody>
<tr>
<td>Solar salt (commercial CSP plants)</td>
<td>Decomposes at T&gt;650°C; solidifies below 228°C</td>
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<tr>
<td>Molten metals</td>
<td>Highly corrosive toward walls of CSP pipes, storage tanks; prone to oxidation</td>
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<td>High-pressure gas (e.g., air, S-CO₂)</td>
<td>Requires high-pressure piping and pump; lacks long-term thermal storage</td>
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<tr>
<td>Molten glass</td>
<td>Typically solidified below 400–600°C; prone to oxidation</td>
</tr>
<tr>
<td>Falling curtain pHTF</td>
<td>Low particle volume fraction (&lt;0.1³), limited heat transfer between particles; sintering of particles during overnight storage</td>
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No Fluidization

Fluidization

Particles flow downward

Gases flow upward
Technical Progress to Date

Research program is advancing two high-temperature technologies:

Particle Heat Transfer Fluid
- Demonstrated particle compositions that resist sintering up to 1,300°C/16 h
- Achieved effective heat transfer coefficient > 600 W/m²-K
- Developed pilot-scale heat transfer unit for operating temperatures above 600°C

Mo-Si-B Material of Construction
- Demonstrated oxidative resistance of hot-pressed coupons up to 1,650°C in air
- Developed two approaches for depositing protective coatings
- Thermal Spray approach chosen to coat tubes for commercial scalability

- All milestones and deliverables have been achieved per plan
- The measured effective heat transfer coefficient of technology has already exceeded project commitments, with many ideas still to investigate (expect to approach 1000 W/m²-K)
- Coating of tube (inside / outside) with zero defects by thermal spray is last high-risk milestone to achieve by 30 September
TEA Highlights: CSP Case

<table>
<thead>
<tr>
<th>Current Plant (Molten salt + Rankine cycle)</th>
<th>Proposed Plant (pHTF + sCO2 cycle)</th>
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<tbody>
<tr>
<td>Costs in $/kWe</td>
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<tr>
<td>Heliostat Field</td>
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<tr>
<td>Power Block</td>
<td>Power Block</td>
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<tr>
<td>Solar Receiver</td>
<td>Solar Receiver</td>
</tr>
<tr>
<td>Storage Cost</td>
<td>Storage Cost</td>
</tr>
<tr>
<td>Power Tower</td>
<td>Power Tower</td>
</tr>
<tr>
<td>Site Improvements</td>
<td>Site Improvements</td>
</tr>
<tr>
<td>$124</td>
<td>$62</td>
</tr>
<tr>
<td>$84</td>
<td>$92</td>
</tr>
<tr>
<td>$492</td>
<td>$609</td>
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<tr>
<td>$828</td>
<td></td>
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<tr>
<td>$662</td>
<td></td>
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<tr>
<td>$290</td>
<td></td>
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<tr>
<td>$900</td>
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HOTTS LCOE reduction due to lower capital costs (per kWe) in
1. Heliostat Field
2. Solar Receiver
3. Storage Costs

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<th>Size = 265 MWt</th>
<th>Molten Salt Plant Cost</th>
<th>pHTF Plant Cost</th>
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<tr>
<td>Total Installed Capital Costs contingency 20%</td>
<td>$405M</td>
<td>$444M</td>
</tr>
<tr>
<td>$/Installed kWe</td>
<td>$4050</td>
<td>$3300</td>
</tr>
<tr>
<td>CSP Levelized Cost of Electricity</td>
<td>$0.26/kWh</td>
<td>$0.22/kWh</td>
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Demo Requirements

- For the CSP application, the next phase requires testing of a solar receiver with pHTF and high temperature coatings integrated with a high-pressure S-CO$_2$ power cycle in simulated, real-life conditions
  - Size of solar receiver equivalent to 0.5 MW$_{th}$
  - $5 – 10$MM
  - Partners include those with testing facilities in place, power cycle integrators and a leading equipment supplier into CSP industry
  - Position technology to be demonstrated at 10-50MW+ scale

- For heat recovery in the float glass industry, the next phase requires demonstration of technology in a float glass facility on a slip-stream
  - Size of slip-stream to ensure each component is at commercial scale
  - $3 – 5$MM
  - Successful demonstration leads to technology commercialization for industry, including both retrofits of existing plants and new-builds
Future Goals/Closing Thoughts

- To close out this project successfully, we need to:
  - Demonstrate complete coating and survivability of a tube with recession rate of less than 0.05 µm/hr at 1300°C in air due to oxidative effects for 100 hours
  - Demonstrate a heat transfer coefficient that approaches 1000 W/m²-K
  - Create interest from future funders for CSP and/or heat integration in float glass industry

- Adoption of RTI’s pHTF technology as a replacement for molten salts in CSP plants could make CSP more competitive with PV when the full cost of energy storage required for grid stability is accounted for

- With low natural gas prices for the foreseeable future, early market adoption for industrial heat recovery does not make sense for the metals industry; opportunities in the float glass industry exist in some geographies
QUESTIONS?