Commodities tend to be produced by mature technologies
Cryogenic Distillation: Proven Oxygen Supply Technology

- Mature, reliable technology
- Large and growing global market (300,000+ mTPD)
- ~15% of the cost of an IGCC facility

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A Typical Air Separation Plant

Major Components
- Main Air Compressor
- Front-end Cleanup
- Main Heat Exchanger
- Reboilers
- Distillation Columns

- Energy intensive
- Requires 100’s of equilibrium stages
Ceramic Membranes: Revolutionary Technology for Tonnage Oxygen Supply

- Single-stage air separation leads to compact designs
- Low pressure drop on the high-pressure side
- High-temperature process has better synergy with power generation systems
ITM Oxygen integrates well with power generation cycles
## ITM Oxygen has Excellent Economic Performance in Many Applications

<table>
<thead>
<tr>
<th>Application</th>
<th>Oxygen (sTPD)</th>
<th>Power (MW)</th>
<th>Capital for Oxygen (%)</th>
<th>Power for Oxygen (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>IGCC</td>
<td>3200</td>
<td>458</td>
<td>35%</td>
<td>37%</td>
</tr>
<tr>
<td>Decarb. Fuel</td>
<td>2400</td>
<td>300</td>
<td>35%</td>
<td>36%</td>
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<tr>
<td>Enrichment</td>
<td>1500</td>
<td>260</td>
<td>27%</td>
<td>69%</td>
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<tr>
<td>Oxyfuel</td>
<td>8030</td>
<td>500</td>
<td>48%</td>
<td>68%</td>
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<tr>
<td>GTL</td>
<td>12,500</td>
<td>n/a</td>
<td>20+%</td>
<td>n/a</td>
</tr>
</tbody>
</table>
ITM Oxygen Development Program

- DOE-sponsored Program (3 Phase, $90 million)
  - Phase I: Technical Feasibility (0.1 TPD O2)
  - Phase II: Prototypes (1 and 5 TPD O2)
  - Phase III: 25-50 TPD Demo/GT integration

- Goal: Reduce cost of oxygen by one-third

- Addresses Key Technical Risks
  - Local Performance
  - Lifetime
  - Machinery Integration
  - Ceramic Processing
  - Reliability
  - Safety

  \{ — Process Economics
  \{ — Feasibility of Manufacture
  \{ — Feasibility of Operation
ITM Oxygen Development Team

- Phase I: Technical Feasibility
  - membrane materials, structure, and performance

- Key Technical Risks:
  - Local Performance
  - Lifetime
  - Machinery Integration
  - Ceramic Processing
  - Reliability
  - Safety

GE Energy

SOFCo EFS (McDermott)

Siemens Westinghouse
Power Corporation
Technical Risk has been reduced to moderate or low levels in all categories during Phases I and II

- Local Performance
- Lifetime
- Machinery Integration
- Ceramic Processing
- Reliability
- Safety
Technical Risk Reduction Through Phase II

**Ceramic Processing**: develop scale-able manufacturing processes for ceramic membranes consistent with target economic benefits

- Selected and devised a planar “wafer” architecture
- Scaled-up and produced commercial-size wafers in large quantities on a prototype manufacturing line
- Built first commercial-scale ITM Oxygen modules

**Current Status:**
- Automating Production Line
- Building commercial scale modules for pilot plant trials
The Heart of ITM Oxygen Technology
Planar Membrane Wafer Stack

Air (vitiated)
800-900°C
200-300 psig

Thin membrane
Porous membrane support
Dense, slotted backbone
Product Withdrawal Tube
Pure Oxygen

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Module Size Progression
Producing Commercial-size Wafers Since 2000
Commercial-scale ITM Oxygen Module Assembly

Submodule Assembly

0.5 TPD O₂
Ceramic Processing Infrastructure

- Continuous Tapecaster
- "Green" Tape
- High Speed Laser Cutter
- Lamination and Cutting Operations
Ceramic Processing Infrastructure

Multiple-wafer firing operations

- Have made 1000’s of commercial-size wafers since 2000
Technical Risk Reduction Through Phase II

**Machinery Integration**: optimize the integration of ITM Oxygen with rotating equipment

- Siemens Westinghouse Power Corporation joined ITM Oxygen development team in 2003

Four-part Statement of Work
1) identify integration issues and solution paths
2) develop conceptual designs
3) estimate n\textsuperscript{th} unit costs
4) estimate development costs

- Reviewing IGCC case for optimum integration with W501G gas turbine
  - No major roadblocks have been identified in cases with >50% air extraction (consistent with target cost reduction)
Technical Risk Reduction Through Phase II

Local Performance: achieve target oxygen flux and purity

✓ Wafers consistently make target flux since 2000
✓ Oxygen purity consistently exceeds 99%

Lifetime: ensure material stability over operating life

✓ Material creep life exceeds 10 years
✓ Excellent sulfur tolerance demonstrated
  (e.g., IGCC study includes MDEA unit for S-removal)
Technical Risk Reduction Through Phase II

**Reliability**: achieve ITM Oxygen plant availability typical of cryogenic oxygen plants

- Demonstrated steady flux for over 5000 hours
- Developing materials database and reliability-assessment approach for ceramic devices
- Developing advanced control techniques to minimize stresses in ceramic modules

**Safety**: “Nothing is more important”

- Identified safe alloys for use in handling hot oxygen
- All risks have been addressed in pilot scale work
1-5 TPD Pilot Demonstration

- Demonstrates operation with multiple commercial-scale devices
- Addresses all key risk factors except machinery integration
- Mid-2005 Start-up

ITM Oxygen Membrane Vessel

Thermal Analysis of Flow Duct

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Pilot scale vessel is a prototype for commercial scale concept
Conceptual 2000 TPD ITM Oxygen Vessel
Commercialization Pathway for ITM Oxygen

Expected timing:
- Near-term: adding commercial partners
- Complete existing development program in 2008
- Build first commercial-scale units in 2009 (100’s TPD) (pipelines, small co-produced power applications, etc.)
- Ready to serve the IGCC and power generation markets toward the end of the decade
Acknowledgment: DOE/NETL

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