ITM Oxygen Technology for Gasification Applications

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Who is Air Products?

- **Merchant Gases**
  - Industrial, medical, and specialty gases supplied to wide array of applications

- **Tonnage Gases, Equipment and Energy**
  - Industrial gases supplied via large on-site facilities or pipeline systems; equipment; technologies to serve future industrial and energy markets

- **Electronics and Performance Materials**
  - Specialty and tonnage gases/chemicals, services and equipment supplied to electronics markets; performance chemical solutions for a variety of industries

FORTUNE 500 COMPANY ♦ $10.2 BILLION SALES FY13 ♦ SAFETY LEADER

- 21,600 Employees ♦ Operations over 50 countries ♦ Sales over 100 countries
- **Production Operator, Equipment & Plant Sales, Pipelines & Distribution**
Cryogenic Distillation is State-of-the-Art for Tonnage Oxygen

- Mature, reliable technology
- Energy intensive
- Requires 100’s of equilibrium stages
- Enables many applications
  - Gasification & IGCC
  - Oxy-combustion
  - Industrial
- Represents significant capital cost and power consumption
Why ITM Oxygen?

- Most oxygen is produced using cryogenic distillation
  - Cryogenic distillation is a mature technology

- Ceramic membranes have the potential to produce oxygen at **lower cost** and **less power requirement**, especially in applications where integration with power or high temperature processes is possible

- Other Benefits of ITM Oxygen
  - Less Water Use – can be as little as 50% of cryogenic ASU water use
  - Less Plot Area Required – approximately 50% less
  - Fuel Flexibility – natural gas, syngas, liquid fuels
  - Excellent integration capability with existing high temperature processes
  - Compact design reduces construction costs, easily meets height restrictions, increases overall mobility of the technology
What is ITM Oxygen?

A proprietary ceramic membrane to separate oxygen from air
- Inputs are high pressure air and heat/fuel
- Outputs are oxygen and power/steam

Unique technology gives high oxygen flux and selectivity and good integration with energy applications
Air Products’ ITM Technology

- **Ion Transport Membranes (ITM)** provide **Oxygen** at high-purity and high-flux
  - Non-porous mixed conducting ceramic membranes are 100% selective for oxygen
  - Material formulation is complex and dependent upon application
  - Multi-component metallic oxide structure incorporates oxygen ion vacancies
  - Operate at high temperature, typically greater than 700°C

- Started R&D in 1988
- Currently 90 U.S. Patents and global equivalents
  - Materials and catalysts
  - Membrane and module structures
  - Process cycles
  - Applications and integrations
- U.S. DOE Cooperative Program since 1998
ITM Oxygen: DOE Cooperative Program

- Phase 1: Technical Feasibility (0.1 TPD O₂)
- Phase 2: Prototype Testing (1 - 5 TPD O₂)

**Current activity Phases 3 and 5 are being conducted simultaneously**

- Phase 3: Intermediate Scale Testing (100 TPD O₂) – 12 MW IGCC
- Phase 4: Reaction Driven Membranes
- Phase 5: Ceramic Module Fabrication to Supply 2000 TPD O₂ Facility
- Planning Next Phase: Energy Scale Development (2000 TPD O₂)  
  - equivalent 250 MW IGCC or 110 MW oxycombustion

*Broad, multi-disciplinary team*

[Logos of various companies and institutions, including GE Energy, NovelEdge, Ceramatec, EPR, ETS, Siemens, University of Pennsylvania, McDermott, and Williams International.]

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ITM Oxygen membranes are supported thin-film planar devices

- Very fast transport for oxygen, very compact
- Low $\Delta P$ on the air side

Oxygen flowing from air through dense membrane

Dense membrane (both sides)

Hot Compressed Air

Porous membrane support

Dense, slotted backbone

High-purity Oxygen Product

Spacer ring

One Membrane in Module

$\frac{1}{2}$-TPD module
Commercial size membrane modules

0.5 ton/day (13 Nm³/h) Stack

1 ton/day (26 Nm³/h) Stack
ITM Oxygen commercial modules continue to be tested in the 5 TPD SEP.
ITM Oxygen commercial modules continue to be tested in the 5 TPD SEP

Over 1000 Days of Operation

- Demonstrated >99% $O_2$ purity
- Demonstrated stable flux at target values
- Demonstrated pressure and temperature cycling
- Testing operations toward scale-up
- Continue testing of next-generation components

Recently relocated from Sparrows Point, Maryland to Convent, Louisiana, U.S.A.
Successfully tested two 1 TPD module stacks

- **Capacity demonstrated** at 0.7 to 1 TPD over 22 days
  - Modules had thicker membranes resulting in flux lower than typical
- Flow and temperature uniformity confirmed
Successfully tested two 1/2 TPD module stacks

- **Oxygen purity established at 99.9 mol% oxygen**
  - Initial 500 hours involved testing at various feed air oxygen concentrations

- **Repeatable performance during P & T cycling** demonstrates the ability of ceramic components to survive plant startups, shutdowns, and upsets
  - Pressure and temperature cycling tests involved complete depressurization and cooling to ambient conditions, followed by return to operating conditions
  - Oxygen purity and flux returned to baseline performance

- **Successful test of Auto-Shutoff Valve** with no adverse effect on neighboring module
Intermediate-Scale Test Unit (ISTU) is in start-up for operation in 2014

- **100-TPD** ITM Oxygen system integrated with hot gas expander to co-produce power
  - equivalent to 5 MW oxycoal or 12 MW IGCC

- Uses commercial design concepts to allow scale-up to the next test platform
  - vessel and internals housing large ITM module array
  - process controls
  - contaminant mitigation

- Provides test platform to generate design data for larger-scale plants (2,000 TPD)
Intermediate-Scale Test Unit (ISTU) Process Flow Diagram

Air → TSA → Exhaust

Fuel line or “hot” equip’t

O_{2} line or equip’t

“ambient” temp equip’t

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Intermediate-Scale Test Unit (ISTU) is in start-up for operation in 2014

ISTU is located adjacent to Air Products Air Separation Unit in Convent, LA, U.S.A.
ISTU ITM Oxygen Vessel
Air Products awarded $71.7 million award as part of the U.S. Recovery Act legislation

Ceramic Manufacturing Scale Up (Phase 5)

Tasks include:

• **Design, build, and operate a ceramic manufacturing facility to supply a 2000 TPD ITM Oxygen test unit**

• Supporting R&D in ceramic processing with emphasis on industrial carbon capture applications

• Conceptual and detailed engineering of ITM-based facilities for industrial carbon capture and for testing the ITM Oxygen technology at the 2000 TPD scale

**CerFab**: The ceramic manufacturing facility in Tooele near Salt Lake City, Utah, U.S.A.

**Kilns installed in the ceramic manufacturing facility**
Electric Power Research Institute (EPRI), Air Products, and WorleyParsons conducted coal-based power plant assessments: Oxy-coal combustion & IGCC with carbon capture

- Detailed engineering studies of large-scale power generation with carbon capture; conducted with input from power industry companies
- Compared ITM Oxygen with traditional cryogenic air separation units (ASUs) integrated into power plants
- Greenfield design basis; included discussions with boiler and turbine manufacturers

Reference publication: AIChE Spring Mtg, April/May 2013.
IGCC power plant with carbon capture

F-class GTs (2) 465 MWe (gross)

Reference publication: AIChE Spring Mtg, April/May 2013.
ITM Oxygen showed substantial benefits for F-class IGCC with CCS

- “Sweet spot” for IGCC at 87% CO₂ capture (regardless of air separation technology).
- ITM Oxygen showed 1.8%pts efficiency advantage.
- ITM Oxygen showed 38% increase in net power output, raising facility power production back above nominal combined cycle rating without carbon capture.

| Equal # of | Equal gasifier loading |
| Equal gasifier | | |
| gasifiers (2) | (100%) |
| Unit capital cost advantage | LCOE* Advantage |
| 12% | 12% |
| 10% | 8% |

* Levelized Cost of Electricity

Reference publication: AIChE Spring Mtg, April/May 2013.
ISTU and CerFab are critical steps to commercialize energy-scale ITM Oxygen
ITM Oxygen is well positioned to meet the needs of clean energy applications

• Gasification: IGCC, Polygen, CtL, XtL, decarbonized fuel; with or without CO₂ capture
• Oxy-combustion
• Clean energy with or without CO₂ capture
• Traditional energy-intensive industrial production
  - Steel, ferrous and non-ferrous metals
  - Cement, fertilizer, glass, pulp and paper
  - Chemicals, petrochemicals, fuels

We are actively pursuing early commercial opportunities
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