Commodity materials production by its nature tends to be based on mature technology that improves only incrementally over time. However, in the case of oxygen, the third-largest produced chemical by volume in the U.S., we have a rare opportunity to effect a substantial reduction in the cost of a commodity. A revolutionary new air separation technology — Ion Transport Membrane Oxygen — based on ceramic membranes that selectively transport oxygen ions when operated at high temperature is being developed by an Air Products-led team in partnership with the U.S. Department of Energy (DOE). This technology has the potential to lower the cost of producing oxygen by 30+%.

Air Products has been developing ITM technology since the late 1980’s. Three distinct applications have emerged, all based on ceramic membranes for oxygen transport. Of these, ITM Oxygen, ideal for tonnage-scale oxygen production and co-production of power, has progressed to the prototype stage of development. This paper details the state of technical progress and future demonstrations, and describes a commercialization pathway that will allow Air Products to offer large tonnage plants based on ITM Oxygen by the end of the decade.

**Figure 1.** The heart of ITM Oxygen technology: a planar ceramic membrane module (wafer stack).

---

**Cryogenic Air Separation Background**

Commercially, most of the oxygen produced is purified by cryogenic distillation, a 100-year-old technology based on a simple thermodynamic cycle that entails compressing air, cooling it, expanding it to further cool the air, forming a portion as liquid, then passing the liquid and vapor streams into a distillation column from which purified oxygen is extracted. After numerous refinements of this process, air separation units (ASU’s) are now some of the most efficient distillation-based separations known. However, because the overall thermodynamic efficiency of the modern-day cryogenic ASU approaches its theoretical limit, few significant technical breakthroughs are expected that would lead to step-change oxygen cost reduction.

**A Promising Alternative**

Alternative air separation technologies, such as adsorption and polymeric membrane separations, are also commercially important technologies that have been refined for many years. However, because of limitations of the special materials used to promote the air separation, historically these technologies have only been commercially viable for smaller production volumes. If, for example, highly selective and active membranes could be identified, membrane-based separations could play a more significant role in large tonnage commercial applications.

Recognizing the potential of membrane technology to impact oxygen cost, Air Products has identified a class of ceramic materials with high flux and selectivity-to-oxygen that can form the basis for cost-efficient membrane devices. These materials separate oxygen from air at high temperature in an electrochemically driven process – the oxygen in air is ionized on the surface of the ceramic and diffuses through the membrane as oxygen ions, forming oxygen molecules on the other side. Impurities, such as nitrogen, are rejected by the membrane.
The air separation system that results from the use of such ceramic oxygen ion transport membranes (ITM’s) produces a hot, pure oxygen stream and a hot, pressurized, oxygen-depleted stream from which significant amounts of energy can be extracted. By integrating the oxygen-depleted stream with a gas turbine system, the overall process co-produces high-purity oxygen, power, and steam if desired. As a result, the technology is ideally suited for advanced power generation processes that require oxygen as a feedstock, such as IGCC and oxygen-enriched combustion, or that are associated with a nearby process requiring oxygen, such as a steel mill, petrochemical complex, or a pulp-and-paper mill.

A simple schematic of one implementation of an ITM Oxygen membrane in a gas turbine-based power cycle is shown in Figure 2. The air stream extracted from the gas turbine and feeding the ITM unit experiences relatively little pressure drop as it passes over the membrane; thus, almost all of the available energy in the hot, compressed air stream is recovered in the turbine. By contrast, if the air is fed to a cryogenic ASU instead of the ITM Oxygen unit, the heat in the air stream would be rejected and much of the pressure energy would be expended during the oxygen extraction.

**Figure 2.** ITM Oxygen unit integrated with a gas turbine-based power cycle. The products are oxygen, power, and (optionally) steam. (In an IGCC application, pressurized oxygen is fed to a gasifier, and the fuel is syngas.)

**Development Program**

Air Products and the DOE entered into a cooperative agreement in 1998 to develop ITM Oxygen membrane technology to the point of commercialization. The overall goal of the program is to reduce the cost of oxygen by one-third over cryogenic distillation-based technology. Air Products assembled a team consisting of Ceramatec, Concepts/NREC, Eltron Research, McDermott Technologies (SOFCo EFS Holdings), Pennsylvania State University, Siemens Westinghouse, Texaco Gasification (GE Energy Gasification), and the University of Pennsylvania. The team is tackling the development effort in three Phases: I) proving the feasibility of the approach, II) scaling up and demonstrating the technology at the prototype stage, and III) demonstrating the technology in an integrated, pre-commercial plant environment. The team completed Phase I in 2001, proving the feasibility of the ITM technology, and is currently demonstrating small tonnage devices in Phase II.

**Technical Risks Addressed**

Risk reduction is the main goal of any development effort. The ITM Oxygen team is focused on lowering technical risk in six key aspects of the technology prior to commercialization.

Three of the technical risk areas directly address economic benefits of the technology: *Lifetime, Local Performance, and Machinery Integration*. The feasibility of economically manufacturing the required ceramic articles is considered in a category called *Ceramic Processing*. Operability of the technology is addressed in the remaining two categories: *Reliability and Safety*. Progress against each of the technical risks is also described.

**Lifetime.** This risk category is materials-focused, and establishes the chemical and mechanical stability requirements consistent with a target operating life for the ITM Oxygen ceramic.

The team developed a novel class of perovskite ceramic compounds that is chemically stable and possesses mechanical properties that allow its use in hot, high pressure and reactive environments. Furthermore the materials are highly ionically conductive and amenable to standard ceramic processing techniques. Oxygen flux from these materials has been shown to be unaffected by feed impurities such as sulfur dioxide at modest levels. In addition, low and
high temperature strength and material creep testing have shown that structures comprised of these materials can achieve a 10-year life.

Local Performance. This category addresses the intrinsic performance of the ITM Oxygen membrane to achieve the commercial target oxygen flux and product purity.

Using high ionic conductivity materials, the team learned to produce very thin, supported membranes to achieve the target flux. The progression in flux as shown in Figure 3 was obtained for real membrane modules in high pressure laboratory-scale equipment and follows materials improvement and reduction in membrane thickness. The commercial target flux was achieved in April 2001 with subscale devices and shortly thereafter with commercial scale membranes. The team also developed a proprietary ceramic-to-metal seal proven in ongoing high pressure flux measurements that routinely register 99+% oxygen purity.

Machinery Integration. This risk category addresses the benefits associated with optimal integration of the ITM Oxygen system with various rotating equipment options to maximize the economic benefits of the technology.

Air Products teamed with Siemens Westinghouse Power Corporation in 2003 to develop solution pathways for integration of IGCC-class turbines with ITM Oxygen. This work builds on previous work in the program with Concepts NREC. The team has confirmed that no major roadblocks to the development of high air-extraction-capable machines exist, based on Siemens’ W501G platform. A costing effort is underway to determine the development path for such machines.

Ceramic Processing. This technical risk area addresses developing manufacturing processes for an engineered membrane device composed of a novel ceramic compound. The processes must be low-cost to enable the potential economic benefits of the technology to be realized in practice.

Figure 4. Commercial-scale ITM Oxygen module capable of producing 0.5 ton/day (TPD) oxygen.

The ceramic processing task is multifaceted – each step in the manufacturing process can affect subsequent steps as well as the performance and operability of the final product. Ceramatec, Inc., is leading the effort to develop processes that rely on established processing techniques. A prototype production line was developed to produce planar membranes, each built from several laminated layers. Thousands of commercial scale wafers have been produced. Special joining techniques have been developed to join multiple wafers together to create commercial-scale air separation modules. This task continues with the automation of the production line and further scale-up of the devices and process.

Reliability. This area considers the overall reliability of commercial processes based on ITM Oxygen technology, expressed as an on-stream time percentage or frequency of unplanned outages. The goal for the technology is to be at least as reliable as incumbent cryogenic oxygen technology.

The key challenge in creating robust commercial ITM Oxygen processes is establishing the reliability of the ceramic devices. Finite element
models are used to establish stress in composite ceramics, supported by a burgeoning material properties database. Reliability models for key material properties are used to predict long-term integrity of membrane modules, and are tested against actual operating experience in laboratory-, pilot-, and (ultimately) early commercial-scale equipment. Phase I and II work has indicated the feasibility of achieving highly reliable systems, with demonstrated stable operation of commercial size wafers in modules at 425 psig and for >5000 h at 200 psig and 800-900° C.

Safety. Nothing is more important to Air Products than safety; that’s why we’ve led the chemical industry in safety performance every year for the last five years. That philosophy carries over to our research and development efforts as well: safety risks unique to ITM Oxygen have been addressed in the pilot work in Phase I of the program. The team sees ITM Oxygen as a low safety-risk technology.

Project and Commercialization Timeline

Phase II activity will culminate in the operation of commercial scale ITM Oxygen modules in a pilot-scale prototype unit at up to 5 TPD oxygen. This unit is scheduled to start-up in 2005. The Phase III plan is to produce 25-50 TPD oxygen from an ITM Oxygen membrane unit coupled with a gas turbine to produce both power and oxygen in 2008. Upon successful conclusion of Phase III, the technology will be ready for commercialization.

A likely progression of the technology after Phase III will be to introduce a product or products into the market that demonstrate the technology at the 100’s-of-TPD scale. These products may be standalone oxygen generators or products capable of co-producing oxygen and modest amounts of power suitable for distributed generation, debottlenecking gasifiers, etc... Late in this decade the technology will be ready for use in the large tonnage oxygen market (1000’s-of-TPD) which is typical of most gasification applications.

Figure 5. The current development program will conclude in 2008 with large tonnage plant offerings available toward the end of the decade.

Benefits

Numerous process economic analyses have substantiated the membrane-based approach to air separation over the cryogenic approach. For large-tonnage oxygen applications requiring high pressure gas such as IGCC, ITM Oxygen affords a 35% capital cost advantage and 37% parasitic power reduction. For lower pressure applications such as oxygen-enriched combustion, the power consumption advantage of ITM Oxygen increases to ~65%. These advantages carry over to co-production cases (oxygen and power). A substantial cost savings even exists when oxygen alone is required, as in a remote gas-to-liquids plant.


Contacts

Air Products and Chemicals, Inc.
7201 Hamilton Blvd.
Allentown, PA  18195-1501
USA
www.airproducts.com

Advanced Gas Separation
Telephone: (610) 481-4475
Fax: (610) 706-7420
E-mail: ITM@airproducts.com

Phillip A. Armstrong, Program Manager
E. P. Ted Foster, Director, Business Development

©2004 Air Products and Chemicals, Inc.