APPENDIX B: CARBON DIOXIDE CAPTURE TECHNOLOGY SHEETS

OXYGEN PRODUCTION

ITM OXYGEN TECHNOLOGY FOR INTEGRATION IN IGCC AND OTHER ADVANCED POWER GENERATION SYSTEMS

primary project goals

Air Products and Chemicals set out to design and develop an ion transport membrane (ITM) based on ceramics that selectively transport oxygen (O_2) ions when operated at high temperature. This high-temperature process may be integrated with advanced power generation processes that require O_2 as a feedstock, such as integrated gasification combined cycle (IGCC) and other clean energy and industrial applications.

technical goals

- Design, construct, and operate a 0.1-ton/day (TPD) technology development unit (TDU) to validate the ITM technology concept, verify the technology prospects for stand-alone O_2 production plants, and integrate with IGCC and other advanced power generation systems.
- Design and construct a 5-TPD Sub-Scale Engineering Prototype (SEP) facility and produce greater than 95 percent O_2 purity.
- Increase the scale of the engineering test facility from 5 TPD of O_2 to 100 TPD of O_2 in an intermediate-scale test unit (ISTU).
- Develop the manufacturing capability needed to support ITM technology commercialization.
- Develop preliminary design concepts for a 2,000-TPD ITM O_2 production plant.

technical content

Air Products and Chemicals set out to design a ceramic ITM that, under high temperatures, separates O_2 from nitrogen (N_2). These non-porous, multi-component metallic oxides have high O_2 flux and selectivity (100%), resulting in high-capacity production of high-purity O_2 at low cost. Figure 1 illustrates the concept of the ITM.

technology maturity:

Prototype, 5 Tons Oxygen Produced/Day

project focus:

ITM O_2 Technology

participant:

Air Products and Chemicals

project number:

FC26-98FT40343

NETL project manager:

Susan Maley
susan.maley@netl.doe.gov

principal investigator:

Douglas L. Bennett
Air Products and Chemicals
bennetdl@apci.com

partners:

Becht Engineering
Ceramatec
Concept NREC
Eltron Research
EPRI
GE-Chevron-Texaco
NovelEdge Technologies
Pennsylvania State University
Siemens Power Group
SofCo
University of Pennsylvania
Williams International

performance period:

10/1/98 – 9/30/15

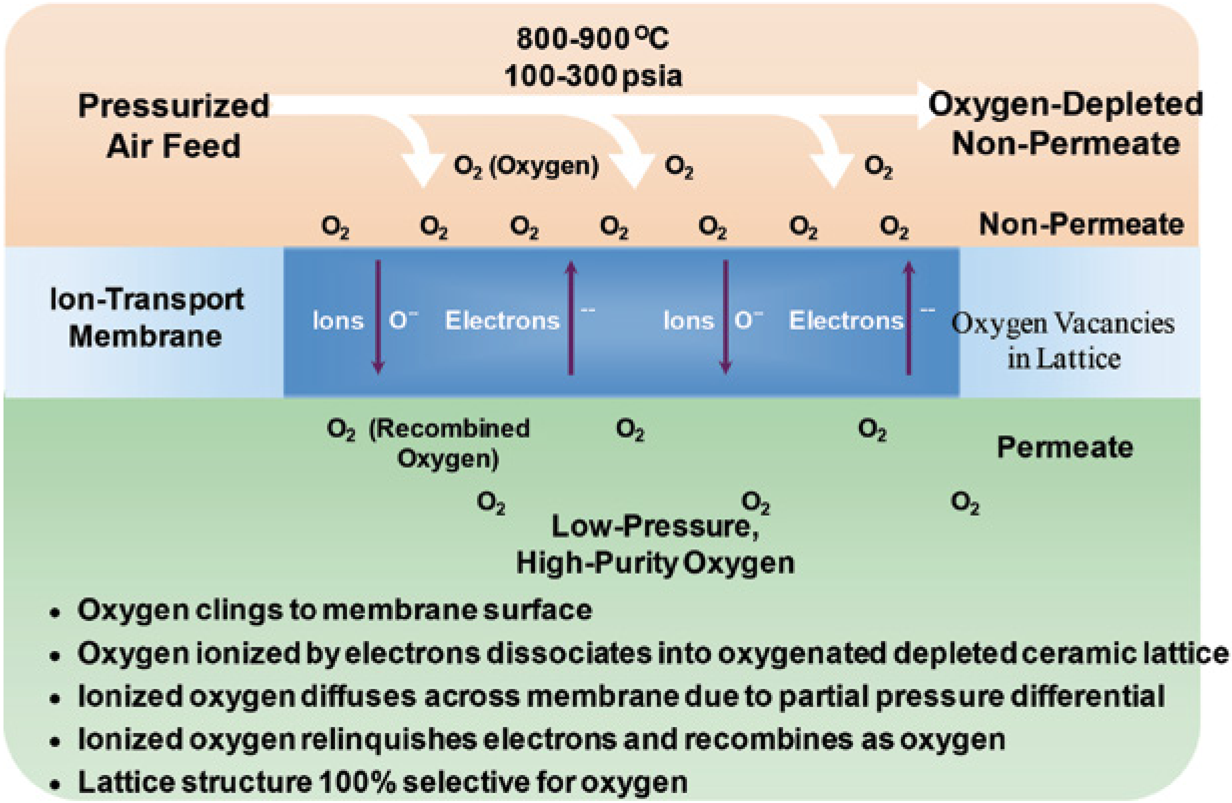

Figure 1: Conceptual Schematic of ITM O_2 Technology

The membrane employs a ceramic planar wafer architecture that incorporates a non-porous ITM on supporting porous and slotted layers that typically operate between 800 and 900°C. The driving force for O_2 separation is determined by the relative O_2 partial pressure gradient across the membrane. Therefore, air is typically supplied at pressures of 7 to 20 atm, while the product O_2 pressure is typically below ambient (≈1 atm). Figure 2 shows a cutaway view of part of a wafer. The wafer consists of two thin outer membrane layers through which the oxygen ions diffuse. The thin layers on the top and bottom of the wafer are supported by a porous layer, which is itself supported by a slotted layer. High-temperature, high-pressure air flows over the membrane surface exterior to the wafer. Oxygen passes from the air outside each wafer through the thin outer membrane layer, through the pores of the porous layer and into the slots of the innermost layer, where it is collected. In a typical membrane module, stacks of wafers are joined together, separated by a spacer ring to form a gap for air flow between the wafers. The oxygen is collected in a central region of the module formed by the open center of each wafer and the spacer rings and passes out of the module through a ceramic tube sealed to a metal pipe. The high-pressure air on both sides of each wafer creates compressive stresses within the ceramic, which stabilize the wafer. The planar design also makes for a very compact separation device, while facilitating good gas phase mass transfer. All of the layers are made of the same ceramic material, and therefore expand and contract together during temperature changes.

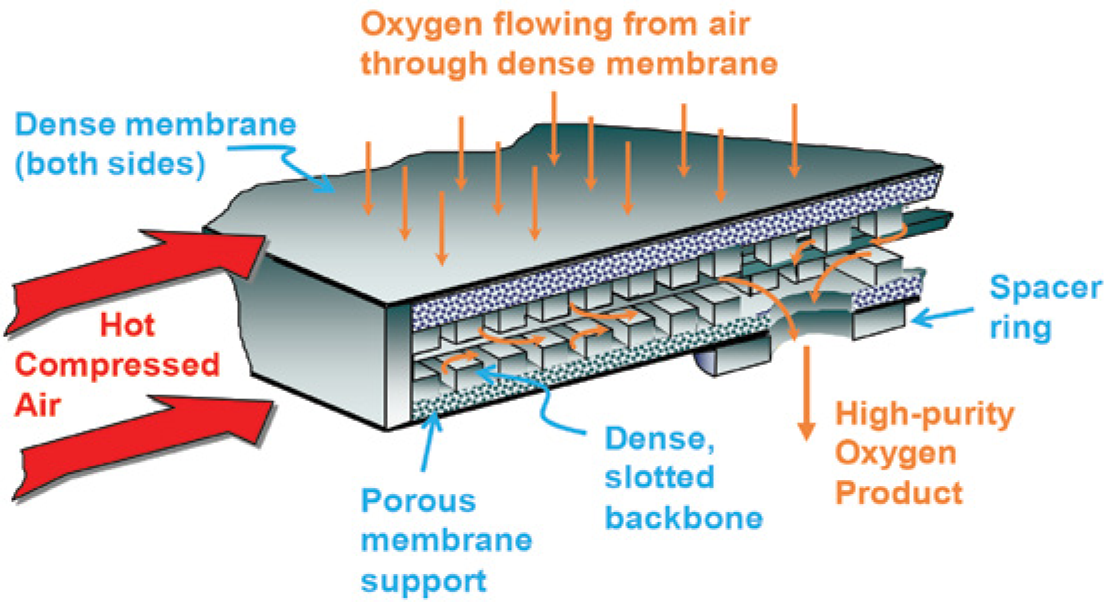

Figure 2: A Portion of an ITM Planar Membrane Wafer Shown in Cutaway View

Figure 3 shows a schematic diagram of an ITM O_2 production plant that includes both indirect and direct heating of the pressurized feed air in order to satisfy the heating requirement of the thermally activated transport mechanism. While not shown in the schematic, the resulting hot, pressurized, non-permeate stream can be recovered if combined with a gas turbine power generation system.

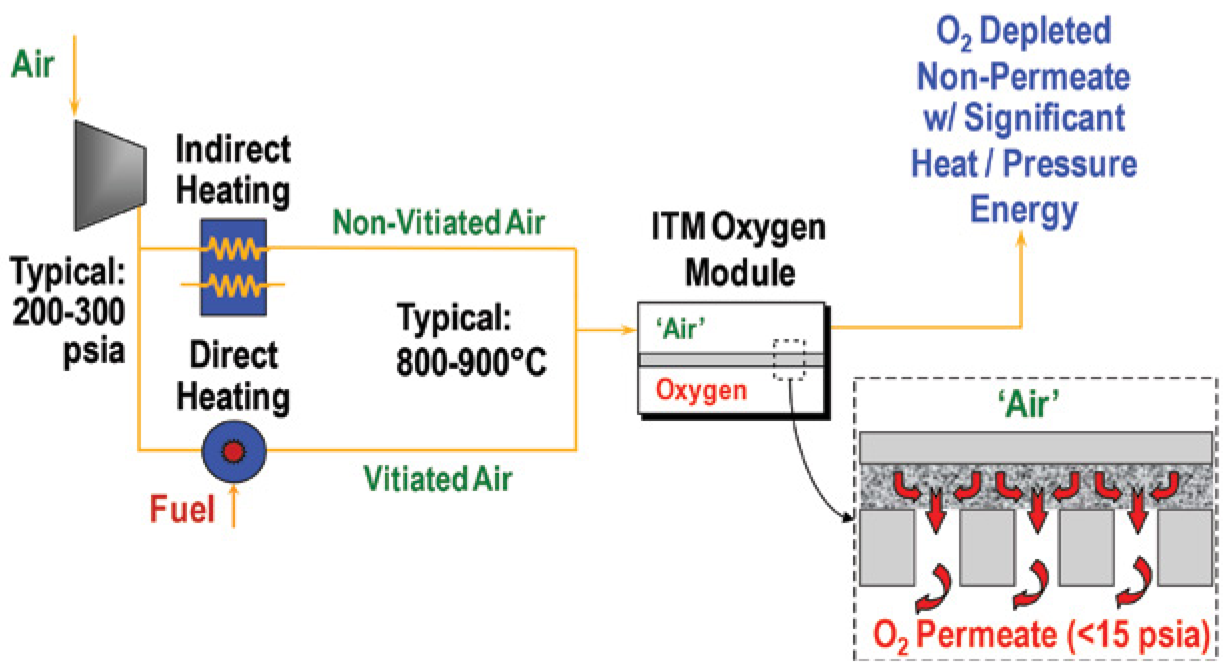

Figure 3: Diagram of O_2 Production Plant

An ITM O_2 plant is projected to decrease the installed capital cost of air separation equipment by more than one-third and the installed capital cost of an IGCC facility by 7 percent, while improving efficiency and reducing the power requirement for air separation by approximately 35 percent. These increases in efficiency and reductions in cost, along with the near-capture ready concentrations of CO_2 in the waste stream, make ITM a technology that may be capable of making CO_2 capture more economically feasible.

technology advantages

- This technology is capable of producing greater than 95% O_2 at high flux rates.
- It is resistant to structural damage and provides consistent performance during thermal and hydraulic cycling.
- It offers low capital and operating costs, improves efficiency and reduces the power requirement for air separation by approximately 35% relative to cryogenic separation, and reduces capital cost of an IGCC facility by 7%.

R&D challenges

Scale-up from 5 TPD to 100 TPD to 2,000 TPD, and obtaining flux rates competitive to other available technologies.

results to date/accomplishments

- Developed a stable, high-flux material; demonstrated stable operation in the 0.1-TPD TDU.
- Demonstrated the commercial flux target under anticipated commercial operating conditions.
- Devised a planar ITM architecture.
- Scaled-up and produced commercial-size wafers in large quantities.
- Built first commercial-scale ITM oxygen modules.
- Completed detailed design, construction, and testing of SEP vessel capable of housing full-size ITM oxygen modules to produce an estimated 5 TPD of 95% pure oxygen at full commercial conditions of 200 to 300 pounds per square inch gauge (psig) and 800 to 900 °C.
- Completed sub-scale wafer flux evaluation studies with feed air impurities and determined the effect of potential impurities on the cost and engineering performance of ITM systems.
- Implemented patented advanced process control techniques during heating and cooling to improve module reliability at the SEP.
- Completed the 100 TPD module conceptual design by including major elements of a commercial ITM oxygen facility.
- The 5 TPD SEP was operated for more than 18,000 hours, commercial flux targets were achieved or surpassed, and product purity exceeded 99%.
- Developed and selected a supported getter material that will remove gas phase chromium species upstream of the ITM modules.
- Temperature Swing Adsorption (TSA) system has been fabricated.
- Mechanical, electrical, and insulating work for the ISTU pilot-scale unit construction has been completed.
- Two 0.5-TPD ITM modules were successfully tested in the SEP utilizing a prototype flow duct design. The flow duct design will be scaled-up to support 1-TPD ITM module operation and fabrication.
- Completed construction of major equipment items for the 5-TPD SEP facility for testing full-size ITM modules for producing 1 to 5 TPD of O_2 at 95% purity.
- Tested full-size ITM Oxygen modules in the SEP facility and produced O_2 near 95% purity and generated process information for further scale-up to the ISTU.

next steps

- Establish design basis scale-up of the ITM process for energy and other industrial applications.
- Operate the ISTU and the ceramic fabrication facility to support scale-up of the technology.

available reports/technical papers/presentations

Repasky, J. M.; Anderson, L. L.; Stein, V. E.; Armstrong, P. A.; and Foster, E. P., "ITM Oxygen technology: scale-up toward clean energy applications," presented at International Coal Conference 2012, Pittsburgh, Pennsylvania, October 2012.

Anderson, L. L.; Armstrong, P. A.; Repasky, J. M.; and Stein, V. E., "Enabling Clean Coal Power Generation: ITM Oxygen Technology," presented at International Coal Conference 2011, Pittsburgh, Pennsylvania, September 2011.

Armstrong, P. A., and Foster, E. P. "ITM Oxygen for Gasification," presented at International Thermal Operations and Heavy Oil Symposium November 2005, Calgary, Alberta. Canada.

Dyer, P.N.; Richards, R.E.; Russek, S.L.; and Taylor, D.M., "Ion Transport Membrane Technology for Oxygen Separation and Syngas Production," Solid State Ionics, 134 (2000) 21-33.

DEVELOPMENT OF NANOFILLER-MODULATED POLYMERIC OXYGEN ENRICHMENT MEMBRANES FOR REDUCTION OF NITROGEN OXIDES IN COAL COMBUSTION

primary project goals

North Carolina A&T State University (NCATSU) set out to design and develop a nanofiller-modulated polymer membrane for the oxygen (O_2)-enrichment of coal combustion and gasification applications that would reduce the volume of waste gas and increase the concentration of near-capture ready carbon dioxide (CO_2) within the waste gas to simplify capture and reduce related costs.

technical goals

- Research and select polymer candidates, as well as functional nanofillers.
- Experiment with the selected nanofiller-modulated polymers and document the fundamental microstructure-property relationships.
- Develop models for selected membranes using Material Studio 4.0 and Groningen Machine for Chemical Simulation (GROMACS) 3.3.

technical content

NCATSU researched membrane technology capable of separating O_2 from nitrogen (N_2). The selected membranes had to be capable of producing a sufficient volume of high-purity O_2 at reasonable operational and capital costs. The primary method of research used to develop a membrane with the required traits has been to vary the amount and type of filler, the type of polymer backbone, and the method of distribution and casting used. The results are used to develop computational models to further study and develop the technology. The membranes evaluated include single-walled carbon nanotube, nanofumed silica polydimethylsiloxane (PDMS), and zeolite-modulated polyimide (a polymer) membranes.

The polyimide selected was Matrimid 5218, due to its high glass transition temperature, high structural and thermal stability, and low cost. For example, a mixed-matrix membrane utilizing Matrimid 5218 as the polyimide backbone and a zeolite as the filler was fabricated on a porous stainless steel substrate. This membrane was exposed to pure N_2 and pure O_2 at 3.4 atm (50 pounds per square inch [psi]) for two hours. The resulting permeability was 0.114 Barrer and 0.380 Barrer, respectively, with a selectivity for O_2 of 3.33. After 12 hours, the results improved to a permeability of 0.093 for N_2 and 0.460 for O_2, with a selectivity for O_2 of 4.95. While the results are still below required values, they show considerable potential that a mixed-matrix polyimide membrane with zeolite nanofiller could meet the requirements necessary for commercial application in the future.

technology maturity:

Laboratory-Scale

project focus:

Nanofiller Oxygen Membranes

participant:

North Carolina A&T State University

project number:

FG26-06NT42742

NETL project manager:

Timothy Fout
timothy.fout@netl.doe.gov

principal investigator:

Jianzhong Lou
North Carolina A&T State University
lou@ncat.edu

partners:

American Air Liquide
Babcock & Wilcox Co.
Battelle Memorial Institute

performance period:

2/17/06 – 12/31/10

As for nanofumed silica PDMS membranes, the fumed silica chosen was CAB-O-SIL TS-530. The hydrophobic silica was chosen because it had greater potential for proper mixing with the elastomer. However, the fumed silica did not produce good dispersion in the polymer, resulting in limited success. The O_2 selectivity observed for 1 and 2.5 percent fumed-silica at 4.1 atm (60 psi) was 2.72 and 2.81, respectively. When compared to an O_2 selectivity of 2.54 for pure PDMS, it is apparent that little improvement was achieved through the use of the fumed silica.

Lastly, molecular dynamics simulations have been conducted to calculate the theoretical O_2 molecular diffusion coefficient and N_2 molecular coefficient inside single-walled carbon nanotube PDMS membranes in order to predict the effect of the nanotubes on the gas-separation permeability. A simulated model of these membranes is shown in Figure 1.

The selectivity achieved from experimentation is 0.86 for PDMS filled with single-walled carbon nanotubes. When compared to pure PDMS, with a selectivity of 1.97, it is apparent that this filler is not appropriate for the purpose of this project.

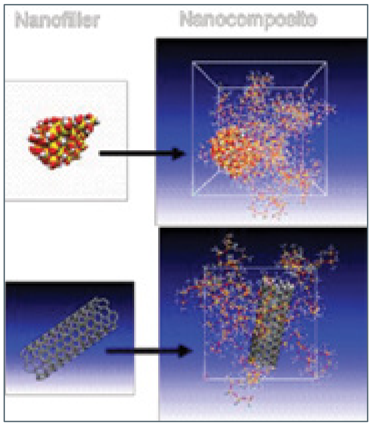

Figure 1: Model of Naofumed Silica (above) and Single-Walled Carbon Nanotube PDMS Membranes

technology advantages

- The membranes researched have several desirable properties, including high glass transition temperatures, high thermal and structural stability, high permeability (0.460 Barrers), and high selectivity (4.95).
- Capital costs are low due to the absence of precious metals found in many other membrane technologies.

R&D challenges

- The experiments performed have shown that the nanofillers and polymers used have unstable properties over extended periods of time.
- It was found that fumed silica did not produce good dispersion in the polymers tested.
- Insufficient permeability and selectivity for O_2.

results to date/accomplishments

- Performed permeation and diffusion experiments using polymers with nanosilica particles, nanotubes, and zeolites as fillers.
- Studied the influence of nanofillers on the self diffusion, free volume, glass transition, O_2 diffusion and solubility, and perm-selectivity of O_2 in polymer membranes.
- Developed molecular models of single-walled carbon nanotube and nanofumed silica PDMS membranes, as well as zeolites-modulated polyimide membranes.

next steps

This project ended on December 31, 2010.

available reports/technical papers/presentations

Zhang, J.; Lou, J.; Ilias, S.; Krishnamachari, P.; and Yan, J., “Thermal properties of poly(lacticacid) fumed silica nanocomposites: Experiments and molecular dynamics simulations,” Polymer, 2008, 49, 2381-2386.

Zhang, J.; Liang, Y.; Yan, J.; and Lou, J., “Study of molecular weight dependence of glass transition temperature for amorphous poly(l-lactide) by molecular dynamics simulation,” Polymer, 2007, 48, 4900-4905.

Vu, D. Q.; Koros, W. J.; and Miller, S. J., “Mixed matrix membranes using carbon molecular sieves: I. Preparation and experimental results,” Journal of Membrane Science 2003, 211 (2), 311-334.

NOVEL SUPPORTS AND MATERIALS FOR OXYGEN SEPARATION AND SUPPLY

primary project goals

Eltron Research set out to design and develop a temperature swing adsorption (TSA) system capable of producing high purity (>99%) oxygen (O_2) for use as an air substitute in power plants, reducing waste gas volume and simplifying carbon dioxide (CO_2) capture and containment.

technical goals

- Produce materials which provide more O_2/m^3*hr than the zeolites currently used in small to mid-size TSA O_2 separation technologies (23 kg O_2/m^3*hr).
- Develop materials capable of producing an O_2 with purity comparable to cryogenic O_2 separation (>99%).

technical content

Eltron Research set out to develop a TSA system that is capable of producing O_2 at purities comparable to those produced by cryogenic methods, but at reduced cost.

This program initially focused on the coating of sintered metal fiber filters (SMFFs) with cerium oxide (CeO_2), silicon oxide (SiO_2), and/or aluminum oxide (Al_2O_3). These base-coated fibers were then separately impregnated using a mixed metal oxide nitrate. The SMFFs used were chosen for their high porosity (80%) and permeability (1,500 L/dm*min), which provided a near-negligible post-reactor pressure drop. Also, due to their high thermal conductivity, the chosen SMFFs had significantly reduced thermal irregularities compared to ceramic monoliths. This feature resulted in near isothermal reactor beds. Cerium- (Ce), silicon- (Si), and aluminum- (Al) based oxides were chosen as base-coating materials for their ability to increase surface area and provide a more ideal binding surface on the SMFFs. Additionally, they also prevent or dramatically decrease agglomeration and its impact on the overall O_2 storage and release capability of the materials. However, based upon an economic analysis, it was determined that the volume needed for the SMFFs was too large, and so the program was then re-focused strictly on fixed beds with no SMFF supports. In addition, the focus was changed from co-precipitated mixed metal oxide materials to perovskite materials produced using ceramic processing methods.

Twelve combinations of materials were selected and produced via ceramic processing methods and calcined at high temperatures (>900°C). Upon testing, results showed that one of the selected materials (K-12), a perovskite, was capable of producing >132 kg O_2/m^3*hr, far surpassing the original mixed metal oxide primary material produced via co-precipitation from nitrate solutions.

Figure 1 compares the O_2 production rates of several leading technologies, including Eltron's primary materials. Figure 2 compares the required reactor volume, based on a 5 ton-per-day (tpd) O_2 system. As indicated, the K-12 sorbent offers significantly improved O_2 production over existing pressure swing adsorption (PSA) zeolite-based sorbents. Utilizing a sorbent capable of such high production rates may significantly reduce the required reactor volume, leading to reduced capital and operational costs.

technology maturity:
Laboratory-Scale, 5-10 lb oxygen/day

project focus:
Materials for Oxygen Separation

participant:
Eltron Research

project number:
FG02-07ER84600.002

NETL project manager:
Arun Bose
arun.bose@netl.doe.gov

principal investigator:
Erick Schutte
Eltron Research
eschutte@eltronresearch.com

partners:
none

performance period:
8/8/07 – 8/7/10

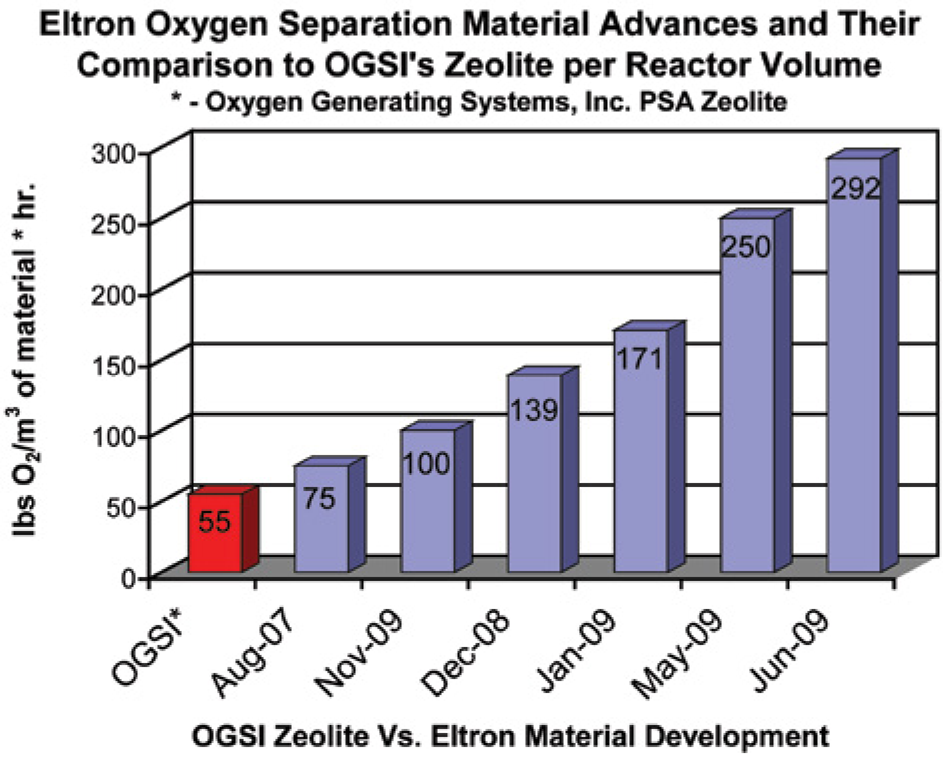

Figure 1: Oxygen Production Comparison

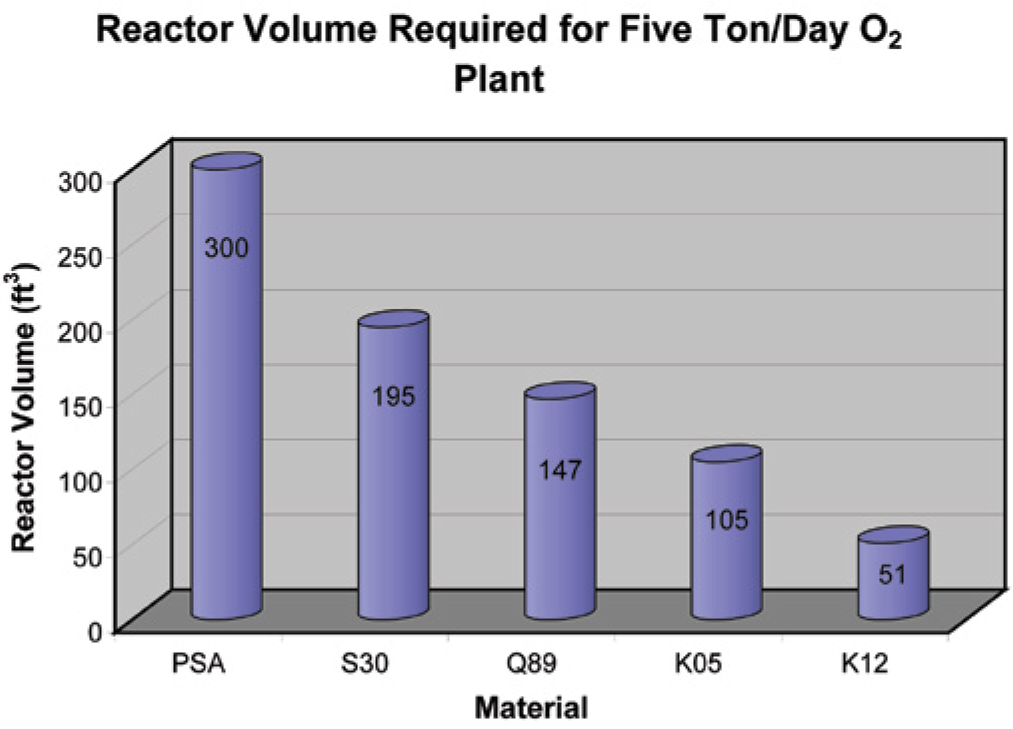

Figure 2: Required Reactor Volume Comparison

technology advantages

Materials being researched have superior mechanical strength, durability, and thermal resistance when compared to current TSA materials. They have the capability of producing O_2 at >99 percent purity, industrially relevant volumes, and at significantly reduced cost in comparison to cryogenic methods.

R&D challenges

- Heating issues (i.e., how to most effectively heat large amounts of material; how to heat and cool a large amount of material fast; how to make sure heating is even; etc.).
- Scale-up – The central focus of the technology was to compete with cryogenic separation on large scale (>1,000 tpd); however, initial development leaned towards competing with current small-scale PSA systems (1 lb – 1,000 tpd), which require additional processes to achieve high O_2 purity >95 percent.

results to date/accomplishments

- Developed a new primary material (K-12) which yields >132 kg O_2/m^3*hr.
- Observed that air flow during calcination is crucial to phase formation.
- Adding polyvinyl butyral (PVB) binder to calcined K-12, pelletizing, and re-firing at calcination temperatures yields a material which produced >130 kg O_2/m^3*hr with no drop-off in performance (>16,000 cycles).

next steps

- This project ended on August 7, 2010.
- Engage industrial partner for scale-up and commercialization push.

available reports/technical papers/presentations

N/A.

SORBENTS FOR AIR SEPARATION

primary project goals

TDA Research set out to design and develop a new regenerable chemical sorbent to selectively remove oxygen (O_2) from air.

technical goals

- Optimize and screen sorbent formulations.
- Scale-up sorbent production.
- Perform long-term testing of the sorbent to demonstrate its durability through a minimum of 5,000 absorption/regeneration cycles.
- Design and size a conceptual air separation system based on experimental results.

technical content

Air separation units (ASUs) are one of the most expensive components of the integrated gasification combined cycle (IGCC) plant, accounting for approximately 18 percent of the overall plant cost and more than 14 percent of the cost of electricity (COE). TDA Research set out to develop a new, highly efficient, sorbent-based air separation technology that can produce high-purity O_2 from air at high temperatures (approximately 800 °C).

By performing the air separation at high temperatures, much of the COE increase is avoided, because much of the energy penalty associated with separating air by cryogenic methods is in cooling the gas to temperatures as low as 80 °K. Additionally, some of the capital cost is reduced due to the faster kinetics, which permits the use of less material.

TDA's sorbent, a mixed metal oxide, has been found to achieve up to 4 wt% O_2 capacity and maintain its capacity for more than 300 cycles. This sorbent can be regenerated under near isothermal and isobaric conditions by changing O_2 partial pressure between the absorption and regeneration bed. This then demands the use of a minimum of two separate reactors, one for absorption and the other for regeneration. A solid circulation system is being developed to eliminate the use of high-temperature valves. Figure 1 is a schematic depiction of this process.

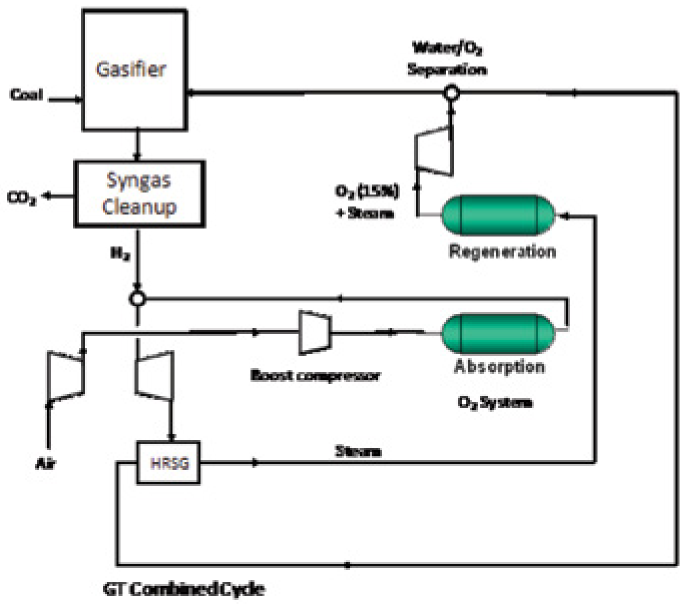

Figure 1: Schematic of Two Reactor Air Separation Units

technology maturity:
Bench-Scale

project focus:
Sorbents for Air Separation

participant:
TDA Research

project number:
FG02-08ER84216

NETL project manager:
Steven Markovich
markovis@netl.doe.gov

principal investigator:
Gokhan Alptekin
TDA Research
galptekin@tda.com

partners:
None

performance period:
8/7/06 – 8/6/10

It is estimated that the cost of O_2 could be as low as $18.5/tonne ($16.8/ton), which is a significant savings compared to cryogenic methods ($31 to $35/tonne) and is below the U.S. Department of Energy's (DOE) target of $22/tonne. Also, capital cost is estimated to be $85 to $104/kWe, which again is well below cryogenic plants ($360/tonne) and achieves DOE's target of $82 to $110/ton.

technology advantages

- The process temperature is maintained at 600 to 800°C to increase the reaction kinetics.
- The sorbent is regenerated under an inert gas (e.g., steam) at the same temperature and pressure, eliminating time required for temperature and/or pressure transitions.
- The oxidized phase is meta-stable and a small change in chemical potential leads to its reduction.

R&D challenges

Scale-up from batch to prototype.

results to date/accomplishments

- Optimized sorbent formulations and screened them under representative IGCC plant conditions.
- Scaled-up sorbent production.

next steps

This project ended on August 6, 2010.

available reports/technical papers/presentations

Alptekin, G.; Jayaraman, A.; Dubovik, M.; and Brickner, L., "Oxygen Sorbents for Oxy-fuel Combustion," presented at the 2008 AIChE Annual Meeting, Philadelphia, Pennsylvania, November 2008.

Alptekin, G.; Jayaraman, A.; Dubovik, M.; and Brickner, L., "Novel Air Separation Sorbents," presented at the Pittsburgh Coal Conference, Pittsburgh, Pennsylvania, September 2008.

Alptekin, G.; Jayaraman, A.; Dubovik, M.; and Brickner, L., "A Novel Air Separation Sorbent for Oxy-Combustion Process," presented at the International Technical Conference on Coal Utilization and Fuel Systems, Clearwater, Florida, June 2008.

PILOT-SCALE DEMONSTRATION OF A NOVEL, LOW-COST OXYGEN SUPPLY PROCESS AND ITS INTEGRATION WITH OXY-FUEL COAL-FIRED BOILERS

primary project goals

The BOC Group (now Linde, LLC) set out to conduct pilot-scale tests of its Ceramic Auto-Thermal Recovery (CAR) oxygen (O_2) generation process, integrated with a coal-fired combustor, to produce a carbon dioxide (CO_2)-rich flue gas.

technical goals

Phase I:

- Evaluate the performance of a 0.7-tonne/day, O_2 pilot-scale CAR system (long- and short-duration), when fully integrated with a pilot-scale coal combustor, and determine the optimum operating conditions of the unit.
- Perform a techno-economic evaluation of a commercial-scale, O_2-fired power plant that utilizes a CAR system to provide the O_2.

technical content

In the CAR process, O_2 is separated from an air stream using a perovskite ceramic oxide adsorbent (composed of lanthanum, strontium, cobalt, and iron) at high temperature (800 to 900°C). As shown in Figure 1, the process involves two separate beds that are cycled to deliver the O_2 flow (one bed is adsorbing the oxygen, while the other is desorbing). The O_2 is desorbed from the catalyst by a partial pressure swing using a purge gas containing low levels of O_2 in standard runs; CO_2 is used for this purpose. Half-cycle times are varied for most efficient operational parameters, but fall in the range of 30 seconds to one minute. Multiple temperatures are monitored in the catalytic bed and are spatially placed to give an accurate representation of the bulk temperatures in the ceramic bed.

technology maturity:

Pilot-Scale, 0.7 tonnes O_2/day

project focus:

Low-Cost Oxygen Supply

participant:

The BOC Group, Inc, now Linde, LLC

project number:

FC26-06NT42748

NETL project manager:

Timothy Fout
timothy.fout@netl.doe.gov

principal investigator:

Krish R. Krishnamurthy
Linde, LLC.
krish.krishnamurthy@linde.com

partners:

Alstom Power Plant Laboratories
Western Research Institute

performance period:

4/1/06 – 9/30/08

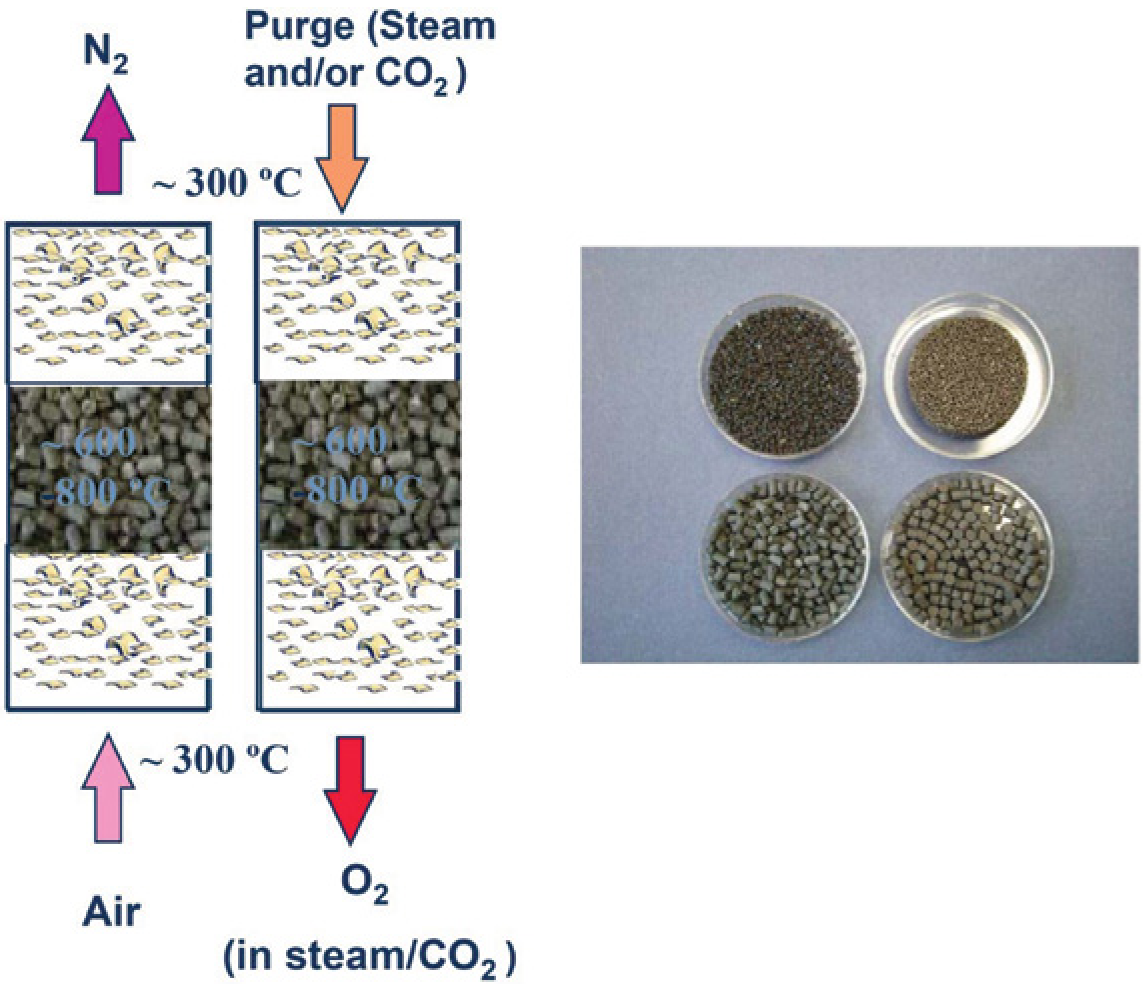

Figure 1: Ceramic Auto-Thermal Recovery (CAR) Two-Bed Oxygen Separation Process

technology advantages

The O_2 production process has shown a clear advantage in performance and cost compared to an air separation unit (ASU).

R&D challenges

Although the CAR process alone compares favorably to an ASU, the techno-economic analysis has shown that overall capital costs, heat losses, and fuel consumption make the CAR process unfavorable compared to an ASU unless the working oxygen capacity of the CAR adsorbent can be increased from the current level of approximately 0.5 wt% to approximately 1.0 wt%. In addition, long-duration tests have shown that the perovskite adsorbent experiences substantial mechanical breakdown and decline in performance when exposed to sulfur dioxide (SO_2).

results to date/accomplishments

Completed Phase I activities include:

- Evaluated the performance of the 0.7-tonne/day, O_2 pilot-scale CAR system (long- and short-duration) and determined the optimum operating conditions of the unit.
- Performed a techno-economic evaluation of a commercial-scale, O_2-fired power plant that utilizes a CAR system to provide the O_2.

next steps

This project ended on September 30, 2008.

available reports/technical papers/presentations

Krishnamurthy, K. R.; Acharya, D.; and Fitch, F. R., "Pilot-Scale Demonstration of a Novel, Low-Cost Oxygen Supply Process and its Integration with Oxy-Fuel Coal-Fired Boilers," Final Report, December 18, 2008. *http://www.netl.doe.gov/File%20Library/Research/Coal/ewr/co2/42748-BOC-O2-supply-CAR-Final-Report_Dec-2008.pdf*.

Krishnamurthy, K. R.; Barton, T.; Braunberger, B.; Omar, K.; and Sethi, V., "Demonstration of a Novel, Low-Cost Oxygen Supply Process and its Integration with Oxy-Fuel Coal-Fired Boilers," presented at 6th Annual Conference on Carbon Capture and Sequestration, Pittsburgh, Pennsylvania, May 2007. *http://www.netl.doe.gov/File%20Library/Research/Coal/ewr/co2/42748-BOC-O2-supply-CAR-6th-CCS-conference-2007.pdf*.