NATIONAL CARBON CAPTURE CENTER

10 Years of Technology Development

Advancing Fossil Energy Technology Solutions

Southern Company has been a phenomenal partner to the U.S. Department of Energy across virtually all energy segments ... I look at the National Carbon Capture Center and see 100,000 hours of testing and more than 60 different technologies. That is amazing.

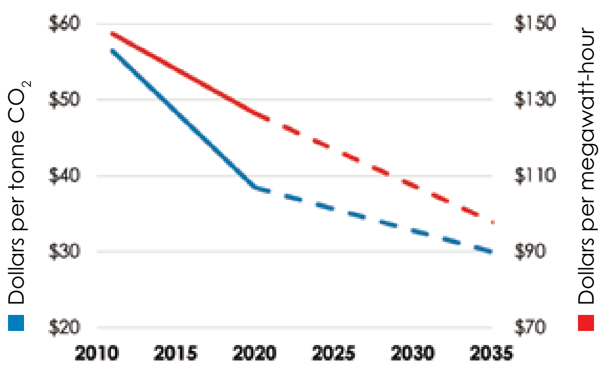
Steven Winberg, Assistant Secretary for Fossil Energy
U.S. Department of Energy

Sponsored by the U.S. Department of Energy (DOE) and operated and managed by Southern Company, the National Carbon Capture Center is a cornerstone of U.S. innovation in advancing fossil energy technology solutions. The center evaluates carbon capture processes from third-party developers, focusing on the early-stage development of the most promising, cost-effective technologies for future commercial deployment.

Since its creation in 2009, the National Carbon Capture Center has achieved remarkable progress. The center has hosted a variety of technology developers, both national and international, fostering the commercialization of new materials and processes for power generation that can meet future environmental standards while limiting the increased cost of electricity. These developers have used their testing experience at the facility to refine and, in many cases, scale up their technologies, and data generated at the site has proved to be reliable and accurate. Through pilot testing of more than 60 technologies, the center has directly participated in the reduction of the projected cost of carbon capture by one-third. *(see chart)*

The National Carbon Capture Center is currently focused on carbon capture technologies for natural gas and coal power plants; however, a significant amount of progress was made on gasification and pre-combustion carbon capture technologies tested at the center. This document highlights the wide variety of projects supported by the National Carbon Capture Center over its 10 years of existence.

Carbon Capture Cost Reduction*



* Supercritical pulverized coal 2011 dollars.
Source: National Energy Technology Laboratory. 2015. Cost and Performance Baseline for Fossil Energy Plants (Vol. 1, Rev. 3) / 2018 CURC-EPRI Advanced Fossil Energy Technology Roadmap.

Post-Combustion Carbon Capture

More than 30 post-combustion projects with the potential to substantially reduce carbon capture costs have been tested at the National Carbon Capture Center. The state-of-the-art facilities, offering technology developers realistic operating conditions and high-quality data acquisition, are routinely modified to expand testing opportunities. In addition to coal-derived flue gas, the center will soon be able to provide natural gas flue gas with various process conditions. Through testing at the site, several technologies have progressed through scale-ups as they move toward commercial deployment.

■ Solvent-Based Carbon Capture Projects

While solvent-based carbon capture, particularly amine scrubbing, enjoys a high degree of technical readiness, the increase in cost of electricity (COE) using the industry-standard solvent monoethanolamine (MEA) could exceed 70 percent. A critical area of research for solvent-based carbon capture is the identification of advanced solvents with high capacity for carbon dioxide (CO_2) loading and lower regeneration energy requirements than MEA. Next-generation solvents must also be low cost, non-corrosive, fast reacting and degradation-resistant. Process improvements are needed as well, since operating solvent systems with conventional scrubbing, even with advanced solvents, could increase COE 40 percent or more. Thus, optimized equipment as well as hybrid systems involving membranes and enzymes are being explored.

■ Sorbent-Based Carbon Capture Projects

Unlike most solvents, CO_2 solid sorbents contain no water and therefore offer much lower heating and regeneration energy requirements. To advance sorbents as a viable carbon capture solution, research and development is underway to demonstrate sorbents' low cost, thermal and chemical stability, resistance to attrition, low heat capacity, high CO_2 loading capacity, and high selectivity for CO_2. Optimization of process equipment designs is also needed to suit the characteristics of each type of sorbent.

■ Membrane-Based Carbon Capture Projects

Gas separation membranes offer several notable advantages for carbon capture applications: simple, modular designs; no need for steam or chemicals; and unit operation as opposed to complex processes. Membranes are being researched as a step-change improvement for carbon capture. Goals in this area are to develop membranes with low cost and durability, enhanced permeability and selectivity, thermal stability, and tolerance to flue gas contaminants.

Solvent Testing in the Pilot Solvent Test Unit

The National Carbon Capture Center's Pilot Solvent Test Unit (PSTU) consists of the necessary equipment to test the absorption and regeneration characteristics of carbon capture solvents and has the flexibility to operate at varying conditions and process

configurations. The center commissioned the PSTU and conducted several test campaigns with MEA solvent. Demonstrating mass and energy balance closures of nearly 100 percent, the testing provided a baseline regeneration energy of 1,500 to 1,720 British thermal units (BTUs) per pound (lb.) of CO_2.

Babcock & Wilcox OptiCap™ Solvent—During three months of testing, B&W's OptiCap solvent demonstrated regeneration energy values in the range of 1,100 to 1,125 BTU per lb. CO_2 at a CO_2 removal efficiency of 90 percent, with further energy savings expected through B&W's optimized heat exchanger design. B&W considers the solvent ready for commercial demonstration, noting that OptiCap performance solvent compares favorably with other commercially ready solvents in areas of regeneration energy, corrosivity and solvent degradation.

Hitachi H3-1 Solvent—More than 1,300 hours of testing with the H3-1 solvent showed that, compared to MEA, a 37-percent lower solvent flow rate is needed to achieve 90 percent CO_2 capture, and the regeneration energy is at least 34 percent lower. With DOE funding, Hitachi-Mitsubishi Heavy Industries (MHI) is conducting a large pilot demonstration of the solvent and supporting equipment design at a Kentucky Utilities generating station to gather additional data for scale-up to commercial operation.

Cansolv DC-201 and DC-103 Solvents—Cansolv performed four test campaigns, involving long-term and parametric tests, with cool and hot climate conditions, and with simulated natural gas conditions. The testing demonstrated a 40 percent reduction in energy requirements and a 50 percent reduction in the required liquid-to-gas ratio over MEA. Cansolv's process using the DC-103 solvent is being demonstrated commercially at the SaskPower Boundary Dam Power Station.

Chiyoda T-3 Solvent— Testing of the Chiyoda T-3 solvent for 1,500 hours of operation showed that, in comparison to MEA, the optimum liquid-to-gas ratio was about 50 percent lower, regeneration energy for 90 percent capture (at 1,110 BTU per lb.) was around 30 percent lower, and corrosivity was significantly lower. Work is ongoing to continue development of the solvent.

Carbon Clean Solutions (CCSL) Solvent— Based on operating experience at the National Carbon

Natural Gas Infrastructure

The National Carbon Capture Center is broadening its research scope to include testing of carbon capture technologies for natural gas power generation in addition to its existing coal-fueled testing capability. Expansion of natural gas testing will drive new breakthroughs and improve confidence in techno-economic analyses.

Advantages of adding natural gas infrastructure to the post-combustion carbon capture test site include:

- Providing operational independence from the host site, Alabama Power's Plant Gaston, by offering a different source of flue gas and steam. This will allow for expanded testing windows that are less dependent on regional energy load demands based on weather.
- Providing a natural gas flue gas stream that can be used for technology commissioning and startup. Natural gas-derived flue gas contains fewer physical and chemical trace impurities than coal-fired flue gas and reduces risk for initial technology testing.
- Creating a single site where technologies can be tested on both coal and natural gas flue gases. This will increase the operating data and experience for technologies in both areas and reduce mobilization-demobilization costs from site to site.
- Utilizing the center's highly-trained, specialized staff. This team of approximately 150 engineers, O&M employees, support staff and construction personnel have experience in implementing and executing carbon capture technology projects.

Integration of the new natural gas flue gas equipment with the existing infrastructure will allow each carbon capture project to receive either coal or natural gas flue gas independently of other projects. Design and construction of the natural gas flue gas infrastructure, designed for flexibility, began in 2019.

Capture Center, CCSL estimated that 90 percent CO_2 removal could be achieved with 1,160 BTU per lb. CO_2. CCSL's solvent was further tested at Technology Centre Mongstad (TCM) in Norway and is currently being employed for carbon capture from three commercial facilities: an alkali chemicals and fertilizers plant with a coal-fired boiler in India, a coal-fired combined heat and power plant in Eastern Europe and a chemical plant with a coal-fired boiler in India.

DOE Carbon Capture Simulation Initiative (CCSI)—Testing was conducted with MEA solvent for two campaigns that supported DOE's CCSI and the $CCSI^2$, the second phase of the project. The goal of the CCSI is to significantly reduce the time required to develop and scale up new technologies in the energy sector. The testing resulted in a CCSI Toolset that can be used to gain more data and information during carbon capture test campaigns. The CCSI project continues to engage with technology developers and test centers to increase deployment of the computational tool. For example, the CCSI Toolset was used at TCM through collaboration with the International Test Center Network.

GE Global Adsorber and GAP-1 Aminosilicone Solvent—GE Global tested its continuous stirred-tank reactor (CSTR) and non-aqueous GAP-1 solvent with the PSTU. The CSTR, a one-stage separation unit that is smaller and less costly than conventional columns, achieved 95 percent capture. Based on solvent operation with the PSTU regenerator, GE showed that the GAP-1 solvent could achieve a 20 to 30 percent improvement in COE over MEA. GE received DOE Phase I funding to evaluate a demonstration-scale 10-megawatt (MW) test at TCM, but GE is not pursuing further development at this time.

ION Engineering Solvent—During a 1,100-hour campaign, ION's advanced solvent consistently demonstrated the potential to substantially reduce capital and operating costs. Results indicated at least 30 percent reduction in regeneration energy requirements, 35 percent higher CO_2 solvent-carrying capacities and significantly less solvent degradation in comparison with MEA. Larger-scale testing was conducted at TCM, and ION is seeking opportunities to continue development.

AECOM/University of Texas at Austin (UT-Austin) Advanced Flash Stripper (AFS) with Piperazine Solvent—The AFS is an energy-efficient alternative to conventional strippers that is projected to achieve optimal performance with piperazine solvent, which features fast kinetics, high capacity, low volatility and degradation resistance. For testing at the National Carbon Capture Center, the AFS skid was integrated with the PSTU to bypass the standard regenerator. The AFS demonstrated more than 40 percent energy reduction over the PSTU regenerator while operating with piperazine solvent. UT-Austin will conduct further testing of the AFS with piperazine solvent at the center using simulated natural gas flue gas in a separate project sponsored by the CO_2 Capture Project.

Technology Developer Solvent Units and Processes

Aker Clean Carbon Mobile Test Unit—Aker Clean Carbon demonstrated its pilot-scale solvent system during more than 2,500 hours of operation with carbon capture. Test results reported by Aker included a significant reduction in emissions of solvent components when using Aker's low-emissions, anti-mist design and reduced energy consumption (about 20 percent lower specific reboiler duty) using Aker's CCAmine solvent compared to MEA solvent at 90 percent CO_2 capture. Aker has advanced the technology through larger-scale testing at TCM.

Trimeric/UT-Austin NOx Reduction—Trimeric and UT-Austin performed testing of a chemical process for removal of nitrogen dioxide (NO_2) from amine-based solvent systems to prevent nitrosamine accumulation in the solvent system and thus minimize solvent oxidation and degradation. The process involved the use of a low-cost additive, thiosulfate, in an existing sulfur dioxide (SO_2) pre-scrubber, combining NO_2 and sulfur removal into one step and achieving 90 percent NO_2 removal. Trimeric is working to deploy the integrated scrubbing chemistry at a commercial site. Confidence in performance is high due to results at the small pilot-scale project at the National Carbon Capture Center.

"The National Carbon Capture Center process and control engineers worked relentlessly with the CCSI² team to implement this first-of-its-kind test run implemented in a pilot plant for CO_2 capture. The implementation was accurate and seamless."

Debangsu Bhattacharyya, Professor
West Virginia University

Codexis Enzymes—Codexis performed testing of a bench-scale system using carbonic anhydrase enzymes to accelerate the rate of carbon capture for low-energy solvents that have desirably low heats of reaction such as methyl diethanolamine (MDEA). The testing confirmed the stability of the enzyme in the presence of trace contaminants and demonstrated robust system operation, with CO_2 capture averaging around 65 percent at a rate of capture more than 25 times greater than for MDEA alone. Plans to further develop the technology were delayed due to company changes in research priorities.

Akermin Enzymes—Akermin successfully confirmed proof of concept of its pilot-scale process featuring immobilized carbonic anhydrase enzymes using low-cost, non-volatile potassium carbonate solvent. Data demonstrated that the enzyme operation resulted in a seven-fold increase in flue gas flow rate while maintaining 90 percent CO_2 capture in the same column and a six-fold increase in the mass transfer coefficient. Akermin was able to scale up the process for further development at the National Carbon Capture Center. With the scaled-up process, lack of catalyst circulation prevented steady-state operation. Despite promising results from the first testing, Akermin was unable to support further development of the technology.

Linde-BASF Solvent Process—Linde and BASF's solvent-based technology incorporates BASF's advanced amine solvent OASE® Blue and novel process along with Linde's process and engineering innovations, such as a gravity-flow interstage cooler and unique reboiler design. Operating the solvent process at a 1.5-MW pilot-scale for more than 4,000 hours, results showed a regeneration energy as low as 1,140 BTU per lb. CO_2 with at least 90 percent CO_2 capture. Testing also proved out the design of the unique equipment features incorporated in the pilot plant. The technology was selected by DOE for Phase I funding of a project to capture 90 percent of the CO_2 from an existing coal-fired plant at a U.S. site, and Linde has submitted a Phase 2 proposal for implementation of the project.

University of Edinburgh Solvent Analyzer—The University of Edinburgh tested a real-time solvent analysis device, developed to allow for rapid process responses to changes in process variables such as load demand in a commercial carbon capture system. The device proved capable of determining solvent concentration and loading within a 10-second response window, a significant improvement over current state-of-the-art technologies for solvent analysis that can take up to 30 minutes to provide data. Following testing at the National Carbon Capture Center, the University of Edinburgh operated the device at two other carbon capture test facilities, and the university has designed a commercial version that is commercially available.

Carbon Capture Scientific Gas Pressurized Stripping (GPS)—Carbon Capture Scientific completed testing of the bench-scale GPS process using an amine-based proprietary blended solvent. The GPS system integrates carbon capture and compression into one step. The energy consumption of the GPS process was much lower than that of the MEA baseline case, with the total heat requirement for the GPS process at about 1,310 BTU per lb. CO_2 captured. Carbon Capture Scientific has identified ways to optimize the GPS process to achieve further energy cost reductions, and the group is continuing work to advance the process to commercialization.

Gas Technology Institute (GTI) Membrane Contactor—GTI is developing a hollow-fiber gas-liquid membrane contactor to replace conventional packed-bed columns in solvent systems to improve CO_2 absorption efficiency. GTI resolved all technical challenges and performed parametric and long-term testing. The system demonstrated 90 percent CO_2 capture with CO_2 purity greater than 97 percent. Additional long-term testing is planned at the National Carbon Capture Center.

Solvent Testing in the Slipstream Solvent Test Unit

The National Carbon Capture Center's Slipstream Solvent Test Unit (SSTU) is conceptually and functionally similar to the PSTU, at about one-tenth the scale, making it well-suited for testing solvents that are in early stages of development. Commissioning of the SSTU with MEA solvent was conducted to provide baseline performance values against which to compare developers' solvents, and results showed a regeneration energy value of 2,200 BTU per lb. CO_2 at optimum conditions.

Research Triangle Institute International (RTI) Non-Aqueous Solvent—RTI's solvent is an alternative to conventional aqueous solvents that lowers regeneration energy by eliminating the energy penalty associated with vaporizing water and by increasing the regeneration pressure at lower temperatures. The project, funded by DOE, is the result of collaboration of RTI and Norway's SINTEF organization. Though the SSTU was not optimized for the RTI solvent, around 75 percent CO_2 capture was accomplished after suitable pressure and temperature combinations were experimentally identified. RTI will use the valuable data gained from this test for their scale-up project at TCM.

"The National Carbon Capture Center's support and cooperation for our membrane module testing were wonderful and professional, and we truly enjoyed working with its people."

W.S. Winston Ho, Professor
Ohio State University

Solvent Emissions Studies

Amine emissions from carbon capture systems in the form of aerosols leaving the absorber are a common challenge with commercial solvent processes where sulfur trioxide (SO_3) is present in the flue gas. The formation of aerosols has been found to correlate with the concentration of SO_3 present in the flue gas. Solvent losses from this effect are significant and must be addressed if a commercial system is to be deployed.

Cansolv Aerosol Mitigation Equipment—Cansolv Technologies' Thermal Swing Adsorber and Brownian Demister Unit were installed on the SSTU. The processes were designed to mitigate amine losses in a carbon capture process by reducing the formation of amine-containing aerosols. Initial testing was conducted while the SSTU operated with MEA. Due to time constraints, limited data was obtained.

Effect of Activated Carbon Baghouse—Using an electrical low-pressure impactor (ELPI+) and a phase doppler interferometer, aerosol measurements were taken in 2015 as baseline data to compare against results obtained in 2016, when a new activated carbon injection baghouse was brought online at Alabama Power's Plant Gaston Unit 5, upstream of the National Carbon Capture Center. In addition to a drastic shift to smaller particle sizes, the total particle count for aerosols dropped by three to five orders of magnitude compared to operation without the baghouse. Amine measurements showed that MEA emissions from the SSTU were between 100 and 110 parts per million (ppm) prior to the installation of the baghouse, dropping to between 5 and 10 ppm after the baghouse startup.

SO_3 Generator—To continue amine aerosol research following the baghouse installation, an SO_3 generator was installed to inject SO_3 directly into the flue gas stream. SO_3 injection testing was performed in conjunction with emissions monitoring during the AECOM/UT-Austin AFS campaign.

"Few have answered the call to help the U.S. lead the world in the next generation of clean energy technologies as loudly as Southern Company. We are especially proud to work with them to develop technologies that improve the environmental impact of natural gas and coal power."

Rich Powell, Executive Director
ClearPath

"The National Carbon Capture Center provides an important venue for helping to accelerate commercialization of advanced carbon capture technologies by creating a collaborative environment to share research results across the energy sector."

Bruce H. March, President, Research and Engineering
ExxonMobil

Through this testing, effective strategies for solvent emissions reductions were identified, and it was shown that piperazine solvent emissions at the wash water outlet can be maintained below 1 ppm for inlet flue gas containing 2 ppm SO_3. Testing with SO_3 injection is planned for future solvent campaigns.

Gas Separation Membranes

Membrane Technology and Research (MTR) Polaris CO_2 Membranes—Because of the large volumes of low-pressure flue gas generated by power plants, creating an affordable pressure ratio to drive membrane separation is a challenge. MTR is developing a two-step membrane, with the first step operating at vacuum and at a low stage cut, and the second step incorporating sweep gas to provide a final CO_2 capture rate of 90 percent. After successfully operating a bench-scale unit at the National Carbon Capture Center, MTR employed the lessons learned to construct and test a pilot-scale version. Continued development includes operation of the larger-scale unit at a Babcock & Wilcox pilot coal-fired boiler for the first operation with CO_2 recycle to a boiler by a membrane process, larger-scale operation at TCM and participation in a DOE Phase I project for demonstration at a commercial NRG Energy coal-fired power plant.

Ohio State University (OSU) Membranes—OSU has been testing a novel prototype membrane with a thin selective amine-containing layer over a nanoporous polymer support, designed to be easily manufactured in a continuous process while achieving high CO_2 permeance and selectivity. After conducting membrane testing in 2015, OSU returned in 2018 and demonstrated improved stability and long-term performance even with several interruptions due to power plant unit shutdowns. The membrane achieved the targeted CO_2 permeance and CO_2 selectivity, and consistent results with duplicate modules proved the reproducibility of the design and viability of the fabrication process. OSU will continue the membrane development with sponsorship from American Electric Power.

National Energy Technology Laboratory (NETL) Post-Combustion Membrane Skid—NETL has been operating its post-combustion membrane skid, which accommodates flat-sheet and hollow-fiber membranes. NETL aims to assess new materials designed to increase CO_2 permeability while maintaining selectivity, thereby reducing the size and cost of membrane capture systems. Testing at the center has encompassed multiple campaigns with materials such as standard polydimethylsiloxane membranes for baseline evaluations, mixed-matrix designs and NETL-developed polymer materials. Further testing at the National Carbon Capture Center is planned.

Air Liquide Cold Membrane— Air Liquide is evaluating a cold membrane process that combines high-permeance membrane materials with high CO_2 selectivity at sub-zero temperatures to efficiently separate CO_2 from flue gas. Current testing is focused on development and scaleup of the novel PI-2 membrane material featuring significantly higher CO_2 flux than commercially available material. The PI-2 module achieved 10 times the normalized CO_2 permeance of the commercial module. This improvement dramatically decreases the module count for a commercial power plant and results in significant capital cost reductions. Air Liquide plans on continued testing at the site.

Carbon Capture Sorbents

SRI International (SRI) Sorbent—The SRI bench-scale sorbent process using carbon microbead sorbents offers several advantages, including low heat requirements, high CO_2 adsorption capacity and excellent selectivity. During operation at the National Carbon Capture Center, performance indicators were lower than expected based on previous testing of SRI's smaller unit at the University of Toledo, with CO_2 capture efficiency at 70 percent and the CO_2 outlet concentration at 93 percent. Design modifications and process optimization are expected to improve performance and increase the capture rate to the targeted value of 90 percent. However, SRI does not currently have plans for further testing at the site.

DOE Sorbents—Researchers from NETL's Research and Innovation Center operated a bench-scale sorbent unit at the National Carbon Capture Center to evaluate accumulation of trace elements and sorbent degradation with silica-supported amine sorbents. The unit operated in circulating and batch modes, with post-test thermogravimetric analysis of sorbent samples showing no permanent loss of carbon capture capacity. Following testing at the center, NETL continued sorbent work to improve material characteristics, although the group's current carbon capture work is focused on membrane material development.

TDA Research Alkalized Alumina Sorbent—TDA is developing a carbon capture process using dry, alkalized alumina sorbent, featuring low cost, low heat of adsorption and capability of near-isothermal, low-pressure operation to achieve lower regeneration energy than solvent-based processes. Formal testing of the small pilot-scale sorbent system will be conducted through early 2019.

Gasification and Pre-Combustion Carbon Capture

As part of its original mission—accelerating the commercialization of advanced technologies to enable fossil fuel-based power plants to achieve near-zero emissions—the National Carbon Capture Center evaluated gasification and pre-combustion carbon capture processes to support the development of next-generation power generation. More than 50,000 hours of technology testing was achieved utilizing syngas generated from the center's Transport Gasifier to evaluate low-carbon energy options and processes to improve the environmental and reliability aspects of gasification. In many cases, testing led to scale-ups and process intensification. These two areas of testing continued through 2017, when test priorities changed to focus more on post-combustion carbon capture for natural gas and coal power plants.

Gasification technology testing focused on the following categories.

- Biomass co-gasification to reduce the carbon footprint of gasification-based power systems
- Sensors and instrumentation for assisting in process control systems
- Syngas utilization, involving projects to convert coal-derived syngas into liquid fuels and hydrogen
- Syngas conditioning, including processes for gas cleaning and facilitating downstream carbon capture

Pre-combustion carbon capture development addressed key challenges—improving capacity, efficiency, robustness of materials, gas selectivity, footprint and costs—involved in the major processes common to post-combustion carbon capture, which include solvents, membranes and sorbents.

Biomass Co-Gasification

The National Carbon Capture Center conducted two gasifier runs with biomass testing to support the DOE goal of development of gasification technologies for the conversion of biomass into clean, sustainable energy and other products. With the gasifier feed consisting of 20 weight percent (wt%) raw, pelletized wood biomass and 80 wt% Powder River Basin (PRB) coal or Mississippi lignite, carbon conversions ranged from 97 to 99.9 percent, with stable operation of the entire gasifier train.

Connecticut Center for Advanced Technology (CCAT) Biomass Operation—Another run with biomass was conducted while operating the gasifier in oxygen-blown mode on behalf of CCAT, which received funding through the Department of Defense as part of the department's initiative to develop domestic, renewable feedstock for liquid fuel production. Using both raw and torrefied (heat treated) biomass at concentrations ranging from 10 to 30 wt% of the total feed rate, carbon conversion ranged from 97.6 to 98.7 percent. Using data from this test and tests at other facilities, the CCAT team produced a study concluding that blending various grades of coal

> *"The National Carbon Capture Center's facilities are recognized internationally as playing a vital role in accelerating the commercial application of carbon capture technologies."*
>
> Keith Burnard,
> Senior Technology Analyst
> International Energy Agency

with biomass presents a credible approach for reducing CO_2 emissions and producing liquid fuel, although further cost reductions for associated unit operations are needed.

Sensors and Instrumentation

Stanford University Tunable Diode Laser (TDL)—Stanford University tested the TDL with particulate-free syngas for real-time, in-situ monitoring of water, CO_2, carbon monoxide (CO), methane and gas temperature in a gasification process. Operation was conducted throughout two gasification runs, from startup to shutdown. The TDL data showed excellent agreement with the existing analyzers and in-situ measurements, and the rapid time resolution of the TDL allowed it to capture variations in syngas conditions that were previously not evident. The TDL data was about 30 minutes ahead of the existing gas chromatographs. The success of the TDL sensor campaigns at the National Carbon Capture Center showed that laser absorption sensing is not only possible in engineering-scale gasifiers, but could be an important new diagnostic tool with the potential for new control strategies in future gasifier utilization and development.

NETL Mass Spectrometer—NETL's gas chromatography inductively coupled plasma mass spectrometer (GC-ICPMS) was used for the first time in the field to measure mercury concentrations directly during National Carbon Capture Center testing of the Johnson Matthey mercury sorbent. Although measured mercury levels from the GC-ICPMS were higher than those determined by Environmental Protection Agency Method 29, the results demonstrated the potential to gather real-time data and facilitate control over key parameters.

Emerson Rosemount Sapphire Thermowells—Multiple tests were conducted with Emerson's sapphire thermowells in gasifier service. The thermowells operated reliably in the highly erosive and corrosive environment. Temperature readings with the sapphire thermowell units tracked well with reference thermocouples, but were slightly lower, with the differences at about 3 and 5 percent relative to the reference thermocouples. Emerson is continuing development of the sapphire thermowell.

Syngas Utilization

Southern Research Fischer-Tropsch (F-T) Catalyst and High-Temperature Reformer—The Southern Research F-T catalyst process for converting syngas into liquid fuel eliminates the conventional product upgrading and refining steps and enhances the ability of coal-to-liquids and coal/biomass-to-liquids processes to compete with petroleum-based processes. Following initial testing at the National Carbon Capture Center, Southern Research incorporated a 2-to-1 scale-up of the F-T reactor and began parallel tests of a high-temperature steam reformer. The reformer, operating upstream of the F-T catalyst in a commercial process for syngas pre-conditioning, showed 90 percent methane conversion and greater than 95 percent conversion of tars, with the exit gas containing the desired 2-to-1 hydrogen-to-CO ratio. The F-T catalyst exceeded project goals, achieving 75 percent selectivity for jet fuel-range hydrocarbons, and performing equally well with 100-percent coal feed in the

"The operations at the National Carbon Capture Center provided OSU with vital results for the syngas chemical looping technology. With the success of the pilot plant testing, we are in the process of scaling the technology to a large demonstration unit. We are grateful for the invaluable experience the Southern Company team shared and their support throughout our project."

Andrew Tong, Research Assistant Professor
Ohio State University

> *MHI is now offering the WGS and COS catalyst for commercial deployment thanks to this achievement at the National Carbon Capture Center.*
>
> Shintaro Honjo, Global Research and Innovation General Manager
> Mitsubishi Heavy Industries

facility's gasifier and with 20-percent biomass co-feed. A techno-economic analysis indicated significant capital cost and product cost reductions with the technology, but competition with petroleum-based liquids will require improvements in other major coal- and coal/biomass-to-liquids plant unit operations.

OSU Syngas Chemical Looping (SCL)—OSU is developing a high-pressure syngas-to-hydrogen chemical looping process for effectively converting carbon-based fuels to electricity, hydrogen and/or liquid fuels while simultaneously capturing all the carbon emissions. Employing counter-current moving beds and iron-based composite oxygen carriers under reduction-oxidation conditions, SCL was successfully demonstrated at bench- and sub-pilot-scale, and was tested at the National Carbon Capture Center at a 250-kilowatt (kW) pilot-scale. The testing demonstrated greater than 98 percent conversion of syngas components (CO, methane and hydrogen) in the reducer reactor as well as hydrogen production from the oxidizer reactor during steam injection. The steam injection experiment confirmed that the SCL system is capable of converting syngas and steam into pure hydrogen. OSU is working to continue moving the technology forward.

NETL Solid Oxide Fuel Cell (SOFC)—Because SOFCs produce electricity through an electrochemical reaction as opposed to combustion, they are more efficient and environmentally benign than conventional power generation processes. Operation of NETL's SOFC multi-cell array at the National Carbon Capture Center demonstrated over 450 hours of continuous operation, with over 4,500 cell-hours of data collected and more than 1 kW of power produced. Performance showed remarkable robustness of SOFC materials to trace material exposure as well as acceptable power density given the modest heating value of the supplied syngas. The test represented the longest-duration continuous SOFC test conducted using direct coal syngas as fuel. NETL's SOFC program maintains a diverse portfolio of cell development projects focused on improving electrochemical performance and cell power density, reducing long-term degradation, developing more robust cells and reducing costs.

Syngas Conditioning

Water-Gas Shift (WGS) Catalysts—Studies at the National Carbon Capture Center to optimize WGS catalyst operation showed that CO conversions adequate to facilitate high carbon capture rates can be achieved at lower steam-to-CO molar ratios than those traditionally recommended. Evaluation of the impact of these test results for a commercial 500-MW gasification-based power plant showed the acceptable reduction in steam-to-CO molar ratio (from 2.6 to 1.6) corresponds to a substantial 40-MW increase in net electrical output.

MHI WGS Catalyst—More than 7,500 hours of testing was achieved with a developmental catalyst from MHI to evaluate long-term stability, and results showed no significant degradation of the catalyst. Conversion of CO was typically around 70 percent with syngas produced from PRB coal. Higher conversions of up to 90 percent were achieved while the gasifier operated with lignite, as the higher moisture fuel increased the syngas steam-to-CO ratio. MHI is offering the WGS catalyst commercially.

Johnson Matthey Mercury Sorbent—In collaboration with NETL, Johnson Matthey has been developing a palladium-based sorbent to remove mercury and other trace contaminants, such as arsenic and selenium, at high temperature in coal gasification processes. Compared to low-temperature capture by activated carbon, high-temperature capture of these trace elements retains the high thermal efficiency of coal gasification power generation. With more than 6,000 hours of operation, the sorbent demonstrated between 96 and 100 percent removal of mercury, arsenic and selenium from syngas at 500°F and pressures of 150 to 200 pounds per square inch gauge (psig). The results also show that the sorbent is not only regenerable, but it remains as effective at capturing metals after regeneration. Future work will focus on the use of lower loadings of palladium, as well as the possible removal of other contaminants.

TDA Research Ammonia Sorbent—TDA Research conducted initial testing of a sorbent-based gas clean-up technology to remove ammonia and hydrogen cyanide as well as mercury and other trace metals from syngas at high temperatures in a single process step. The sorbent operates in a regenerable manner to remove ammonia and mercury, while irreversibly absorbing hydrogen cyanide and other contaminants. TDA completed 50 hours of testing and demonstrated greater than 99 percent ammonia removal. TDA was awarded a DOE Small Business Innovation Research Phase IIB option to further develop the sorbent.

MHI Carbonyl Sulfide (COS) Hydrolysis Catalysts—Multiple tests were conducted with MHI's COS hydrolysis catalyst to facilitate sulfur removal from syngas. Testing of the catalyst—which features a honeycomb configuration, high performance at around 570°F and high durability in the presence of halogens—was performed for a total of 4,000 hours, demonstrating long-term stability. The catalyst achieved 80 percent conversion. MHI is continuing development of the catalyst.

Carbon Capture Solvents

Batch Reactor Solvent Testing—In establishing a database of solvent characteristics, National Carbon Capture Center researchers evaluated well-known chemical and physical solvents such as ammonia (used to define solvent testing and sampling techniques), potassium carbonate, potassium prolinate and dimethyl ether of polyethylene glycol (DEPG). In addition to CO_2 absorption characteristics, solvents were evaluated for co-absorption of hydrogen sulfide (H_2S), regeneration characteristics and performance with water addition. Much of the solvent testing supported DOE studies at the University of Pittsburgh.

"The National Carbon Capture Center has an excellent operations and support staff who often went out of their way to accommodate our needs of pilot operation and data collection. Their timely support was vital to the successful completion of the project. It was a great experience that helped us propel the CO_2 capture technology further."

Anoop Nagar, Senior Materials Engineer
SRI International

University of Alabama Solvents—The National Carbon Capture Center conducted a series of tests in support of the University of Alabama's research on alkylimidazoles, a group of low-volatility, low-viscosity liquids as physical solvents for economical CO_2 separation. Results showed the CO_2 capacity was in the range of other physical solvents tested previously, and regeneration of the solvent renewed its CO_2 capacity but not that of H_2S. The university is continuing solvent research.

Carbon Clean Solutions Solvent—Testing of CCSL's CO_2 solvent showed it compared favorably with the commercially used solvents MDEA and DEPG, achieving significantly higher CO_2 loading. Using the vapor-liquid equilibrium test data, CCSL estimated that the heat of reaction for the CCSL solvent was 39.2 kilojoule per mole CO_2, 20 percent lower than that of MDEA.

Air Products Pressure-Swing Adsorption (PSA)—Air Products designed an alternative to acid gas removal with physical solvents that consists of two process blocks: PSA that separates CO_2 and H_2S from the desired products, and a tailgas disposition block that separates the sulfur-containing compounds and purifies the CO_2 to a sequestration-grade product. During testing, the PSA system separated more than 95 percent of the CO_2 and 99.7 percent of the H_2S in the feed gas, and post-test evaluations indicated the adsorbent material maintained its capacity. Air Products is continuing independent development of the pressure-swing adsorption process as a carbon capture solution applicable to a wide range of gasification technologies, including power plants and hydrogen fuel production.

SRI International Solvent and Bechtel Pressure-Swing Claus Processes—SRI's ammonium carbonate-ammonium bicarbonate (AC-ABC) solvent process features high capacity for CO_2 and H_2S, high regeneration pressure (which lessens downstream compression requirements) and thermal stability of the regenerated solvent solution. Operation of SRI's pilot-scale system demonstrated greater than 99 percent capture of CO_2 and H_2S, and regeneration of high-purity CO_2 and H_2S at pressure. The downstream Claus system showed a conversion of more than 99.5 percent of H_2S gas to elemental sulfur, with H_2S in the product gas at ppm levels. SRI is pursuing ways to continue development of the AC-ABC solvent process.

Gas Separation Membranes

MTR Proteus™ Hydrogen and Polaris™ CO_2 Membranes—Both CO_2- and hydrogen-selective membranes offer potentially high-efficiency gas separation in various gasification applications. A dual-membrane design concept developed by MTR, which combines high-temperature hydrogen- and CO_2-selective membranes, may offer significant cost and energy savings over conventional acid gas removal. Development of MTR's membranes led to several scale-ups of both membrane types and the demonstration of a pilot-scale membrane-assisted CO_2 liquifaction process. The membranes are being operated in a biowaste-to-ethanol process and in a gas-to-liquids process.

Media & Process Technology (MPT) Carbon Molecular Sieve (CMS) and Palladium-Based Hydrogen Membranes—Through testing at the National Carbon Capture Center, MPT successfully scaled up its CMS from single tubes to a full-scale 86-tube bundle. MPT also incorporated WGS functionality into the CMS bundle to produce a catalytic membrane reactor, providing separation

of hydrogen simultaneously with its formation. Test results validated the membrane's high stability in the presence of aggressive gas-phase contaminants such as sulfur- and nitrogen-based species, allowing it to operate with untreated syngas. Treatment of the desulfurized permeate stream with MTR's palladium membrane achieved 99 percent hydrogen purity.

SRI Polybenzimidazole (PBI) Hydrogen Membranes—SRI conducted the first syngas testing of a hydrogen membrane fabricated with spun hollow fibers of the temperature- and chemical-resistant polymer PBI. Testing confirmed that greater than 90 percent recovery of CO_2 is possible at temperatures above 375°F.

Worcester Polytechnic Insitute Palladium-Based Hydrogen Membranes—WPI's membrane testing led to a seven-fold scale-up, and with only 1 percent deviation in thickness among the tubes, the consistent fabrication of the membranes demonstrated the replicability of the technology. Syngas operation demonstrated material robustness and steady permeance values, with hydrogen product purity as high as 99.9 percent.

Eltron Hydrogen Transport Membrane (HTM)—Eltron's HTM uses a multi-layer metal alloy tube for hydrogen separation at high pressures typical of gasification environments. Testing showed the membrane to be capable of producing 99.9 percent pure hydrogen, and the module was in good condition following testing.

Carbon Capture Sorbents

TDA Research Sorbents— TDA Research's testing of a solid CO_2 sorbent at the National Carbon Capture Center consistently demonstrated the capability to remove more than 90 percent CO_2. TDA also tested a combined WGS/CO_2 sorbent system with an innovative heat management component. When parameters were adjusted to achieve 90 percent CO conversion in the WGS stage, the overall carbon capture rate was greater than 95 percent. TDA scaled up testing from bench- to small pilot-scale with a 0.1-MW CO_2 sorbent (without WGS) process, again demonstrating high CO_2 capture and stable operation. After tests at the center, TDA began testing the 0.1-MW system at China's Sinopec facility.

"*National Carbon Capture Center testing has allowed optimization and scale-up of Proteus and Polaris membranes in a real-world syngas environment. Lessons learned show the importance of testing with real gases … the center's tests have provided confidence to pursue industrial pilots.*"

Tim Merkel, R&D Director
Membrane Technology & Research

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