National Carbon Capture Center

Topical Report
Budget Period 7

Reporting Period: October 1, 2021 – September 30, 2022
Project Period: June 6, 2014 – September 30, 2025

DOE Cooperative Agreement
DE-FE0022596

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Abstract

Sponsored by the U.S. Department of Energy (DOE), the National Carbon Capture Center (NCCC) is a cornerstone of U.S. innovation in the research and development of cost-effective, technically viable carbon capture and conversion technologies. Bridging the gap between laboratory research and large-scale demonstrations, the center evaluates carbon capture processes from third-party developers, focusing on the early-stage development of the most promising technologies for future commercial deployment.

The NCCC includes multiple slipstream units that allow the development of carbon dioxide (CO_2) reduction concepts using fossil fuel-derived flue gas in industrial settings. Because of the ability to operate under a wide range of flow rates and process conditions, research at the NCCC can effectively evaluate technologies at various levels of maturity and accelerate their development to commercialization.

During the Budget Period 7 (BP7) reporting period, spanning from October 1, 2021, through September 30, 2022, efforts at the NCCC focused on post-combustion carbon capture and conversion technology development. Testing was conducted with membrane, solvent, catalyst, and sorbent technologies during three test runs, and several improvements were made to the site to enhance testing capabilities.

Acknowledgement

The authors wish to acknowledge the contributions and support provided by DOE project manager Brian A. "Andy" O'Palko. We would also like to thank our co-funding partners: American Electric Power, BP, ClearPath, Electric Power Research Institute, ExxonMobil, National Rural Electric Cooperative Association, Peabody Energy, Tennessee Valley Authority, TotalEnergies, and Wyoming Integrated Test Center. The material in this report is based upon work supported by the DOE under award DE-FE0022596. However, any opinions, findings, conclusions, or recommendations expressed herein are those of the authors and do not necessarily reflect the views of the DOE.

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List of Abbreviations

AFS	Advanced Flash Stripper
aMDEA	Activated methyl diethanolamine
BP7	Budget Period 7
BP8	Budget Period 8
CO_2	Carbon dioxide
DOE	Department of Energy
GPU	Gas permeation unit, where 1 GPU = 10^{-6} $cm^3/(cm^2\ s\ cm\ Hg)$ at standard temperature and pressure
LSTU	Lab-Scale Test Unit
MEA	Monoethanol Amine
NCCC	National Carbon Capture Center
NGCC	Natural gas combined-cycle
NETL	National Energy Technology Laboratory
OSU	Ohio State University
PCI	Precision Combustion Inc.
PO-11	Post-Combustion Run 11
PO-12	Post-Combustion Run 12
PO-13	Post-Combustion Run 13
PSTU	Pilot Solvent Test Unit
SSTU	Slipstream Solvent Test Unit
UCLA	University of California, Los Angeles
UT-Austin	University of Texas at Austin

1.0 EXECUTIVE SUMMARY

Sponsored by the U.S. Department of Energy (DOE), the National Carbon Capture Center (NCCC) is a world-class neutral research facility working to advance innovative fossil energy technology solutions. Bridging the gap between laboratory research and large-scale demonstrations, the NCCC 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.

The NCCC has achieved more than 130,000 hours of testing, successfully advancing a wide range of technologies toward commercial scale while improving their performance and reducing cost. The NCCC testing of 74 technologies from more than 45 developers has already confirmed the reduction of the projected cost of CO_2 capture by approximately 40% with real-world data points. Additional cost savings are likely in the future as the center continues to focus on transformational approaches to CO_2 capture.

1.1 Project Partnerships

The DOE Office of Fossil Energy's National Energy Technology Laboratory (NETL), in cooperation with Southern Company, established the NCCC in 2009 to become a cornerstone for U.S. leadership in advanced clean coal technology development. In a renewed five-year collaborative agreement with DOE, valued at $140 million and effective October 1, 2020, the NCCC formally broadened its evaluation of CO_2 capture technologies for natural gas power generation and added testing of CO_2 conversion systems and CO_2 removal technologies such as direct air capture.

Since the NCCC is a cost-shared corroborative research and development venture, private-sector partners provide funding and act in an industrial advisory capacity. The NCCC is active in partnering with these private-sector entities.

1.2 Reporting Period

This report covers the work performed during Budget Period 7 (BP7) of the NCCC's second cooperative agreement with DOE, DE-FE0022596, covering October 1, 2021, through September 30, 2022.

1.3 Test Facilities

The NCCC provides test facilities and wide-ranging support to researchers developing lower-cost carbon capture technologies that will enable fossil fuel-based power generation to remain a key contributor to the energy mix in a net-zero environment. The facilities accommodate a range of equipment sizes and operating conditions and provide commercially representative settings that allow results to be scaled confidently to commercial application, a crucial element in shortening development times. Flue gas used for technology testing is derived from a commercially dispatched supercritical pulverized coal unit and from a natural gas boiler.

The site accommodates solvent testing with the Pilot Solvent Test Unit (PSTU) and the bench-scale Slipstream Solvent Test Unit (SSTU), as well as technology developer units in pilot bays, bench-scale bays, and the Lab-Scale Test Unit (LSTU).

1.4 Accomplishments

During the reporting period, the NCCC supported carbon capture and conversion projects and provided testing opportunities with three test runs:

- Run PO-11, beginning in BP6 on June 1, 2021, and ending on December 1, 2021
- Run PO-12, occurring from February 24, 2022, through July 31, 2022
- Run PO-13, starting on August 1, 2022, and continuing into Budget Period 8 (BP8)

Table 1 lists the technology developer projects tested during the reporting period, as well as those currently being developed for testing in 2023. New projects that are planned for testing in 2023 or later but are not yet in the NCCC's engineering support phase are listed in Section 1.5. In addition to supporting the projects listed in the table below, the NCCC conducted solvent baseline testing with its PSTU to enhance performance and data analysis capabilities for solvent developers.

Table 1. Projects Tested and Under Development During Budget Period 7

	Venue/ Scale	Tested in Run PO-11	Tested in Run PO-12	Tested in / Planned for Run PO-13	Planned for 2023
CO_2 Capture Projects					
GTI Energy membrane contactor	Pilot-scale	✓	✓		
TDA Research alkalized alumina sorbent	Pilot-scale	✓			
ION Clean Energy ICE-31 solvent	PSTU	✓			
University of Texas at Austin (UT-Austin) PZAS™ process	PSTU			✓	✓
Susteon ionic liquid catalyst	PSTU			✓	
Carbon America FrostCC process	Pilot-scale				✓
GTI Energy ROTA-CAP™ rotating packed bed solvent process	Bench-scale	✓	✓	✓	✓
Carbon Clean solvent for ROTA-CAP process	SSTU	✓			
Altex Technologies sorbent process intensification	LSTU				✓
NETL membrane materials	LSTU			✓	✓
Ohio State University (OSU) membrane	LSTU			✓	
Precision Combustion Inc. (PCI) Microlith sorbent	LSTU		✓		

	Venue/ Scale	Tested in Run PO-11	Tested in Run PO-12	Tested in / Planned for Run PO-13	Planned for 2023
GTI Energy graphene oxide-based membrane	LSTU				✓
EPRI/Pacific Northwest National Laboratory/RTI International water-lean solvent	PSTU				✓
MEA baseline testing	PSTU	✓	✓		
CO_2 Conversion Projects					
Southern Research ethane-to-ethylene process	Bench-scale	✓			
Helios-NRG algae for CO_2 conversion	Bench-scale		✓	✓	
Texas A&M algae for CO_2 conversion	Bench-scale				✓

Highlights of the current technology developer projects are described below.

GTI Energy Hollow Fiber Membrane Contactor

GTI is continuing development of a hollow fiber gas-liquid membrane contactor to replace conventional packed bed columns in solvent systems to improve CO_2 absorption and desorption efficiency. The membrane contactor test campaign began in 2017 and concluded in March 2022 for a total of more than 3,000 hours on both coal and natural gas flue gases. The system achieved a 90% CO_2 removal rate using 50 wt% activated methyl diethanolamine (aMDEA) solvent during the initial tests with four modules and actual coal-fired flue gas. However, continuous testing with 28 membrane modules did not match the single module results; the CO_2 capture performance declined with time. Further improvements in materials and manufacturing are needed for future project development.

TDA Research Alkalized Alumina Sorbent

TDA is developing a CO_2 capture process using a low-cost alkalized alumina sorbent. Building on previous testing at the site, TDA completed over 1,800 hours of long-term testing in October 2021, marking the end of this phase of the project. The process met TDA's success criteria of greater than 90% CO_2 capture and more than 95% CO_2 product purity with both natural gas and coal flue gases. Testing demonstrated low heats of adsorption and near-isothermal operation at up to 150°C (302°F). TDA's modified sorbent demonstrated high stability over the three-month test period. TDA will update a techno-economic analysis based on the test data.

ION Clean Energy ICE-31 Solvent

ION completed a six-month testing campaign with the ICE-31 solvent in October 2021. The ICE-31 campaign at the NCCC lasted for over 4,000 hours including parametric and long-term steady-state testing using natural gas combined-cycle (NGCC) surrogate flue gas (4.4% CO_2), gas-fired boiler gas (7.8% CO_2), and coal-fired flue gas (13% CO_2). ION demonstrated 95% CO_2 capture on all three flue gases, achieved steady-state capture efficiencies of up to 98% with NGCC flue gas, and reached over 99% capture during dynamic operations. Using the Advanced Flash Stripper (AFS) configuration, ION demonstrated a minimum specific reboiler duty of

2.6 GJ/tCO_2 at 91% CO_2 capture for NGCC flue gas with a slight increase to 2.7 GJ/tCO_2 at 97% capture. ION plans to continue to advance the commercial readiness of ICE-31 with future pilot demonstrations.

UT-Austin PZAS Process

Since performing previous successful test campaigns at the site with the PZAS process featuring the AFS and piperazine solvent in the PSTU, UT-Austin plans to conduct another test campaign combining multiple objectives focusing on degradation studies beginning in December 2022. The NCCC completed several modifications to accommodate the testing, including the addition of a flue gas heater, a new hot-rich bypass on the AFS skid, carbon filter upgrades, and a new two-stage water and acid wash configuration.

Susteon Ionic Catalyst

Susteon is developing an ionic liquid catalyst designed to improve reaction kinetics of CO_2 absorption and desorption when added to amine-based solvent. Testing began in August 2022 using 30% MEA solvent without the catalyst to establish reference performance. Parametric tests with diluted (4.4% CO_2) and undiluted (9.8% CO_2) NCCC boiler flue gas were completed. The catalyst was then added, and the parametric test matrix was repeated. The test campaign concluded in September 2022, with 680 operating hours achieved. Data analysis is underway.

Carbon America FrostCC Process

Carbon America is developing the FrostCC cryogenic process to remove CO_2 from typical industrial flue gases. The process is designed to compress and expand the flue gas stream with proper heat integration, producing near-pure solid CO_2. The Carbon America team plans to begin testing in the second quarter of 2023.

GTI Energy ROTA-CAP Solvent Process

GTI's process features the ROTA-CAP rotating packed bed gas-liquid contacting device to replace conventional packed bed columns for CO_2 absorption and regeneration using an intensive solvent from Carbon Clean. After completing parametric studies and long-term operation, GTI concluded a test campaign in August 2022 while focusing on comparative performance for the rotating packed bed technology across various solvent formulations, including Carbon Clean's CDRMax™, MEA, and aMDEA. Testing was carried out with flue gas CO_2 concentrations ranging from 4 to 22%, solvent concentrations ranging from 35 to 55%, and CO_2 capture efficiencies up to 90%. GTI began reviewing the data and considering alternative approaches for further evaluation of the technology.

Carbon Clean Solvent for GTI Energy ROTA-CAP Process

Evaluation of the Carbon Clean solvent in the SSTU was completed in November 2021. This test campaign entailed various process conditions exploring the impacts of solvent concentration and liquid and gas flow on overall system performance, using both coal-derived and natural gas-derived flue gases in a conventional packed-bed column. The solvent testing provided critical comparison points for testing of the ROTA-CAP skid.

Altex Technologies Sorbent Process Intensification

The Altex bench-scale project will employ a prototype of the Compact Rapid Cycling CO_2 Capture system using a heat exchanger coated with Penn State's high-capacity, high-selectivity molecular basket sorbents. Preparations have been underway for testing in 2023.

NETL Membrane Materials

The NETL membrane development program is working to reduce the costs of post-combustion carbon capture by creating transformational membrane materials with high permeability and CO_2 selectivity. The team has continued preparing new membrane samples for testing based on previous efforts to optimize membrane performance and integrity. Operation will resume in late 2022, with at least five membrane coupons to be tested over the next year.

Ohio State University Lab-Scale Membranes

OSU is developing a novel polymeric composite membrane to capture 60 to 90% CO_2 from flue gas. The membranes are designed to achieve high CO_2 permeance of over 3,300 gas permeation units (GPU, where 1 GPU = 10^{-6} cm^3/(cm2 s cm Hg)) and more than 140 CO_2/nitrogen selectivity at 77°C. The membranes were fabricated in spiral-wound modules of eight-inch diameter and 20 feet long and tested at the OSU lab using simulated flue gas. Flue gas testing at the NCCC will begin in November 2022.

Precision Combustion Inc. Microlith Sorbent

PCI is developing a modular post-combustion carbon capture system utilizing metal-organic framework nanosorbents supported on a Microlith mesh substrate. In May 2022, PCI conducted a test campaign with flue gas from the natural gas boiler. Multiple test conditions were achieved to measure the efficiency of the contactor and the sorbent performance. The sorbent was stable thorough the duration of the test and proved to be resistant to effects of humidity and contaminants.

GTI Energy Graphene Oxide-Based Membrane

GTI is preparing to test a carbon capture process using GO-1 and GO-2 membranes in a two-stage configuration (GO^2 process) to demonstrate its performance with both natural gas- and coal-derived flue gases at the NCCC in 2023.

EPRI/Pacific Northwest National Laboratory/RTI International Water-Lean Solvent

EPRI is working with Pacific Northwest National Laboratory and RTI International to scale up a water-lean solvent for CO_2 capture. In this project, the NCCC will work with EPRI and its team to modify the PSTU design to achieve the desired process conditions for operation with this solvent. The test campaign is scheduled for 2023 and will use both coal- and natural gas-derived flue gases.

MEA Baseline Testing in the PSTU

MEA baseline testing began in November 2021 and ended in July 2022, with 2,678 test hours achieved using coal and natural flue gases and two configurations for solvent regeneration—the simple stripper and the Advanced Flash Stripper. The new baseline performance data will serve as a reference for future solvent developers.

Southern Research Ethane-to-Ethylene Process

Southern Research is developing a technology for thermo-catalytic ethylene production using ethane and CO_2. Southern Research conducted the test campaign from August through December 2021, achieving 1,600 hours of operation using captured CO_2 and flue gas. Results showed that catalyst performance using captured CO_2 was comparable with results observed in the laboratory, achieving 35 to 40% single-pass conversion of ethane with monetizable productivity of ethylene, carbon monoxide, and hydrogen.

Helios-NRG Algae for CO_2 Conversion

Helios-NRG is developing a process to convert CO_2 to algae biomass that can be used to create value-added products, such as nutraceuticals. This is achieved using three key technologies: (1) algae cultivation with high productivity and robust performance in a flue gas environment, (2) energy-efficient algae dewatering, and (3) final product creation. Testing at the NCCC was performed from June to September 2022.

Texas A&M Algae for CO_2 Conversion

Texas A&M AgriLife Research is developing an integrated process with sorbent-based CO_2 capture and algae-based technologies to produce value-added products and biomass at ultra-high yield and low costs. The project features (1) a synthetic biology design to trigger auto-sedimentation of algal cells with high solid load for continuous cultivation by periodic auto-cell removal/harvesting, (2) a sorbent that allows CO_2 storage overnight with controlled release during daytime cultures, and (3) hydrogel-based phosphate, ammonia, and bicarbonate controlled delivery to enhance algae productivity and reduce CO_2 loss from flue gas. The NCCC will follow the development of this project and help the project team prepare for field testing at the site in 2023.

Site Modifications

Progress continued on several projects for enhancing testing capabilities and improving site conditions.

- Moisture measurement installation on the natural gas boiler flue gas header
- Sump and waste handling improvement
- PSTU solvent filter improvement
- Control system modifications for lock-out test/try
- Instrument air improvements
- PSTU steam condensate flow meter improvements
- Natural gas system reliability upgrades
- Computer modeling of flue gas and solvent systems

1.5 Future Test Plans

New projects confirmed for testing at the site in 2023 or later include the first direct air capture project for the NCCC—Southern States Energy Board solid-amine absorption/desorption contactor—and the carbon capture and conversion technologies listed below.

- State University of New York at Buffalo membrane
- Membrane Technology & Research membrane
- State University of New York at Buffalo sorbent
- Clean Energy Research Institute solvent in the PSTU
- UCLA concrete technology
- Helios NRG algae process
- Cormetech sorbent
- Innosepra direct air capture
- Helios-NRG membrane in the LSTU
- University of Sheffield MEA solvent in PSTU

2.0 TEST FACILITIES

The NCCC provides test facilities and wide-ranging support to researchers developing lower-cost carbon capture technologies that will enable fossil fuel-based power generation to remain a key contributor to the energy mix. The facilities, shown in Figure 1, accommodate a range of equipment sizes and operating conditions and provide commercially representative settings that allow results to be scaled confidently to commercial application, a crucial element in shortening development times. Flue gas used for technology testing is derived from a commercially dispatched supercritical pulverized coal unit and from the NCCC's natural gas testing infrastructure.

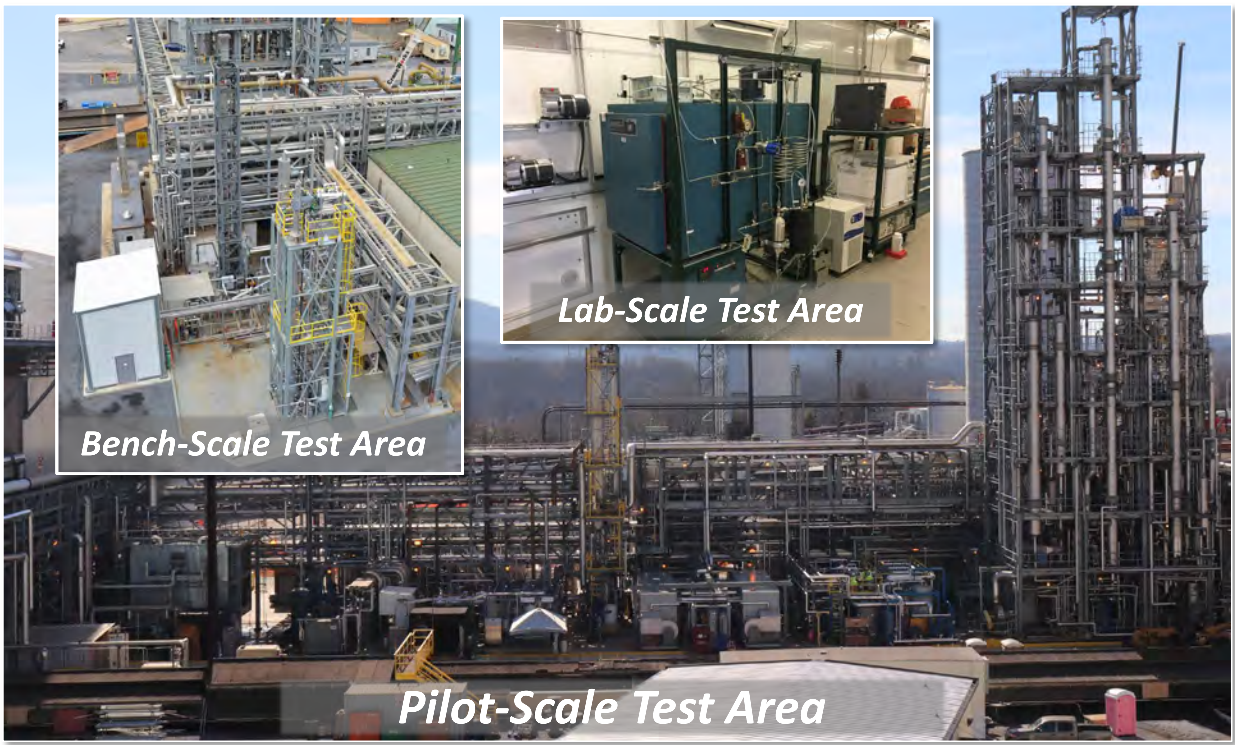

Figure 1. Photographs of Post-Combustion Carbon Capture Test Facilities

The commercial unit supplying coal-derived flue gas, Alabama Power's Plant Gaston Unit 5, meets all environmental requirements through state-of-the-art controls. These include a selective catalytic reduction unit to decrease nitrogen oxides, sodium bicarbonate injection to control sulfur trioxide emissions, hot-side electrostatic precipitators, a baghouse for particulate and mercury control, and a wet flue gas desulfurization unit to control sulfur dioxide emissions. Thus, the flue gas extracted for testing is fully representative of commercial conditions. Up to 35,000 lb/hr of flue gas is extracted downstream of the Unit 5 desulfurization unit and is utilized for testing.

A dedicated natural gas-fired boiler supplies flue gas containing 4% to 10% CO_2, depending on the amount of dilution air added. Commissioned in early 2021, this addition allows the NCCC to simulate flue gas from a conventional natural gas combined-cycle plant. The natural gas test system also creates operational independence from Plant Gaston, increases operational flexibility and available testing time, and supplies a contaminant-free flue gas source to allow testing of new technologies on both natural gas- and coal-derived flue gas.

As illustrated in Figure 2, the site accommodates solvent testing with the PSTU and the bench-scale SSTU, as well as technology developer units in pilot bays, bench-scale bays, and the LSTU. The site includes an independent control room, electrical infrastructure, and a balance-of-plant area containing utilities and chemical storage/handling facilities.

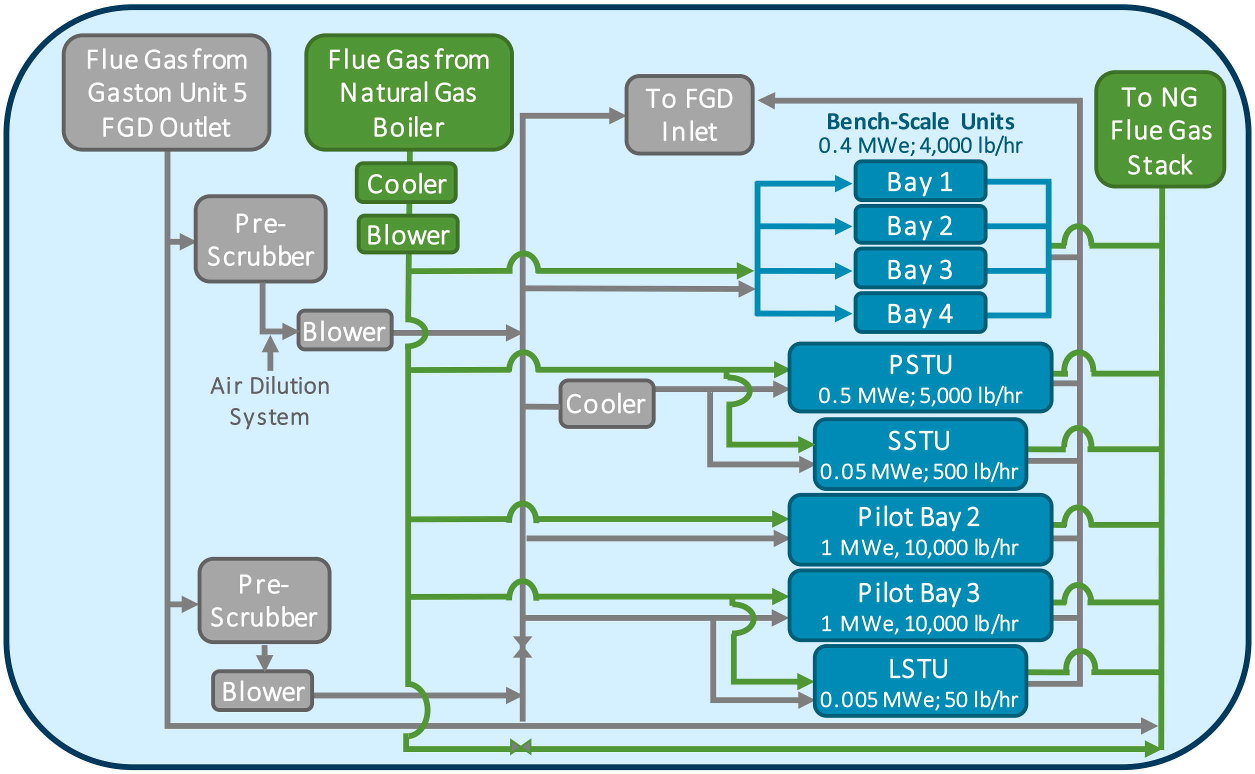

Figure 2. Schematic of Flue Gas Distribution at NCCC Test Facilities

3.0 TECHNICAL PROGRESS

During the reporting period, the NCCC supported multiple carbon capture and conversion projects and provided testing opportunities during three test runs:

- Run PO-11, beginning in BP6 on June 1, 2021, and ending on December 1, 2021
- Run PO-12, occurring from February 24, 2022, through July 31, 2022
- Run PO-13, starting on August 1, 2022, and continuing into Budget Period 8 (BP8)

The following sections describe the current projects at the site.

3.1 CO_2 Capture Projects

3.1.1 GTI Energy Membrane Contactor

GTI Energy, under DOE funding, is developing a hollow fiber gas-liquid membrane contactor to replace conventional packed bed columns to improve CO_2 absorption and desorption efficiency. It is a hybrid system that combines the advantages of membrane gas separation and solvent absorption mechanisms. The use of a hollow fiber membrane configuration provides five to 10 times higher gas/liquid contacting surface area than a conventional packed bed column, which could offer significant capital cost reductions. GTI tested the technology with a small pilot-scale, 0.5-MW process installed at the NCCC. Figure 3 provides a photograph of the installed equipment.

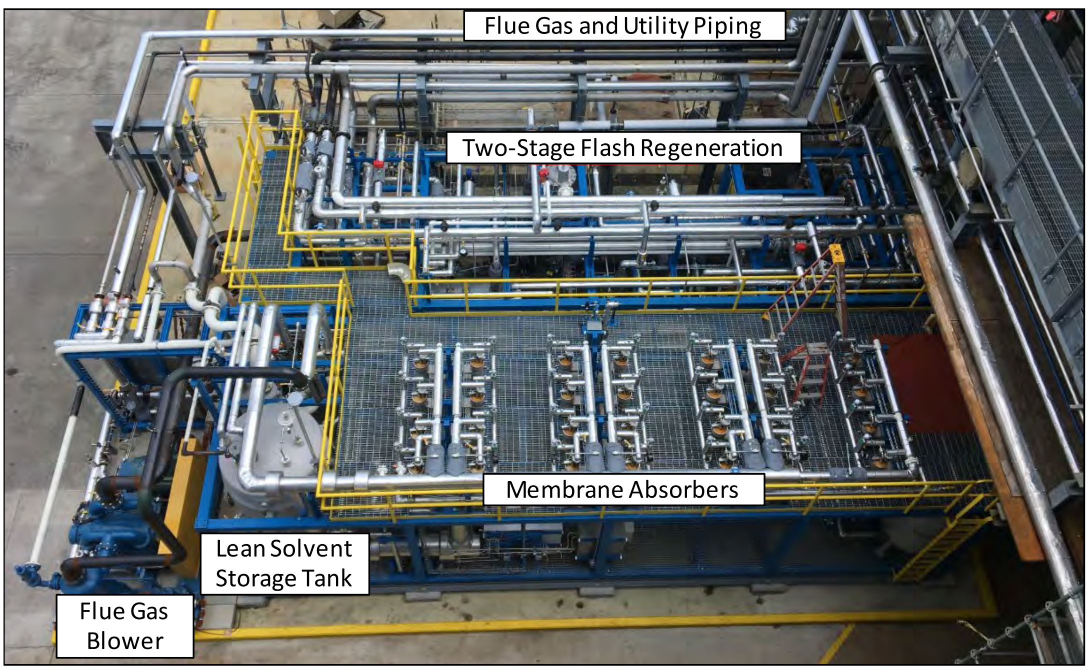

Figure 3. GTI Energy Membrane Contactor

The membrane contactor test campaign began in 2017 and concluded in March 2022 for a total of more than 3,000 hours on both coal and natural gas flue gases. The main events from the campaign are described below.

A 90% CO_2 removal rate was achieved by the system using 50 wt% aMDEA solvent during the initial tests with four modules and coal-fired flue gas at NCCC. The stripped stream from the two-stage flash desorber had a CO_2 concentration of more than 98.6 vol%. Further tests indicated an issue of liquid-side concentration polarization, i.e., higher CO_2 concentration in the fluid boundary layer (next to the fiber) relative to the bulk flow stream. This issue was resolved by decreasing the aMDEA concentration from 50 to 35 wt%.

Parametric tests were then conducted to investigate the effects of flue gas temperature, solvent temperature, flue gas feed pressure, and solvent flow velocity on CO_2 capture performance. Based on the parametric testing, the operating conditions for full-scale (28 modules) and two-month continuous testing were determined.

Continuous testing with 28 membrane modules, however, did not match the single module results; the CO_2 capture performance declined with time. Quantitative analysis as well as inspection and measurements of the spent modules were conducted to investigate the potential causes. The major issue identified was the tubesheet leaking from patch points and potentially from fiber/epoxy separation due to non-uniform bonding. Corrective actions addressing cartridge shortcomings were incorporated into the fabrication of four membrane modules that were tested at the NCCC. The results indicated that the decline trends for CO_2 removal rate and CO_2 removal flux were identical to those of the previous tests conducted in 2018 and 2021.

Analysis of the fiber and tubesheet identified no specific defects or any loss in hydrophobicity of the super-hydrophobic coating that could directly be attributed to the liquid leakage seen during the field operation. Tubesheet leaking, while smaller in size (volumetrically) than previously tested contactors, was evident. The lack of improvement of the CO_2 capture performance and stability of this performance indicated that not all leak paths were addressed and/or additional mechanisms were responsible for it. Moving forward, technical hurdles in materials and manufacturing will need to be resolved in a bench-scale program.

3.1.2 TDA Alkalized Alumina Sorbent

TDA is developing a CO_2 capture process using dry, alkalized alumina sorbent. TDA's process uses counter-current operation to maximize capture efficiency and sorbent loading, operates at near-isothermal conditions (at 140 to 160°C) and ambient pressure, and achieves sorbent regeneration with low-pressure steam. TDA's test equipment, including two reactor skids and a service skid, shown in Figure 4, was installed at the NCCC in October 2017. Testing concluded in October 2021 for a total of 2,900 hours on both coal and natural gas flue gases.

Figure 4. TDA Research Alkalized Alumina Sorbent Process

After the equipment was installed and the sorbent was loaded into the reactors, TDA found the sorbent was manufactured incorrectly at the factory of TDA's partner. The lab test showed the sorbent had good performance initially, but it lacked long-term stability. Further characterization tests determined the sorbent contained unreacted raw materials, which led to the lack of stability. TDA worked with a partner to develop a sorbent reprocessing procedure, and the original sorbent was extracted from the 10 pilot reactors and reprocessed in 2018. Due to unavoidable volume loss in the sorbent reprocessing, only eight reactors were filled with reprocessed sorbent. Beds 1 and 2 were loaded with Dynocel, which is based on a commercial sorbent but modified using a process developed at TDA that improves its performance.

To hydrate the fresh sorbent, TDA developed a procedure to flow hot humid air though the bed where the water content gradually increased from 0.4 mol% to 100 mol%. This procedure controlled the temperature rise during the exothermic hydration in the reactors.

The 2019 pilot test showed the significant benefits of the purge and steam saver steps in the TDA process. A CO_2 capture rate of 90% with 95% CO_2 purity were achieved for both coal and natural gas flue gases. The test campaign was paused in October 2019 due to a plant outage. In late January 2020, it was found the sorbent had changed into a different form and had much lower capture capacity than before the 3.5-month shutdown.

The compromised sorbent was extracted, and fresh sorbent was loaded in the second quarter of 2021. Five beds were loaded with Dynocel and five beds with Chlorocel (a commercial sorbent). Though these two sorbents were not as good as the TDA sorbent developed in the lab, they were the best available options based on the budget and the manufacturer's schedule.

During the pilot test in 2021, the skid successfully met the performance target for flue gas with CO_2 in the range of 4 to 11%. For coal flue gas, the system reached performance targets when processing up to 0.62-MW flue gas, 24% higher than the design capacity. The strip air flow was designed to be 0.25 of that of the flue gas. The test data showed the strip/flue gas ratio can be reduced to as little as 0.18, potentially reducing the power consumption of the strip air blower. The test was concluded in October 2021. Table 2 summarizes the result of the long-term testing.

Table 2. TDA Research Skid Performance During Long-Term Test

Date	Flue Gas Space Velocity, 1/hr	CO_2 Concentration in Flue Gas, wet %	CO_2 Capture Rate	CO_2 Purity
8/25/2021	261	10.9	90.9%	99.2%
9/2/2021	268	4.0	90.4%	99.7%
9/9/2021	264	4.2	93.5%	95.0%
9/23/2021	268	4.2	90.6%	96.3%
9/29/2021	258	4.2	90.2%	99.2%
10/4/2021	260	9.0	90.8%	97.9%
10/12/2021	265	8.9	90.7%	97.2%

After the three-month test, the Dynocel sorbent maintained a 91% CO_2 capture capacity, and the degradation rate reached a plateau. The degradation for the Chlorocel sorbent was much worse, as expected, since it is not designed for use as a long-term carbon capture sorbent. Figure 5 plots the degradation of the two sorbents.

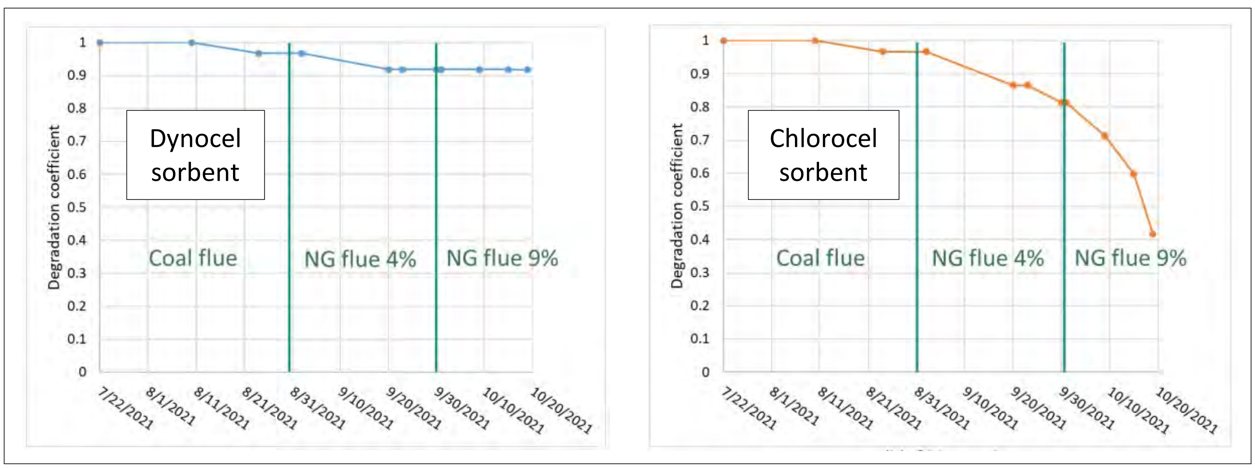

Figure 5. Degradation Plots for Dynocel and Chlorocel Sorbents During Long-Term Test

TDA Research plans to test a new reactor in future studies and demonstrate the technology at a scale equivalent to process flue gas from a 25-MW power generation unit.

3.1.3 ION Clean Energy Solvent

ION is developing and scaling up a novel amine-based solvent technology, ICE-31, which is expected to demonstrate transformational stability and excellent key CO_2 capture performances such as low energy. The project objectives were to confirm the initial findings of the solvent performance on a larger scale at the NCCC and validate the solvent module in the ProTreat® model, which was developed for future operations strategies at any scale. The results will provide key input values to an updated techno-economic analysis for an industrial scale.

The ICE-31 solvent test campaign was conducted from March through October 2021, accumulating over 4,000 hours of operation on coal and natural flue gases using both the PSTU simple stripper and the AFS. The solvent consistently demonstrated 95% CO_2 capture during long-term testing, as shown in Figure 6.

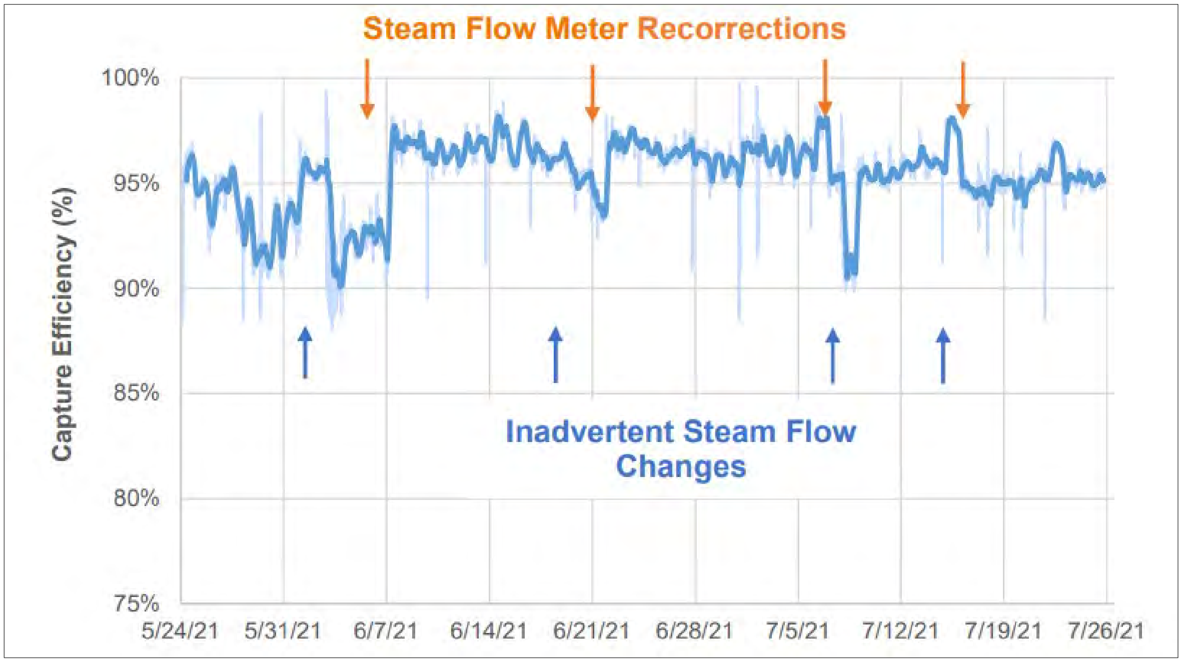

Figure 6. CO_2 Capture Efficiency of ION Clean Energy Solvent During Long-Term Testing

When the capture rate was increased to 98%, a small penalty on specific reboiler duty of 2 to 3% was observed using flue gas representative of that from a NGCC unit. The solvent operation demonstrated 2.6 GJ/tCO_2 at 91% capture for NGCC flue gas and a slight increase of 2.7 GJ/tCO_2 at a 97% capture rate using the AFS configuration. Test data also validated ION's proprietary ProTreat model prediction with an average error of 0.4% ± 1.7%.

In addition, long-term testing demonstrated the stability of the solvent and low emissions for clean flue gas existing the wash tower. Figure 7 plots the mass balance calculated during the testing and provides a photograph of solvent samples taken over the duration of the test campaign. Throughout the campaign, solvent reclamation and solvent make-up were not required, and the overall mass balance for the original solvent components was 99 ± 1%. The solvent's stability was further demonstrated by the emissions monitoring and extractive sampling, with ammonia emissions below the practical detection limit of 1 ppm and solvent emissions below 40 ppb.

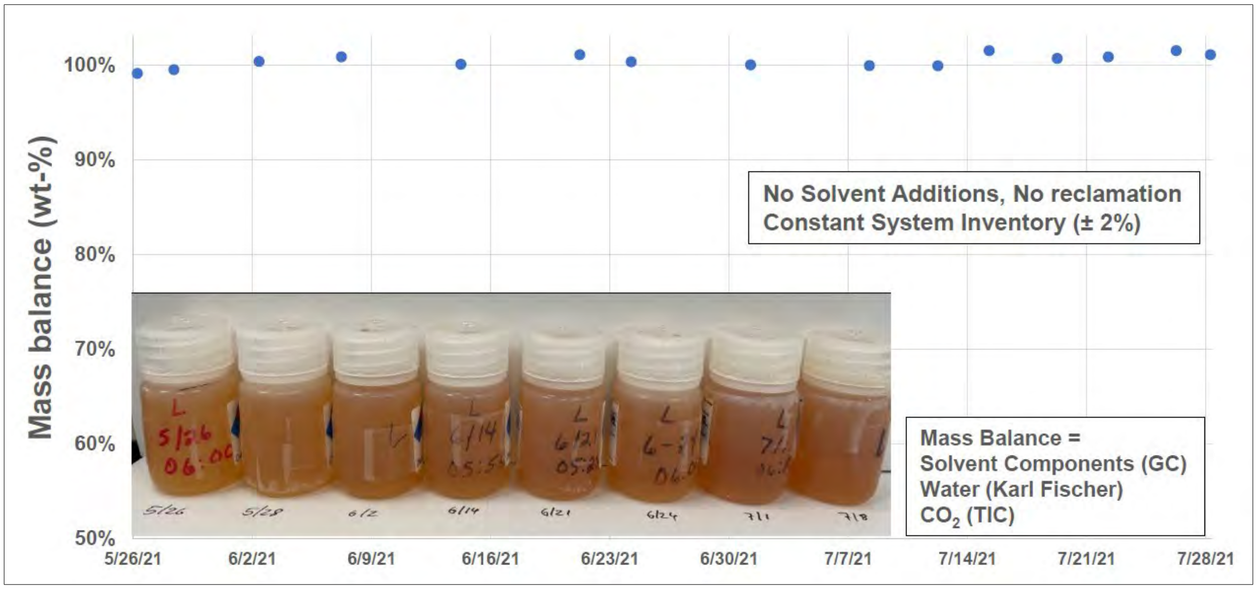

Figure 7. Mass Balance of ION Clean Energy Solvent during Long-Term Testing

ION concluded from the process performance results that ICE-31 is an exceptional solvent for post-combustion carbon capture in general, but more specifically is extremely well suited for high oxygen environments such as NGCC facilities. ION plans to continue to advance the commercial readiness of ICE-31 with future pilot demonstrations.

3.1.4 UT-Austin PZAS Process

UT-Austin is continuing development of the PZAS process using natural gas flue gas to study solvent degradation and oxidation. The six-month test campaign, which is being supported by DOE, EU LAUNCH, and private companies, will entail a study of solvent degradation and oxidation, as well as mitigation measures. In addition, the test will demonstrate that the solvent can take hot flue gas directly from a NGCC plant without cooling.

The NCCC completed several modifications to accommodate the testing, including the addition of a heater to heat the flue gas to 110°C (230°F), a new hot-rich bypass on the AFS skid, carbon filter upgrades, and a new two-stage water and acid wash configuration. Also, seven additional corrosion ports were installed on the PSTU/AFS system to study the solvent corrosion. A new process was designed and implemented for solvent preparation in order to add piperazine solvent to the PSTU from drums of solid piperazine by melting it before pumping it into the system. Operation will begin in late 2022.

3.1.5 Susteon Ionic Catalyst with Amine Solvents

Susteon has developed an ionic liquid catalyst designed to improve reaction kinetics in CO_2 absorption and desorption when added to amine-based solvent. This leads to a reduction in absorber height, desorption temperature and solvent degradation, and hence lower capital and operating expense and lower regeneration energy consumption. The catalyst is also designed to be stable at high temperatures.

Catalyst testing began in August 2022 using 30% MEA solvent without the catalyst to establish reference performance. Parametric tests with diluted (4.4% CO_2) and undiluted (9.8% CO_2) NCCC boiler flue gas were completed. The catalyst was then added, and the parametric test matrix was repeated. The test campaign concluded in September 2022 for a total of 680 operating hours.

While data analysis is ongoing, Susteon's preliminary results listed in Table 3 show the improvement in energy consumption achieved by the catalyst under NGCC and coal-fired flue gas conditions. The catalyst yielded a 5% reduction in energy consumption for the 80% CO_2 capture case with coal flue gas and 11 to 12% reduction in energy consumption for NGCC flue gas. With a constant liquid/gas ratio, the catalyst achieved a 11 to 12% reduction in energy consumption at 90 to 95% CO_2 capture with coal flue gas.

Table 3. Preliminary Results of Susteon Catalyst Test Campaign

Case	Flue Gas CO_2 Concentration, %	CO_2 Capture Rate, %	Liquid/Gas Ratio, mass/mass	Stripper Temperature,°C	Energy consumption (GJ/tonne CO_2)		Improvement (%)
					without catalyst	with catalyst	
NGCC Flue Gas	4.41	82	0.83	119.8	3.96	3.52	11.0
	4.41	80	0.99	118.8	4.01	3.54	11.7
	4.41	81	1.24	118.2	4.10	3.61	11.9
Coal Flue Gas	8.95	81	2.48	117.5	3.72	3.54	4.8
	9.22	80	2.49	117.0	3.75	3.56	5.0
	9.20	91	3.44	117.4	4.34	3.83	11.9
	9.08	95	3.38	118.3	4.85	4.28	11.6

3.1.6 Carbon America FrostCC Process

Carbon America is developing a cryogenic carbon capture process called FrostCC. The process separates CO_2 from the gas stream by controlled solidification and melting of the CO_2. This is accomplished through compressing, cooling, and expanding the gas stream in a sequence of steps, as exhibited in Figure 8. Potential benefits of the process include: no chemical or water usage; energy inputs are electricity only, no steam required; estimated capital costs three to five times lower than the current state-of-the-art; and potential co-capture of condensable pollutants such as sulfur oxides (SOx), nitrogen oxides (NOx), mercury, and particulate matter.

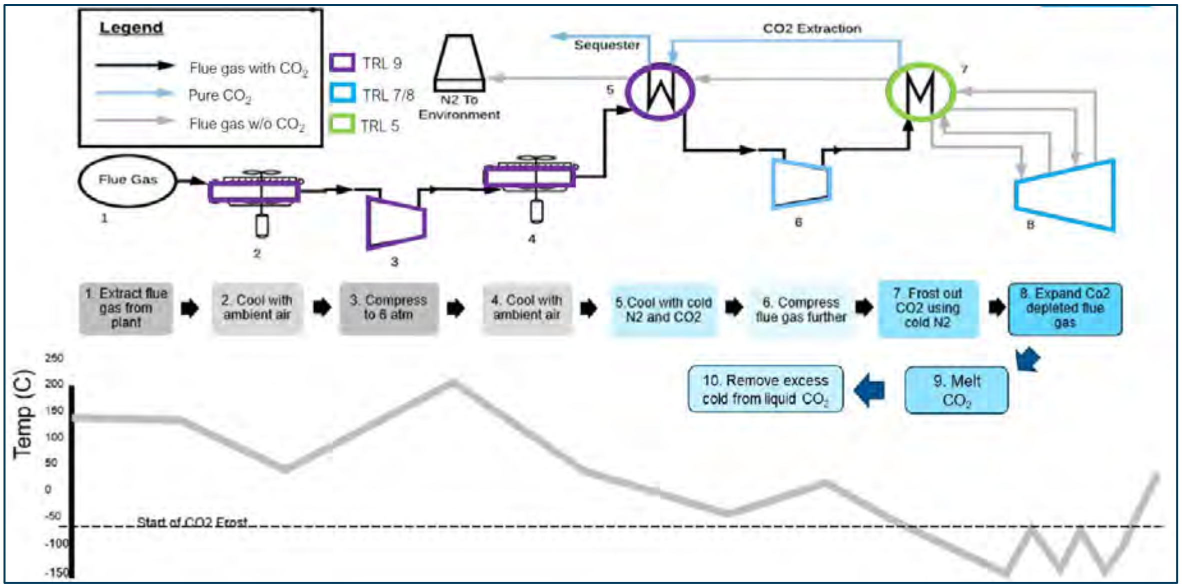

Figure 8. Carbon America FrostCC Process Diagram

To date, Carbon America has performed in-house testing and modeling focused on the CO_2 solidification heat exchanger. Capture rates of greater than 95% through continuous frosting has been demonstrated with a cyclic melting process. The field test at the NCCC will be the first end-to-end test of the overall process, integrating flue gas compression and expansion with the core heat exchanger technology. In-house testing at Carbon America has also used simulated gas streams, whereas the NCCC field test will occur on real flue gas from the NCCC's natural gas boiler. The primary goals of the test plan are to de-risk the fundamental thermodynamic cycle of the process, advance the technology readiness level, and demonstrate continuous operation to update dynamic models and operational strategies, optimize the melting process, and refine process control strategies. Skid delivery to the NCCC is expected in the first quarter of 2023. Commissioning and operation will follow.

3.1.7 GTI Energy Rotating Packed Bed Solvent Process

GTI's process features the ROTA-CAP rotating packed bed gas-liquid contacting device to replace conventional packed bed columns for CO_2 absorption and regeneration using an intensive solvent from Carbon Clean. The rotating packed bed is designed to provide a significant reduction in equipment footprint and offers a pathway for higher viscosity solvents and higher solvent concentrations to be used in carbon capture systems. Figure 9 provides a schematic of the ROTA-CAP process.

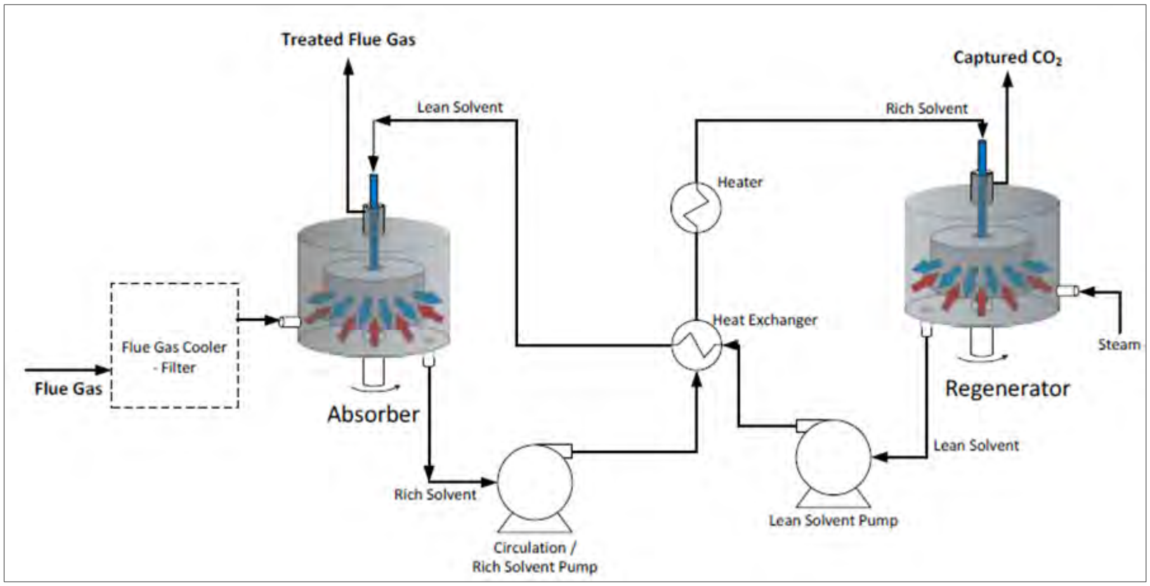

Figure 9. Simplified ROTA CAP Flow Design

After completing parametric studies and long-term operation, GTI concluded a test campaign in August 2022 while focusing on comparative performance for the rotating packed bed technology across various solvent formulations, including Carbon Clean's CDRMax, MEA, and aMDEA. Testing was carried out at CO_2 concentrations ranging from 4 to 22%, solvent concentrations ranging from 35 to 55%, and CO_2 capture efficiencies up to 90%. GTI began reviewing the data and considering alternative approaches for further evaluation of the technology. GTI plans to make a couple of modifications to bring the skid back to its original designed capacity. They plan for additional testing in 2023.

3.1.8 Carbon Clean Solvent for GTI Energy's ROTA-CAP Process

Evaluation of the Carbon Clean solvent in the SSTU was conducted beginning in August and ending in November 2021. The campaign entailed various test conditions exploring the impacts of solvent concentration and liquid and gas flow on overall system performance, using both coal-derived and natural gas-derived flue gases. The solvent testing provided a critical comparison point for future testing of the ROTA-CAP skid.

3.1.9 Altex Sorbent Process Intensification

Under previous DOE-Small Business Innovation Research support, Altex and Penn State University have been developing a method to coat CO_2 sorbents onto one side of a heat exchanger for process intensification. In this proposed project, a prototype of the Compact Rapid Cycling CO_2 Capture system will be designed to coat both sides of a heat exchanger with Penn State's high-capacity, high-selectivity molecular basket sorbents. This system, operating the adsorption cycle on one side of the heat exchanger and the desorption cycle on the opposite side, is designed to reduce the cooling and heating requirement and half the number of CO_2 sorbent reactors required in a commercial unit. Collaboration between Altex and the NCCC was underway to prepare for testing, which was originally planned for 2022. Due to delays in reactor fabrication, testing was delayed until early 2023.

3.1.10 NETL Membrane Materials

The NETL Research & Innovation Center's membrane material development program aims to reduce the costs of post-combustion carbon capture by creating transformational membrane materials with high permeability and CO_2 selectivity. A major focus area for the program is high-performance mixed-matrix membranes, which combine a polymer with metal-organic framework particles for enhanced transport of CO_2. Other materials under evaluation include ion gels and cross-linked polyphosphazenes.

NETL developed an automated bench-scale membrane test skid and membrane modules, shown in Figure 10, to support the evaluation of the materials at Technology Readiness Level 1 or 2 with exposure to flue gas conditions. The skid can house flat sheet or hollow fiber membrane materials, and the small area required makes it uniquely accessible for developing materials. The unit has operated at the NCCC in several test campaigns since 2015, and operation will resume in late 2022, with at least five membrane coupons to be evaluated over the next year.

Figure 10. NETL Membrane Test Equipment

3.1.11 Ohio State University Membrane

OSU is developing a novel polymeric composite membrane to capture 60 to 90% CO_2 from flue gas. The membranes are designed to achieve high CO_2 permeance of over 3,300 GPU and more than 140 CO_2/nitrogen selectivity at 77°C. The membranes were fabricated in spiral-wound modules of eight-inch diameter and 20 feet long and tested at the OSU lab using simulated flue gas. Flue gas testing at the NCCC will begin in November 2022. A techno-economic analysis will be completed at the end of the project to verify the technology's ability to achieve a 70% CO_2 capture rate at less than $30/tonne CO_2.

3.1.12 Precision Combustion Microlith Sorbent Technology Testing

PCI is developing a modular post-combustion carbon capture system utilizing metal-organic framework nanosorbents supported on a Microlith mesh substrate. The system is designed to enable low pressure drop, high volumetric utilization, and high mass transfer and to operate with rapid heat transfer and low-temperature regeneration operating modes. PCI operated their sorbent test skid (shown in Figure 11) at the site in 2020 with bottle gases and returned in 2022 for flue gas testing.

Figure 11. PCI Sorbent Skid Installed in LSTU

Testing began in April 2022 with natural gas flue gas containing 4.4% CO_2, with the system operating in batch mode, i.e., two to three adsorption and desorption cycles per day. The NCCC supported operation by providing analytical instrument for CO_2 analysis from five different sampling points as well as pure CO_2 from cylinders.

PCI completed parametric tests in May 2022, with a total of 25 cycles and about 60 hours of testing conducted. Multiple test conditions were investigated to measure the efficiency of the contactor and the sorbent performance. The sorbent was stable thorough the duration of the test and proved to be resistant to the effects of humidity and contaminants. The CO_2 capture rate correlated with capacity, and a capture rate of over 80% was achieved.

Before testing at the NCCC again, the sorbent skid will be returned to PCI for inspections and modifications. Future testing at the NCCC, which is currently scheduled for 2023, will entail optimization of regeneration and the capture rate. These experiments will include regeneration at varying temperatures and sweep gas flow rates and examination of capture rate versus capacity at varying on-stream adsorption times and flue gas flow rates.

3.1.13 GTI Energy Graphene Oxide-Based Membrane

GTI is developing a graphene oxide-based membrane technology expected to achieve at least 70% CO_2 capture from natural gas- or coal-derived flue gas with a single-stage process and 90% CO_2 capture with a two-stage process. GTI is pursuing two membrane approaches. One is GO-1, which has high CO_2 permeances up to 1,200 GPU with close to 700 CO_2/N_2 selectivity.

The other is GO-2 with high permeance as high as 2,500 GPU. In this project, GTI will design and operate a skid that combines GO-1 and GO-2 membranes in a two-stage configuration (GO^2 process) to demonstrate its performance with both natural gas- and coal-derived flue gases at NCCC. Operation is expected to begin in the second quarter of 2023.

3.1.14 EPRI/Pacific Northwest National Laboratory/RTI International Water-Lean Solvent

EPRI is working with PNNL and RTI to scale up a water-lean solvent for CO_2 capture. In this project, the NCCC will work with EPRI and its team to modify the PSTU design to achieve the desired process conditions for operation with this solvent. Both coal- and natural gas-derived flue gases will be used.

The NCCC kicked off the project in May 2022 with an internal project team meeting to discuss the project background and scope of work. A weekly recurring meeting was established to discuss the details of the scope of work, process modification markups, and any issues raised. The test campaign is scheduled to begin in 2023.

3.1.15 MEA Baseline Testing in the PSTU

MEA baseline testing began in November 2021 and ended in July 2022, with 2,678 test hours achieved using coal and natural flue gases and two configurations for solvent regeneration—the simple stripper and the Advanced Flash Stripper. The new baseline performance data will be a reference for future solvent developers.

The test campaign objectives were to:

- Reestablish the MEA baseline data at 90% CO_2 capture with coal-derived flue gas containing 13% CO_2 with varying liquid/gas ratios, number of absorber beds (one, two, or three), operation of intercooling (on/off), and solvent buffer tank concentration (rich versus lean)
- Determine new baseline values with natural gas flue gas containing 4.4% CO_2 to simulate conditions of a natural gas combined-cycle unit, demonstrating higher CO_2 capture rates (up to 99%) and use of the AFS

MEA solvent testing was initially conducted in November through early December 2021, with a total of 37 test conditions completed using both natural gas and coal flue gases. The testing resumed in April 2022 with natural gas at full and diluted CO_2 concentrations. Testing with the simple stripper was completed in May, and the system was transitioned to AFS operation, which was completed in late June 2022. Further operation with the simple stripper at high CO_2 capture rates was then conducted through mid-July. A total of 160 test conditions was completed, collecting over 2,800 hours of test data using coal and natural flue gas in both simple stripper and AFS configurations. New baseline performance data will be established as references for future solvent developers.

3.2 CO_2 Conversion Projects

3.2.1 Southern Research Ethane-to-Ethylene Process

Southern Research is developing a technology for thermo-catalytic ethylene production using ethane and CO_2. The nano-catalyst is designed to use the CO_2 in flue gas from a coal-fired power plant as the oxidant in a reaction called oxidative dehydrogenation. Southern Research expects that the CO_2 oxidative dehydrogenation process will benefit from several advantages over steam methane cracking for ethylene production:

- Operating temperature is reduced by at least 150^{o}C.
- Process footprint is reduced due to the high reaction selectivity of the catalyst.
- Rather than using steam and external reductants such as hydrogen, the process uses CO_2 and can be adapted to streams with impurities, thus reducing the overall CO_2 emissions from ethylene production by 50% or more.
- The co-production of valuable carbon monoxide-rich syngas may further reduce costs.

Southern Research has conducted lab testing using cylinder gases, showing promising results for the catalyst. As part of their current DOE-funded project, Southern Research scaled up the catalyst and reactor and began field testing at the NCCC using flue gas and captured CO_2. Performance criteria include product yield, catalyst stability, and tolerance to impurities. A simplified schematic of the process and a photograph of the installed test skid are shown in Figure 13. The NCCC provided captured CO_2, flue gas, utilities, and cylinder ethane for the project.

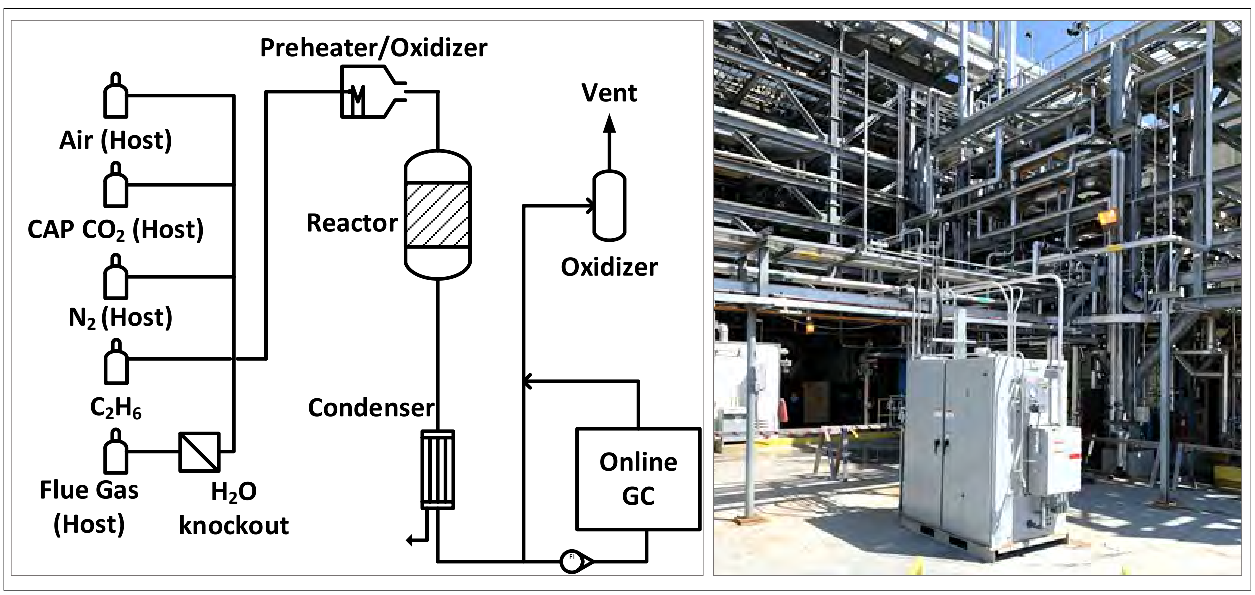

Figure 12. Schematic and Photograph of Southern Research Ethane-to-Ethylene Process

Testing was initially slated for 2020 but was delayed due to the COVID-19 pandemic response. Operations began in earnest in the summer of 2021 and then wrapped up in the fourth quarter of 2021. Southern Research analyzed the test data and produced a final report. Results showed that catalyst performance using captured CO_2 was comparable with results observed in the laboratory, achieving 35 to 40% single-pass conversion of ethane with monetizable productivity of ethylene, carbon monoxide, and hydrogen. Strong activity and selectivity were maintained throughout the test. Lower ethylene production costs ($0.291/kg) and greater than a 50% reduction in global warming potential were observed.

However, the presence of oxygen in the coal-derived flue gas pushed the reaction selectivity from ethylene production to ethane combustion unless excess ethane was used to pre-combust and consume oxygen upstream of the reactor. While this operation scheme did enable operation with high conversion and selectivity, this led to high ethylene production costs ($0.412/kg) and diminished environmental benefits. Southern Research would need to engage industrial partners to further this technology and prepare it for commercialization.

3.2.2 Helios-NRG Algae for CO_2 Conversion

Helios-NRG is developing a multi-stage, continuous system to grow algal biomass in the presence of sunlight and CO_2 from flue gas to obtain high productivity and CO_2 capture efficiency. With DOE funding, Helios-NRG brought a prototype of this system to operate on desulfurized coal flue gas in an outdoor setting. This testing program was the first biological or algae-based system to be tested at the NCCC.

The technology is a top-lit, closed system to facilitate controllable and predictable operation. The continuous gas and liquid flow process can be tailored to other applications, such as natural gas power plants or direct air capture.

Prior to testing at the NCCC, several designs were tested in the laboratory under artificial light, in a greenhouse, and outdoors for summer operation in western New York. These tests allowed for the development of a control system to enable unattended operation while maintaining stable operation. An overview of the system can be seen in Figure 14.

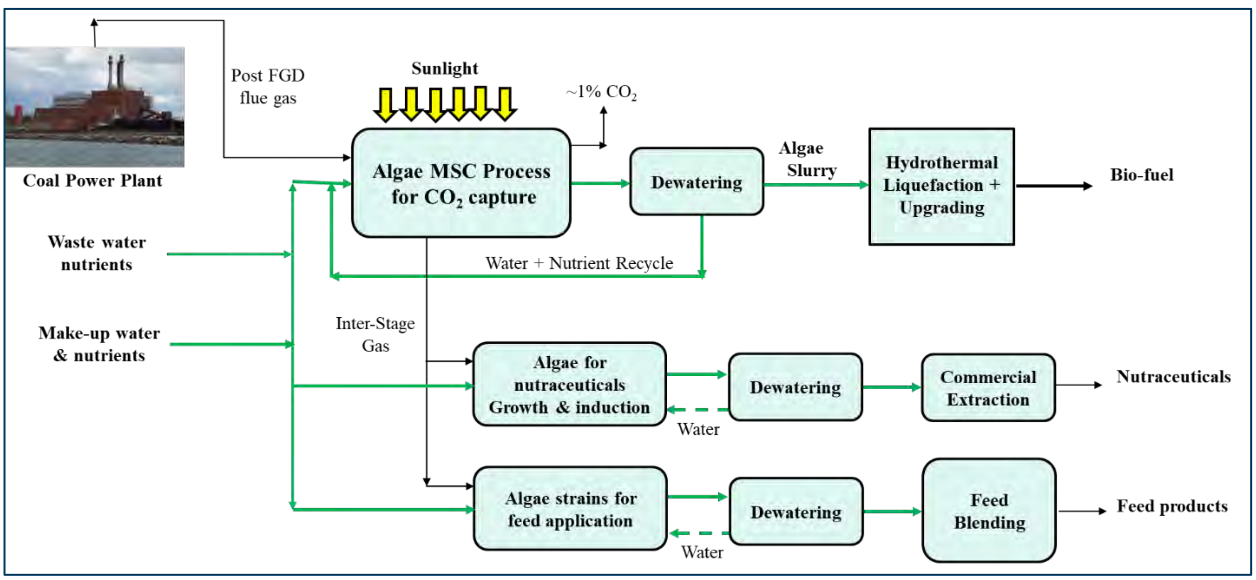

Figure 13. Flow Diagram of Helios-NRG Algae System

The equipment for the field test was shipped to the NCCC in early June 2022. After establishing an algae culture in an inoculum system set up in the NCCC's laboratory, the system began outdoor operation, as shown in Figure 15. While the project planned to use coal-derived flue gas, the power plant operated on a mixture of coal and natural gas throughout the summer. To ensure a minimum CO_2 concentration of 10.8% throughout the test, NCCC provided pure CO_2 to augment the flue gas stream.

Figure 14. Helios-NRG Algae System in the NCCC Bench-Scale Area

Higher ambient temperatures in Alabama than previously experienced in western New York initially caused operational difficulty, but Helios-NRG and the NCCC worked together to integrate a water chiller unit to resolve that consideration. Despite periodic sunlight impairment from weather and surrounding infrastructure, the system achieved a continuous period of operation with an average algae productivity of 30.7 g-dry weight algae/square meter/day and 87.2% CO_2 capture efficiency. These both exceeded the project targets of 25 g/m^2/d and 80% CO_2 capture efficiency. In September, Helios-NRG ceased operations, and the equipment was returned to their offices in New York. Further development of other process components will continue within this project, and Helios-NRG will continue seeking opportunities to promote scale-up and commercialization.

3.2.3 Texas A&M Algae for CO_2 Conversion

Texas A&M AgriLife Research is developing an integrated process with sorbent-based CO_2 capture and algae-based technologies to produce value-added products and biomass at ultra-high yield and low costs. The project features (1) a synthetic biology design to trigger auto-sedimentation of algal cells with high solid load for continuous cultivation by periodic auto-cell removal/harvesting, (2) a sorbent that allows CO_2 storage overnight with controlled release during daytime cultures, and (3) hydrogel-based phosphate, ammonia, and bicarbonate-controlled delivery to enhance algae productivity and reduce CO_2 loss from flue gas. NCCC will follow the development of this project and help the project team prepare for field testing at the site in 2023.

3.3 Site Modifications

3.3.1 Moisture Measurement on the Natural Gas Boiler Flue Gas Header

Solvent technology developers have expressed a desire to have real-time data on flue gas moisture content from the natural gas boiler. This would allow for more detailed mass balance calculations with fewer assumptions of moisture content. The NCCC consulted with an analyzer vendor and determined that a tunable diode laser device is the best option for this application. In early 2022, the instrument was installed and commissioned to provide moisture data for developers using natural gas flue gas. Data is now available to developers during test campaigns.

3.3.2 Sump and Waste Handling Improvement

The project was initiated to improve the sump water transfer, storage, and pre-treatment system to ensure environmental compliance. With the increased testing of non-aqueous solvents at the site, spill and leak containment has become more critical because the disposal of non-water-soluble fluids is problematic and requires special handling. The original system provided only a single destination for liquids collected in the sump, including rainwater falling on the process equipment area and any unknown leaks or accidental spills. Installation of the new system, which will include a new tank and associated equipment to allow the separation of rainwater and process fluids, was completed in BP7.

3.3.3 PSTU Solvent Filter Improvement

A project was initiated to improve the sealing performance and operability of the PSTU solvent filter housings, which are a potential source of leaks and personnel exposure to process fluids and were identified as a priority area for reducing environmental and safety concerns. Installation of new filter housings was completed in BP7.

3.3.4 Control System Modification for Lock-Out Test/Try

This project added a function to the plant control systems to allow for testing/trying to operate motors under lock-out to verify proper energy isolation. The function reduces the time and effort required for the lock-out process and reduces worker exposure to hazardous voltage during the verification process. Installation and testing are planned for early 2023.

3.3.5 Instrument Air Improvements

The project made improvements to the instrument air supply system based on operational experiences to further improve the reliability of this critical utility. The project scope included additional water separation, coalescing filters to remove any residual moisture, and improvements to the automatic system that provides backup instrument air supply from the alternative Plant Gaston supply. The system was installed in BP7.

3.3.6 PSTU Steam Condensate Flow Meter Improvements

This project will improve the accuracy and repeatability of the PSTU steam condensate flow measurement. The measurement is the key indicator of energy used during solvent regeneration and the overall CO_2 capture process. The project focuses on the lower condensate flow rate ranges likely to be applicable to CO_2 capture on a natural gas combined-cycle process. Design, procurement, and construction were completed, and commissioning and functional testing will be conducted in late 2022.

3.3.7 Natural Gas Reliability Upgrades

This project will improve the natural gas flue gas system by upgrading flue gas condensate drain operation, enabling easier instrumentation calibration during startup, and accommodating operations feedback on piping and instrumentation diagram layouts. The project also involves reviewing the existing pumps and motors for vulnerabilities. Design and construction began, with several work packages to be completed in late 2022 and project completion scheduled for the third quarter of 2023.

3.3.8 Computer Modeling of Flue Gas and Solvent Systems

The NCCC will incorporate two software applications to model the solvent (AFT Fathom) and flue gas (AFT Arrow) systems. These models will allow for better front-end engineering design by allowing the insertion of proposed changes or additions by technology developers or for infrastructure projects to see the impacts on the system from a holistic point of view. The NCCC design group defined the project scope and completed a plan for the project execution. The necessary documents for model build out will be prepared by the second quarter of 2023, and the first model is expected to be complete by the third quarter of 2023.

4.0 CONCLUSIONS AND LESSONS LEARNED

During the reporting period, the NCCC supported multiple carbon capture and conversion projects and provided testing opportunities during three test runs:

- Run PO-11, beginning in BP6 on June 1, 2021, and continuing through December 1, 2021
- Run PO-12, occurring from February 24, 2022, through July 31, 2022
- Run PO-13, starting on August 1, 2022, and continuing into Budget Period 7 (BP7)

Active projects during the budget period are listed below.

- GTI Energy membrane contactor—The membrane contactor test campaign began in 2017 and concluded in March 2022 for a total of 2,600 hours on both coal and natural gas flue gases. A 90% CO_2 removal rate was achieved by the system using a 50 wt% aMDEA solvent during the initial tests with four modules and actual coal-fired flue gas at NCCC. Continuous testing with 28 membrane modules showed performance declined with time, indicating the need for improved materials and manufacturing.
- TDA Research alkalized alumina sorbent—TDA's test campaign concluded in October 2021 for a total of 2,900 hours on both coal and natural gas flue gases. Greater than 90% capture and 95% purity CO_2 product were achieved for both coal and natural gas flue gases. TDA's Dynocel sorbent performed well throughout a three-month test.
- ION Clean Energy ICE-31 solvent—The ION Energy ICE-31 solvent test campaign was conducted from March through October 2021, accumulating over 4,000 hours of operation on coal and natural flue gases using both the PSTU simple stripper and the AFS. The solvent consistently demonstrated 95% CO_2 capture during long-term testing.
- UT-Austin PZAS process—Since performing previous successful test campaigns at the site with the PZAS process featuring the AFS and piperazine solvent in the PSTU, UT-Austin plans to conduct another test campaign combining multiple objectives focusing on degradation studies beginning in December 2022.
- Susteon ionic catalyst—Susteon is developing an ionic liquid catalyst designed to improve reaction kinetics in CO_2 absorption and desorption when added to amine-based solvent. The test campaign concluded in September 2022, with 680 operating hours achieved. Data analysis is underway.
- Carbon America FrostCC process—Carbon America is developing the FrostCC cryogenic process to remove CO_2 from typical industrial flue gases. The process is designed to compress and expand the flue gas stream with proper heat integration, producing near-pure solid CO_2. The Carbon America team plans to begin testing in the second quarter of 2023.
- GTI Energy ROTA-CAP process—GTI's process features the ROTA-CAP rotating packed bed gas-liquid contacting device to replace conventional packed bed columns for CO_2 absorption and regeneration using an intensive solvent from Carbon Clean. After completing parametric studies and long-term operation, GTI concluded a test campaign in August 2022 while focusing on comparative performance for the rotating packed bed technology across various solvent formulations, including Carbon Clean's CDRMax,

MEA, and aMDEA. GTI began reviewing the data and considering alternative approaches for further evaluation of the technology.

- Carbon Clean solvent for GTI Energy ROTA-CAP process—Evaluation of the Carbon Clean solvent in the SSTU was completed in November 2021. The solvent testing provided critical comparison points for testing of the ROTA-CAP skid.
- Altex Technologies sorbent process intensification—The Altex bench-scale project will employ a prototype of the Compact Rapid Cycling CO_2 Capture system using a heat exchanger coated with Penn State's high-capacity, high-selectivity molecular basket sorbents. Preparations have been underway for testing in 2023.
- NETL membrane materials—The NETL membrane development program is working to reduce the costs of post-combustion carbon capture by creating transformational membrane materials with high permeability and CO_2 selectivity. Membrane operation will resume in late 2022, with at least five membrane coupons to be tested over the next year.
- Ohio State University membrane—OSU is developing a novel polymeric composite membrane to capture 60 to 90% CO_2 from flue gas. Flue gas testing at the NCCC will begin in November 2022.
- Precision Combustion Inc. Microlith sorbent—PCI is developing a modular post-combustion carbon capture system utilizing metal-organic framework nanosorbents supported on a Microlith mesh substrate. In May 2022, PCI conducted a test campaign with flue gas from the natural gas boiler. The sorbent was stable thorough the duration of the test and proved to be resistant to effects of humidity and contaminants.
- GTI Energy graphene oxide-based membrane—GTI is preparing to test a carbon capture process using GO-1 and GO-2 membranes in a two-stage configuration (GO2 process) to demonstrate its performance with both natural gas- and coal-derived flue gases at the NCCC in 2023.
- EPRI/Pacific Northwest National Laboratory/RTI International water-lean solvent—EPRI is working with Pacific Northwest National Laboratory and RTI International to scale up a water-lean solvent for CO_2 capture. The NCCC will work with EPRI and its team to modify the PSTU design to achieve the desired process conditions for operation with this solvent. The test campaign is scheduled for 2023 and will use both coal- and natural gas-derived flue gases.
- MEA baseline testing in the PSTU—MEA baseline testing began in November 2021 and ended in July 2022, with 2,678 test hours achieved using coal and natural flue gases and two configurations for solvent regeneration—the simple stripper and the Advanced Flash Stripper. The new baseline performance data will be a reference for future solvent developers.
- Southern Research ethane-to-ethylene process—Southern Research conducted a test campaign with thermo-catalytic ethylene production using ethane and CO_2 from August through December 2021, achieving 1,600 hours of operation using captured CO_2 and flue gas. Results showed that catalyst performance using captured CO_2 was comparable with results observed in the laboratory, achieving 35 to 40% single-pass conversion of ethane with monetizable productivity of ethylene, carbon monoxide, and hydrogen.

- Helios-NRG algae for CO_2 conversion—Helios-NRG is developing a process to convert CO_2 to algae biomass that can be used to create value-added products, such as nutraceuticals. Testing at the NCCC is planned for the second quarter of 2022.
- Texas A&M algae for CO_2 conversion—Texas A&M AgriLife Research is developing an integrated process with sorbent-based CO_2 capture and algae-based technologies to produce value-added products and biomass at ultra-high yield and low costs. The NCCC will follow the development of this project and help the project team prepare for field testing at the site.

Other projects that are scheduled for testing include:

- Southern States Energy Board solid-amine absorption/desorption contactor
- State University of New York at Buffalo membrane
- State University of New York at Buffalo sorbent
- Clean Energy Research Institute solvent in the PSTU
- Membrane Technology & Research membrane
- UCLA concrete technology
- Helios NRG algae process
- Cormetech sorbent
- Innosepra direct air capture
- Helios-NRG membrane in the LSTU
- University of Sheffield MEA solvent in PSTU

The following site modifications projects were underway during BP7:

- Moisture measurement installation on the natural gas boiler flue gas header
- Sump and waste handling improvement
- PSTU solvent filter improvement
- Control system modifications for lock-out test/try
- Instrument air improvements
- PSTU steam condensate flow meter improvements
- Natural gas system reliability upgrades
- Computer modeling of flue gas and solvent systems