National Carbon Capture Center

Topical Report
Budget Period Six

Reporting Period: October 1, 2020 – September 30, 2021
Project Period: June 6, 2014 – September 30, 2025

DOE Cooperative Agreement
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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 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 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 6 (BP6) reporting period, spanning from October 1, 2020, through September 30, 2021, efforts at the NCCC focused on post-combustion carbon capture and utilization technology development. Testing was conducted with membrane, solvent, and sorbent technologies during two test runs, and the first test campaign with a CO_2 utilization process was successfully completed. A new natural gas flue gas supply system was commissioned, and several other improvements were made to the site.

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

BP6	Budget Period 6
BP7	Budget Period 7
CO_2	Carbon dioxide
DOE	Department of Energy
GTI	Gas Technology Institute
ITC	Wyoming Integrated Test Center
LSTU	Lab-Scale Test Unit
MEA	Monoethanol Amine
NCCC	National Carbon Capture Center
NETL	National Energy Technology Laboratory
PCI	Precision Combustion Inc.
PO-10	Post-Combustion Run 10
PO-11	Post-Combustion Run 11
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 123,000 hours of testing, successfully advancing a wide range of technologies toward commercial scale while improving their performance and reducing cost. The NCCC testing of 70 technologies from more than 40 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 utilization 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 funds 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 6 (BP6) of the NCCC's second cooperative agreement with DOE, DE-FE0022596, covering October 1, 2020, through September 30, 2021.

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 newly installed 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 utilization projects and provided testing opportunities with two test runs:

- Run PO-10, with short periods of operation in 2020 followed by resumed operation from January 14 through May 31, 2021
- Run PO-11, beginning June 1, 2021, and continuing into Budget Period 7 (BP7)

Table 1 lists the projects tested during the reporting period, as well as projects currently being developed for testing in 2022.

Table 1. Projects Tested and Under Development During Budget Period 6

	Venue/Scale	Tested in Run PO-10	Tested in Run PO-11	Planned for 2022
CO_2 Capture Projects				
Gas Technology Institute (GTI) membrane contactor	Pilot-scale	✓	✓	✓
NETL membrane materials	LSTU			✓
GTI graphene oxide-based membrane	LSTU			✓
TDA Research alkalized alumina sorbent	Pilot-scale	✓	✓	
Precision Combustion Inc. Microlith sorbent	LSTU			✓
ION Clean Energy ICE-31 solvent	PSTU	✓	✓	
GTI ROTA-CAP rotating packed bed solvent process	Bench-scale		✓	✓
Carbon Clean solvent for ROTA-CAP process	SSTU		✓	
University of Texas at Austin (UT-Austin) PZAS™ process	PSTU			✓
LumiShield anti-corrosion coating	SSTU			
Altex Technologies sorbent process intensification	LSTU			✓
Carbon America FrostCC process	Small pilot-scale			✓
Susteon liquid catalyst	PSTU			✓
CO_2 Utilization Projects				
University of California, Los Angeles (UCLA) Reversa™ process	Bench-scale	✓		✓
Southern Research ethane-to-ethylene process	Bench-scale		✓	
Helios-NRG algae for CO_2 utilization	Bench-scale			✓

Highlights of the current projects are described below.

Gas Technology Institute 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. Testing in 2021 showed some performance decline of membrane modules similar to that seen in previous testing. GTI plans to test improved membrane modules in 2022.

NETL Membrane Materials

The NETL team has continued preparing new membrane samples for testing based on previous efforts to optimize membrane performance and integrity. They plan to return to the site in 2022.

GTI 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 2022.

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 began a 1,500-hour long-term test in August 2021 with coal flue gas and natural gas flue gas. Operation will continue into BP7.

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. PCI operated their sorbent test skid at the site in 2020 with bottle gases and plans to return in 2022 for flue gas testing.

ION Clean Energy ICE-31 Solvent

ION is developing and scaling up a novel amine-based solvent technology, ICE-31, that is expected to demonstrate transformational stability and excellent key CO_2 capture performances such as low regeneration energy. During the reporting period, ION achieved about 1,500 hours of long-term testing with the PSTU simple stripper. Operation was transitioned to the Advanced Flash Stripper and will continue in BP7.

GTI 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. Preparations were underway to install the ROTA-CAP skid and begin parametric testing. Testing of the Carbon Clean solvent in the SSTU was started to evaluate the impact of solvent concentration and liquid and gas flow on overall system performance. GTI plans to return to the site in 2022 to complete parametric testing with the ROTA-CAP process and begin a 1,500-hour long-term test.

UT-Austin PZAS Process

UT-Austin is continuing development of the PZAS process, a solvent-based carbon capture technology using the Advanced Flash Stripper with piperazine solvent. A six-month test campaign is planned for 2022 with natural gas flue gas to evaluate solvent degradation and oxidation.

LumiShield Anti-Corrosion Coating

LumiShield has developed a metal oxide coating that is resistant to the forms of corrosive attack commonly found in carbon capture processes. Testing was originally planned at the NCCC for 2021, but due to priority changes and resource constraints, LumiShield canceled the testing.

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. Collaboration has been underway for testing in 2022.

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 2022.

UCLA Reversa Process

UCLA is developing a CO_2 mineralization process that synergistically utilizes CO_2 in flue gas and coal combustion residues to synthesize an alternative to ordinary Portland cement. Testing at the NCCC was completed in 2021, with over 5,000 concrete blocks produced with flue gas CO_2. The test demonstrated (1) CO_2 utilization efficiency in excess of 75%, (2) CO_2 uptake greater than 0.5% of concrete (mass basis), and (3) compliance of carbonated blocks within industry standard specifications (ASTM C90) verified by a third party. UCLA plans to conduct further testing at the site in a follow-on project in 2022.

Southern Research Ethane-to-Ethylene Process

Southern Research is developing a technology for thermo-catalytic ethylene production using ethane and CO_2. Southern Research began testing in August 2021, achieving 500 hours of operation using captured CO_2. Operations will transition to direct flue gas feed in the next reporting period.

Helios-NRG Algae for CO_2 Utilization

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 is planned for the second quarter of 2022.

Texas A&M Algae for CO_2 Utilization

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.

Site Modifications

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

- Completion of natural gas flue gas supply system
- Study for providing high-purity CO_2
- Increased natural gas flue gas flow through the PSTU
- New moisture measurement on the natural gas boiler flue gas header
- Restoration work at the former gasification/pre-combustion test site
- Sump and waste handling improvement
- PSTU solvent filter improvement
- Control system modification for lock-out test/try
- Instrument air improvements
- SSTU modifications and MEA baseline testing

1.5 Future Test Plans

New projects confirmed for testing at the site in 2022 or later include the first direct air capture project for the NCCC—Southern States Energy Board bench-scale solid-amine absorption/desorption contactor—and the carbon capture technologies listed below.

- State University of New York at Buffalo bench-scale membrane
- Ohio State University bench-scale membrane
- Membrane Technology & Research bench-scale membrane
- GTI bench-scale membrane
- State University of New York at Buffalo bench-scale sorbent
- Clean Energy Research Initiative solvent
- Susteon ionic liquid catalyst
- Electric Power Research Institute/Pacific Northwest National Laboratory/RTI International water lean solvent

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

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.

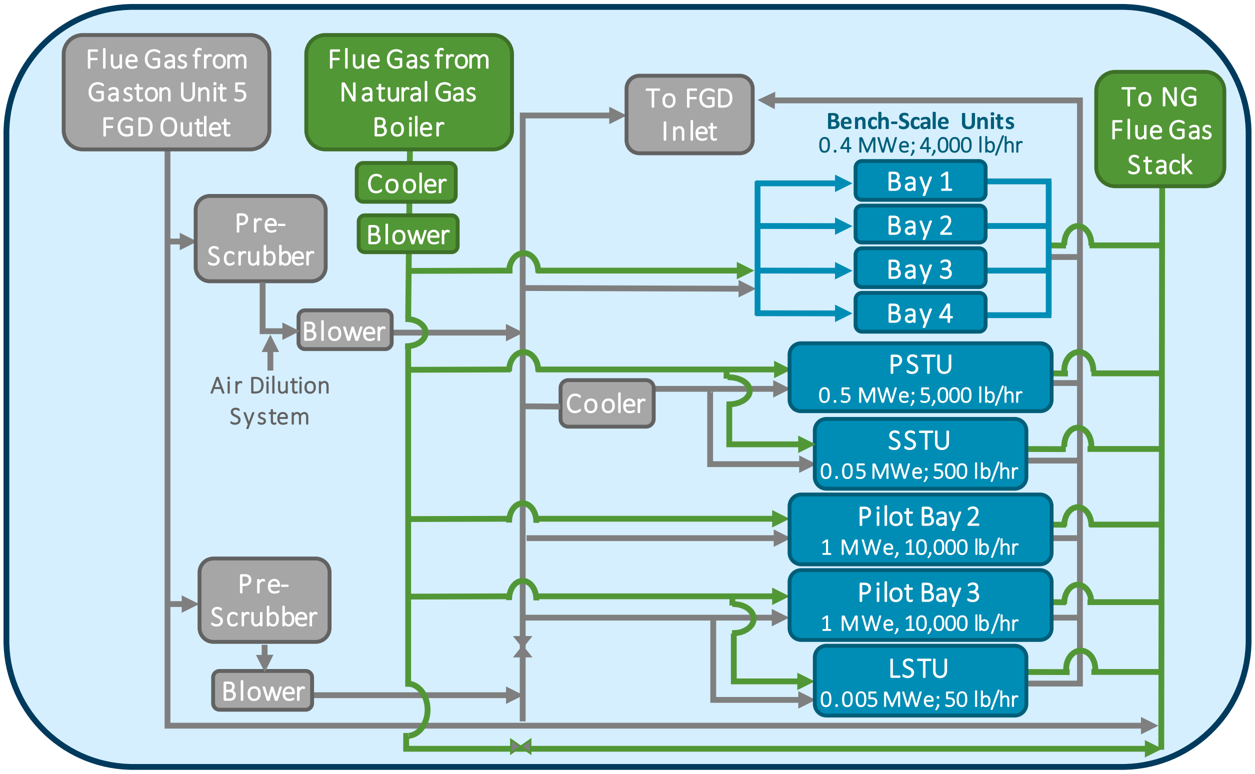

Figure 2. Schematic of Flue Gas Distribution at Post-Combustion Carbon Capture Test Facilities

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.

3.0 TECHNICAL PROGRESS

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

- Run PO-10, with short periods of operation in 2020 followed by resumed operation from January 14 through May 31, 2021
- Run PO-11, beginning June 1, 2021, and continuing into Budget Period 7

The following sections describe the current projects at the site.

3.1 CO_2 Capture Projects

3.1.1 Gas Technology Institute Membrane Contactor

GTI, 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. After completing a small bench-scale project at another location, GTI is moving the technology forward with a small pilot-scale, 0.5-MW process currently installed at the NCCC. Figure 3 provides a photograph of the installed equipment.

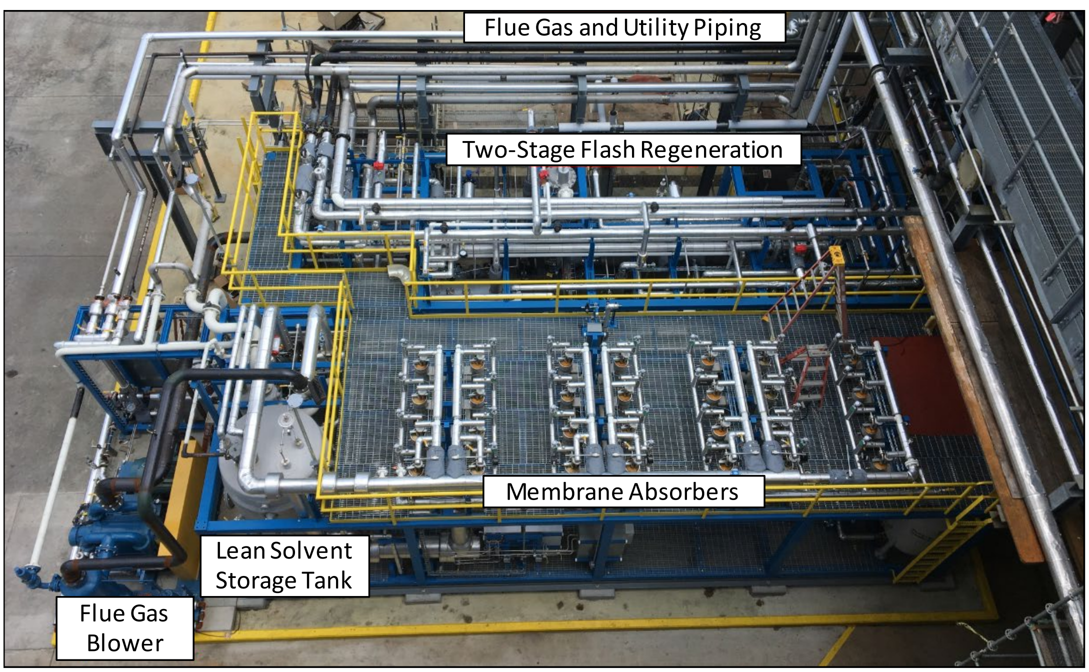

Figure 3. Gas Technology Institute Membrane Contactor

GTI's testing of the membrane contactor has been ongoing since 2017. Testing resumed with coal flue gas in January 2021 using all new 28 membrane modules. In February, testing with natural gas flue gas began, showing an initial CO_2 capture rate of 90%. However, due to declining membrane performance like that observed previously, operation ended in February. Figure 4 shows the performance decline of the membrane modules over 400 hours of operation.

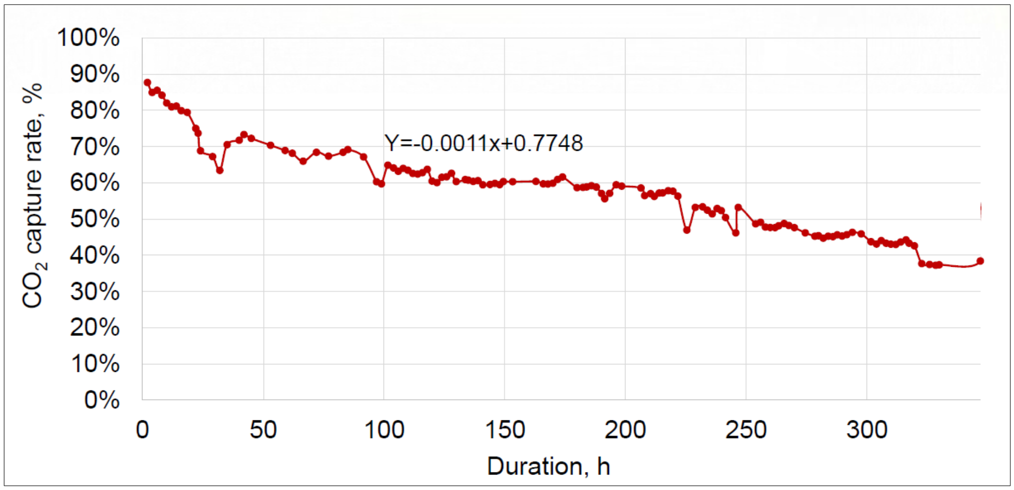

Figure 4. CO_2 Capture Rate Decline over Time for GTI Membrane Contactor

In collaboration with the membrane manufacturer Air Liquide, GTI conducted root cause analysis and evaluated methods of recovering membrane performance. Although one of the methods successfully regenerated the initial membrane performance, the performance still declined over time.

In July 2021, GTI conducted testing for over 100 hours using natural gas flue gas with 4.3% CO_2 for the first time to determine if membrane performance decline also happened with natural gas flue gas having fewer contaminants than coal flue gas. GTI reported an initial CO_2 capture rate of 90%, followed by a declining capture rate, similar to previous coal flue gas results. GTI determined that solvent was present on the gas side of the membranes, possibly caused by fiber breakage, defects on the superhydrophobic coating, and solvent vapor permeation and condensation. It is anticipated that new membrane modules will be fabricated to address those issues, and additional testing is planned for 2022 to verify performance improvements.

3.1.2 NETL Membrane Materials

NETL'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 5, to support the evaluation of these novel materials at Technology Readiness Level 1 or 2 with exposure to industrial 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 was initially operated at the NCCC in 2015 and was subsequently operated after skid modifications, an upgrade to the gas chromatograph, and relocation of the skid to the LSTU. During test campaigns to date, NETL has achieved more than 5,300 hours of membrane material testing.

Figure 5. NETL Membrane Test Equipment

Pandemic-related travel restrictions prevented membrane testing at the NCCC during the reporting period. NETL project personnel continued developing new materials, and they hope to return to the NCCC in 2022 to resume the test program.

3.1.3 GTI 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 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.

The project kick-off meeting was held with the GTI team and their project partner, University of Buffalo, and a design hazard review was conducted in August 2021. The test skid will be located in the LSTU, with operation expected to begin in March or April 2022.

3.1.4 TDA Alkalized Alumina Sorbent

TDA is developing a CO_2 capture process using dry, alkalized alumina sorbent. TDA's sorbent features durability, low cost, and extremely low heat of adsorption (15 kJ/mole). The sorbent 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, as shown in Figure 6, was installed at the NCCC in October 2017.

Figure 6. TDA Research Alkalized Alumina Sorbent Process

TDA replaced the sorbent from all 10 of the reactors due to performance loss after long-term storage. Half of the sorbent is a commercially available material, and the other half is a specially processed commercial sorbent. In July 2021, TDA restarted the testing with coal flue gas after hydrating the sorbent. The initial test focused on parametric tests using coal flue gas at regular and diluted conditions. Long-term testing began in August with coal flue gas, and operation transitioned to natural gas flue gas testing. Operation will continue to achieve 1,500 hours of long-term testing.

3.1.5 PCI 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 design enables low pressure drop, high volumetric utilization, and high mass transfer and is suitable for rapid heat transfer and low-temperature regeneration operating modes. PCI operated their sorbent test skid (shown in Figure 7) at the site in 2020 with bottle gases and plans to return in 2022 for flue gas testing.

Figure 7. PCI Sorbent Skid Installed in LSTU

3.1.6 ION Clean Energy Solvent

ION is developing and scaling up a novel amine-based solvent technology, ICE-31, that is expected to demonstrate transformational stability and excellent key CO_2 capture performances such as low energy. This project not only will confirm the initial findings of the solvent performances now on a larger scale at NCCC but also validate its 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.

Several modifications to the PSTU were incorporated to accommodate ION's test, including new absorber packing, piping, instrumentation, a sampling system, and heat tracing. A solvent spill management procedure was developed, and several seals and gaskets were replaced with solvent compatible materials.

Parametric testing with natural gas flue gas began in March 2021. NCCC process engineers, lab staff, and operators worked closely with the ION team to execute 60 test conditions. The data was used to identify optimum process conditions for long-term testing and for verification of ION's process simulation model. Long-term testing began in May, and about 1,500 hours of steady-state operation was completed by the end of July using natural gas flue gas at combined cycle unit conditions (4% CO_2 concentration) using the simple stripper with 95% CO_2 capture.

Figure 8 graphs the CO_2 capture efficiency during the long-term testing. At the conclusion of this testing, operation was transitioned from the PSTU simple stripper to the Advanced Flash Stripper with coal flue gas, with adjustments made to the flue gas flow, cold and warm rich bypass, and CO_2 inlet concentration to achieve a 90% CO_2 capture rate. Testing continued with natural gas flue gas, with the conclusion of the test campaign expected in early October.

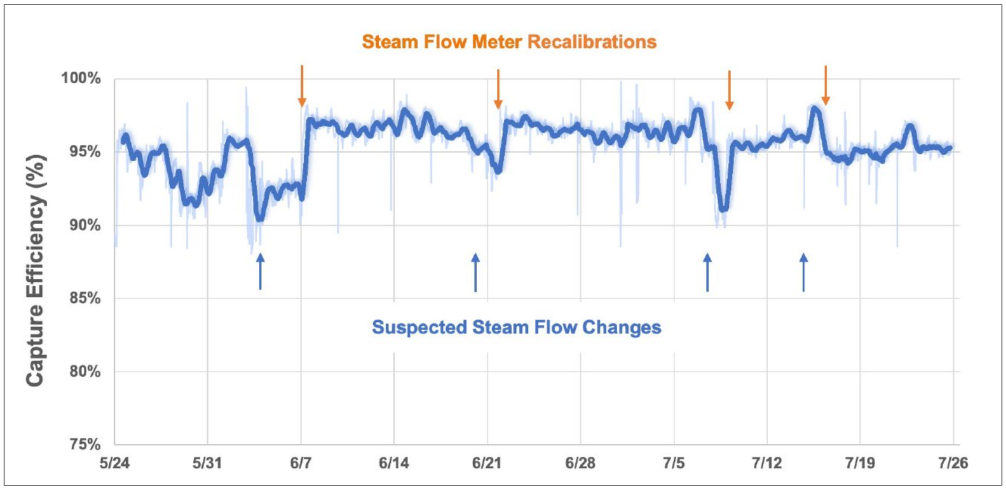

Figure 8. CO_2 Capture Efficiency of ION Solvent during Long-Term Testing

3.1.7 GTI 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 provides 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.

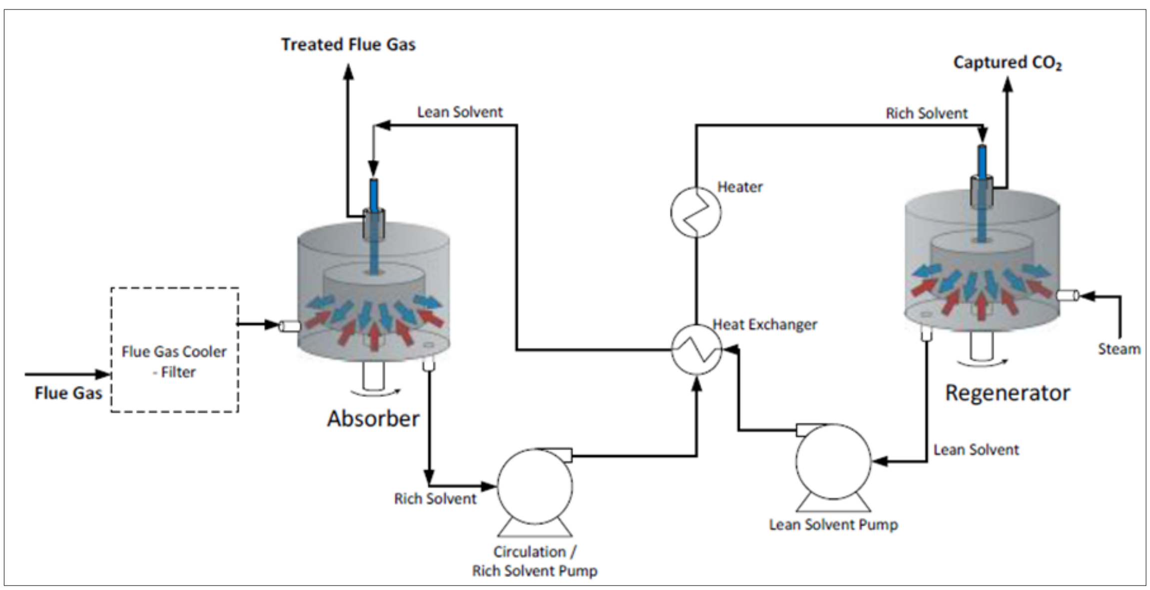

Figure 9. Simplified ROTA CAP Flow Design

The project accomplishments included the construction, commissioning, and testing of the ROTA-CAP skid at the GTI facility. Plans were made to install the skid and begin operation in late 2021.

Testing of the ROTA-CAP skid at the NCCC will focus on initial parametric testing to validate the test data collected by GTI at their facility. Compared to the testing conducted at the GTI facility, testing at the NCCC, with its higher level of utility supply, will allow a fuller exploration of the system capabilities. The NCCC assisted GTI in improving their electrical panel and PLC logic through knowledge of industry best practices. These improvements lessened the likelihood of upset conditions that might result in a loss of test time and also gave the GTI team more information on how to scale up the technology further and on considerations for future testing.

Evaluation of the Carbon Clean solvent in the SSTU began during the PO-11 run. This test campaign entails 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 will provide a critical comparison point for future testing of the ROTA-CAP skid.

GTI plans to return to the site in 2022 to complete parametric testing with the ROTA-CAP process and begin a 1,500-hour long-term test.

3.1.8 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, is scheduled to begin in the second or third quarter of 2022. For this test, a new flue gas heater will be installed to heat the flue gas to 110^{o}C, and additional corrosion ports will be installed on the Advanced Flash Stripper skid.

3.1.9 LumiShield Anti-Corrosion Coating

LumiShield has developed a metal oxide coating resistant to the forms of corrosive attack commonly found in carbon capture processes. When applied to carbon steels, the coating is expected to improve their corrosion resistance beyond that of more expensive materials like stainless steels, leading to lower CO_2 capture costs.

Due to priority changes and resource constraints, LumiShield canceled their planned testing at the NCCC in 2021. The two new corrosion ports installed on the SSTU for this project will be available for future testing by other developers.

3.1.10 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 is currently planned for 2022.

3.1.11 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 (see Figure 10).

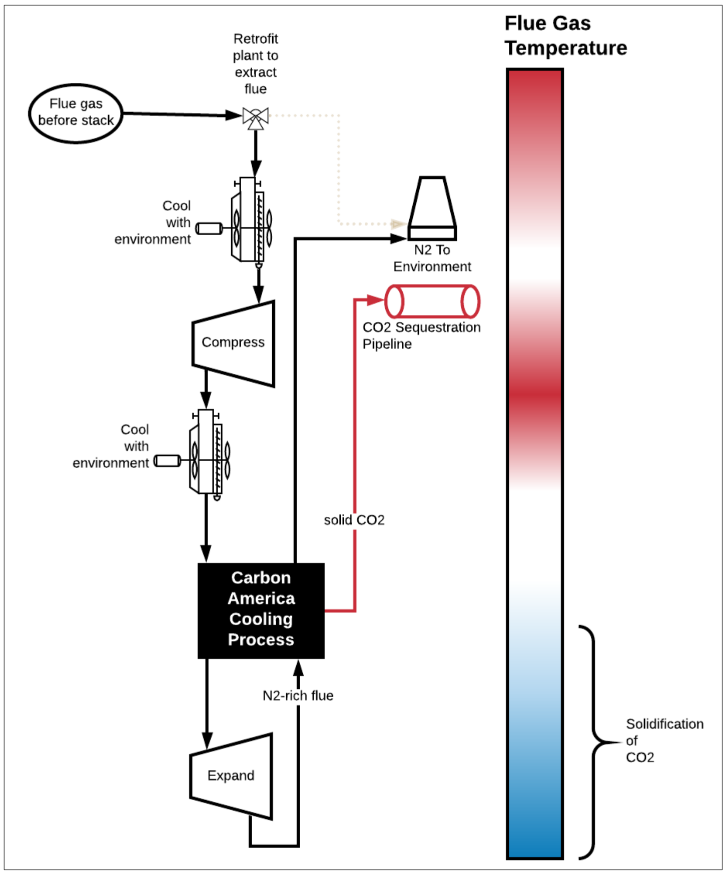

Figure 10. Carbon America FrostCC Process Diagram

Carbon America has conducted early development at their facilities, and they plan to increase the system to a pilot scale for field testing at the NCCC. Carbon America will design and construct the appropriate test equipment, transport it to the NCCC, and provide operational support throughout the test. NCCC will provide access to both coal- and natural gas-derived flue gas streams and utilities. The Carbon America team should complete their design in BP7, and the NCCC will design the interconnections to the existing infrastructure. The project team hopes to begin testing in the second quarter of 2022.

3.2 CO_2 Utilization Projects

3.2.1 UCLA Reversa™ Process

UCLA is developing the Reversa CO_2 mineralization process that synergistically utilizes CO_2 in flue gas and coal combustion residues (e.g., fly ash) to synthesize concrete material as an alternative to ordinary Portland cement. The process produces prefabricated hardened concrete products (e.g., blocks, beams, and slabs) with CO_2 emission footprints up to 75% lower than those of performance-equivalent ordinary Portland cement-based components. A system that consumes about 0.1 tonnes of CO_2 per day was tested initially at the Wyoming Integrated Test Center (ITC) under funding of DOE and NRG-COSIA XPRIZE. This system was relocated to the NCCC in late 2020 for testing with real coal-flue gas directly without first capturing CO_2.

The first batch of semi-cured concrete blocks was delivered to the site in March 2021 from a local concrete block manufacturer and loaded into the curing chamber (see Figure 11), marking the beginning of the test. A total of six batches were completed, four using coal flue gas and two using natural gas flue gas. Over 5,000 concrete blocks were produced with flue gas CO_2. The test demonstrated (1) CO_2 utilization efficiency in excess of 75%, (2) CO_2 uptake greater than 0.5% of concrete (mass basis), and (3) compliance of carbonated blocks within industry standard specifications (ASTM C90) verified by a third party.

Figure 11. Loading of Concrete Blocks into UCLA Reversa Curing Chamber

Figure 12 provides the results from the six batch runs at the NCCC in comparison with results from ITC. Section (a) of the figure graphs the CO_2 uptake and utilization efficiency over the 18-hour carbonation duration, Section (b) shows electricity usage per batch, and Section (c) plots the net area compressive strength of the coal and natural gas flue gas concrete blocks. The energy consumption during the NCCC testing was reduced significantly by modifying the curing steps. UCLA plans to conduct future testing at the NCCC for a follow-on project in 2022.

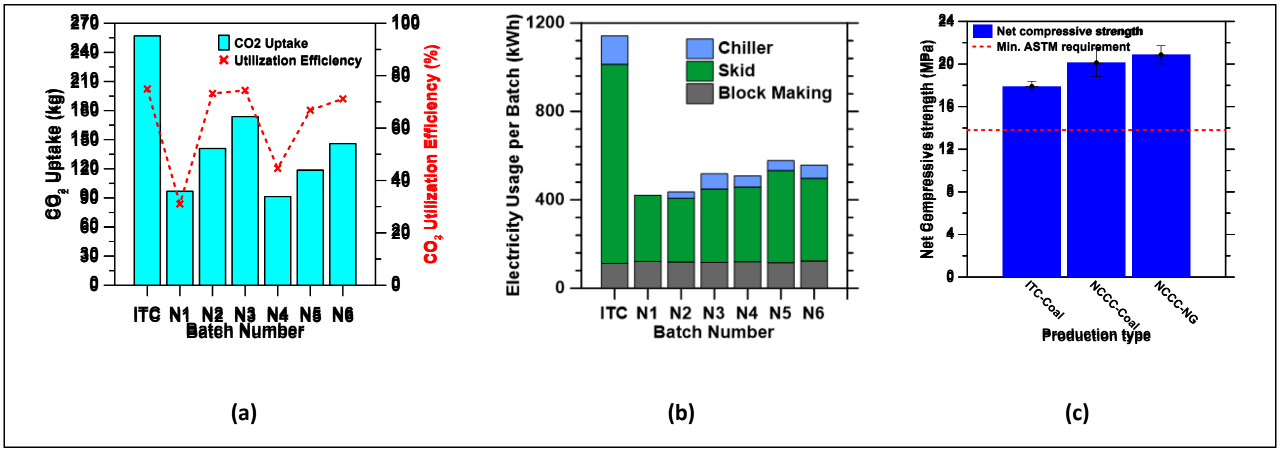

Figure 12. Batch Performance of UCLA Reversa Process at NCCC and Wyoming ITC

3.2.2 Southern Research Ethane-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°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 is shown in Figure 13, and Figure 14 provides a photograph of the installed test skid. The NCCC is providing captured CO_2, flue gas, utilities, and cylinder ethane for the project.

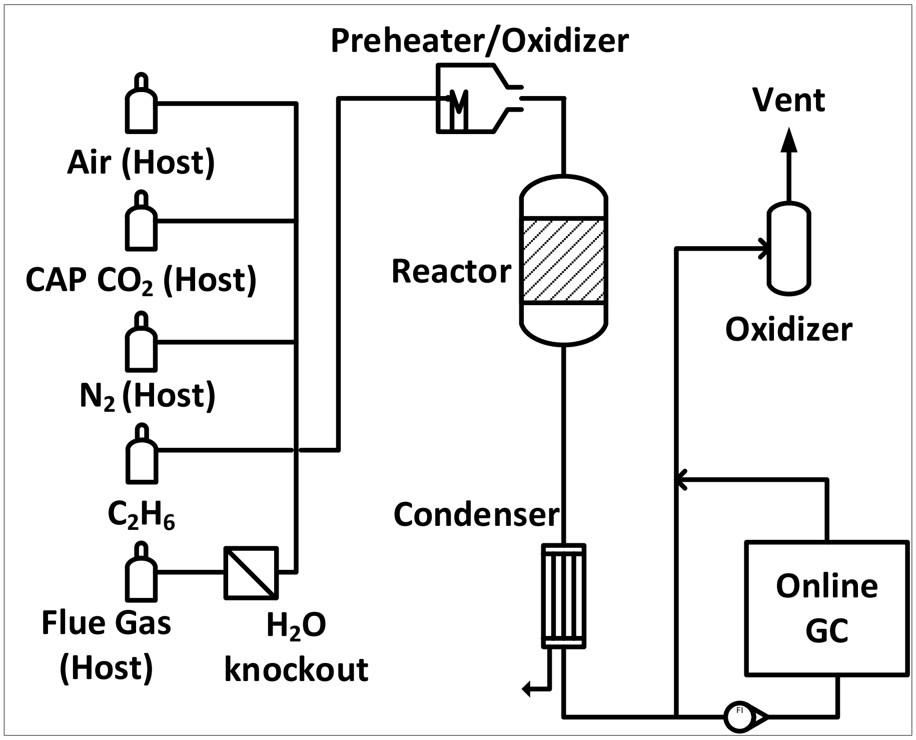

Figure 13. Schematic of Southern Research Ethane to Ethylene Process

Figure 14. Southern Research CO_2 Utilization Test Skid

Southern Research began testing in August 2021. The team achieved 500 hours of operation using captured CO_2 and will transition to direct flue gas operation in the next reporting period.

3.2.3 Helios-NRG Algae for CO_2 Utilization

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. The NCCC has been selected for a field test of the multi-stage, continuous flow system for algae production. Helios-NRG has been working to design, build, and operate the system at their facilities in preparation for the field test.

Helios-NRG personnel visited the NCCC in August 2021 to become familiar with the existing test infrastructure and prepare for the field test in 2022. Following the visit, NCCC installed sunlight sensors in the two potential test locations to inform Helios-NRG's test planning. Work also began to develop the required contract and technology screening information for testing. NCCC will continue collecting sunlight data, and Helios-NRG will deliver equipment for the testing in the second quarter of 2022.

3.2.4 Texas A&M Algae for CO_2 Utilization

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. Texas A&M's proposal was selected for negotiation in June 2021. NCCC will follow the development of this project and help the project team prepare for field testing at the site.

3.3 Site Modifications

3.3.1 Natural Gas Flue Gas Infrastructure

The first fire of the newly installed natural gas boiler was achieved in December 2020. The project team worked with the boiler vendor to address issues identified during startup in early 2021, and the boiler was made available for testing in March 2021. Figure 15 provides a photograph of the natural gas flue gas system.

Figure 15. Natural Gas Flue Gas System

The boiler system was used to support developer testing for the remainder of the reporting period, more than 4,500 technology testing hours. With the new infrastructure, the NCCC testing availability is independent of Plant Gaston Unit 5 coal operation, and operation of the new system resulted in 62% more operating time. The natural gas flue gas system also has the flexibility to provide natural gas combined cycle conditions of 4% CO_2 concentration up to the higher 10% CO_2 concentration flue gas.

3.3.2 CO_2 Utilization Infrastructure Study

Increasing interest in CO_2 utilization technologies led the NCCC to consider what infrastructure additions would best support future testing of these technologies. The NCCC identified three tiers of CO_2 supply scope that could support these tests: (1) a dedicated CO_2 product header from the PSTU (2) CO_2 compression with vapor-phase storage, and (3) CO_2 compression, liquefaction, liquid-phase storage, and a vaporizer. Each of those would increase the availability of CO_2 supply for utilization tests but would also add cost. The NCCC completed this estimating study in October 2020, presented the information to DOE and project stakeholders, and determined that it was not necessary to pursue the implementation of any of these scopes at this time. The NCCC will work with DOE and technology developers to pair CO_2 capture and utilization projects for mutual benefit. If demand increases further, NCCC can revisit the implementation of the most appropriate scope.

3.3.3 Increased Natural Gas Flue Gas Flow through the PSTU

As the demand for carbon capture from natural gas flue gas has increased over that from coal flue gas, more developers have sought higher flue gas flow rates through the NCCC's PSTU than previously required. The NCCC created a project to explore options to make this possible. Design engineers reviewed the system process data and determined that the existing equipment and valving should be capable of delivering the requested flow rates. Field evaluations are underway.

3.3.4 Moisture Measurement on the Natural Gas Boiler Flue Gas Header

NCCC's natural gas flue gas at lower CO_2 concentrations is diluted with air, making it difficult to quickly calculate the true moisture concentration during operations. Technology developers have emphasized the importance of this data point to the NCCC, and a project was created to add an instrument to the natural gas flue gas supply header to provide continuous moisture content measurements. The NCCC determined that a tunable diode laser instrument would provide the requested information accurately and with minimal maintenance and troubleshooting requirements. The instrument will be installed in late 2021.

3.3.5 Restoration Work at Former Gasification/Pre-Combustion Test Site

Following the conclusion of the NCCC's gasification and pre-combustion carbon capture programs, the main site demolition and removal work scope was completed in Summer 2020. Work in Fall 2020 focused on restoring the site to a finalized, usable configuration. The NCCC completed final site grading, modifications to the site stormwater collection system, reconfiguration of the site surveillance camera systems, modifications to the site fire protection water lines, and final as-built revisions of site engineering drawings. Project close-out was completed in December 2020.

3.3.6 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 only provided 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, will be completed in BP7.

3.3.7 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 have been identified as a priority area for reducing environmental and safety concerns. Installation of new filter housings will be completed in BP7.

3.3.8 Control System Modification for Lock-Out Test/Try

This project will add 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 will reduce the time and effort required for the lock-out process and reduce worker exposure to hazardous voltage during the verification process. Completion of the project is planned in BP7.

3.3.9 Instrument Air Improvements

The project will make improvements to the instrument air supply system based on operational experiences to further improve the reliability of this critical utility. The project scope includes 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. Installation of the system is planned for BP7.

3.3.10 SSTU Modifications and MEA Baseline Testing

Based on lessons learned from testing of non-aqueous solvent, modifications were made to the SSTU to achieve the following objectives:

- Replace instruments with better models and range capabilities to improve the mass balance closure and operational flexibility
- Improve process bottlenecks such as increasing the size of the lean tank and heat exchangers, eliminating and rearranging piping that caused vapor locking, and increasing the maximum regenerator operating pressure
- Improve operations and maintenance by rerouting tubing that obstructed access to valves, adding flanges to make pump maintenance more practical, and installing an automatic water makeup system

After issues from initial water commissioning had been successfully resolved, commissioning of the modified SSTU with MEA was ongoing throughout early 2021. MEA baseline testing was conducted for more than 1,600 hours, providing data for coal flue gas and the first MEA baseline dataset using natural gas flue gas. These data will form a new baseline for the comparison of developer solvents.

Figure 16 plots the SSTU regeneration energy as a function of liquid/gas ratio on coal flue gas with 90% CO_2 capture for 2017 operation and current operation. An improvement is clearly indicated as a result of the SSTU modifications.

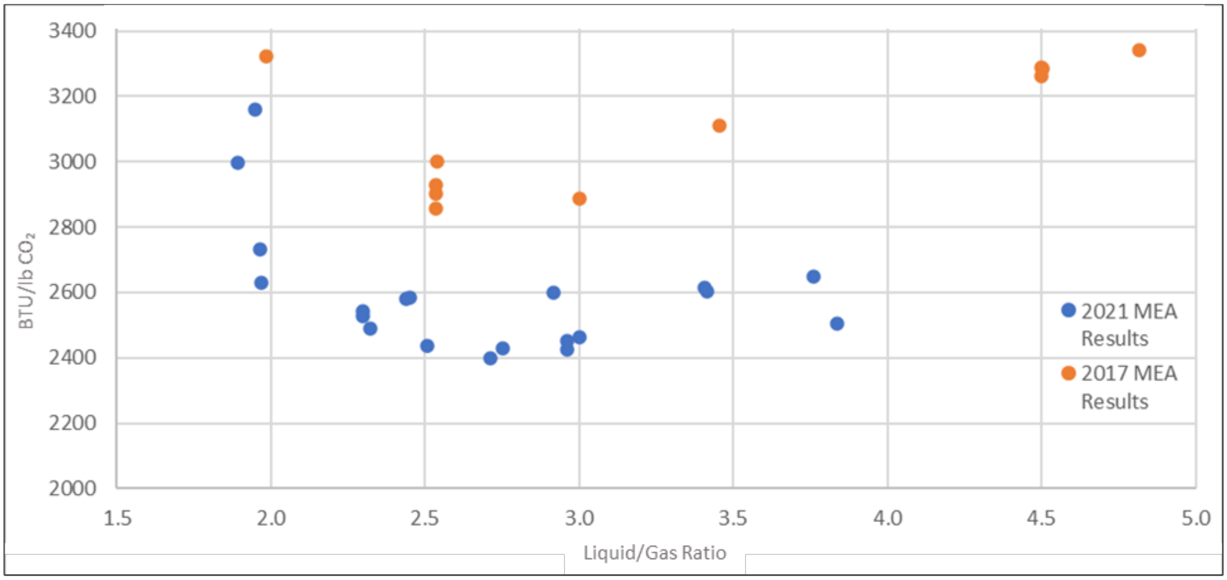

Figure 16. SSTU Regeneration Energy as a Function of Liquid/Gas Ratio Before and After Modifications

4.0 CONCLUSIONS AND LESSONS LEARNED

During BP6, the new natural gas flue gas system was brought online for the first time to support technology developer testing, resulting in 62% more testing time than that provided by Plant Gaston Unit 5 operation. The test runs conducted in BP6 included:

- Run PO-10, with short periods of operation in 2020 followed by resumed operation from January 14 through May 31, 2021
- Run PO-11, beginning June 1, 2021, and continuing into Budget Period 7

Operation supported testing of the following projects:

- GTI membrane contactor—Testing by GTI during both runs showed some performance decline of membrane modules similar to that seen in previous testing. GTI plans to test improved membrane modules in 2022.
- TDA Research alkalized alumina sorbent—Building on previous testing at the site, TDA began a 1,500-hour long-term test in August 2021 with coal flue gas and natural gas flue gas. Operation will continue into BP7.
- ION Clean Energy ICE-31 solvent—During the reporting period, ION achieved about 1,500 hours of long-term testing with the PSTU simple stripper. Operation was transitioned to the Advanced Flash Stripper and will continue in BP7.
- GTI ROTA-CAP solvent process—Preparations were underway for installation of the GTI skid to be following by parametric testing, and operation of the SSTU with the Carbon Clean solvent began to evaluate the impact of solvent concentration and liquid and gas flow on overall system performance. GTI plans to return to the site in 2022 to complete parametric testing with the ROTA CAP process and begin a 1,500-hour long-term test.
- UCLA Reversa process—UCLA's process was the first CO_2 utilization project completed at the NCCC. The test demonstrated CO_2 utilization efficiency in excess of 75%, CO_2 uptake greater than 0.5% of concrete (mass basis), and compliance of carbonated blocks within industry standard specifications. UCLA plans to conduct further testing at the site in a follow-on project in 2022.
- Southern Research ethane-to-ethylene process—Southern Research began testing in August 2021, achieving over 500 hours of operation using captured CO_2. Operations will transition to direct flue gas feed in the next reporting period.

Projects that were under development during the reporting period included the following:

- NETL membrane materials—The NETL team continued preparing new membrane samples and will return to the site for testing in 2022.
- GTI graphene oxide-based membrane—GTI began preparing to test a two-stage process using GO-1 and GO-2 membranes to demonstrate its performance with both natural gas- and coal-derived flue gases at the NCCC in 2022.

- Precision Combustion Inc. Microlith sorbent—After operating their sorbent test skid at the site in 2020 with bottle gases, PCI plans to return in 2022 for flue gas testing.
- UT-Austin PZAS process—UT-Austin is continuing development of the PZAS process, with a six-month test campaign planned for 2022 using natural gas flue gas to evaluate solvent degradation and oxidation.
- LumiShield anti-corrosion coating—The NCCC installed corrosion coupon ports for LumiShield's testing. Although LumiShield canceled their test campaign, the ports are available for use by future technology developers.
- Altex Technologies sorbent process intensification—Collaboration was underway for testing in 2022.
- Carbon America FrostCC process—The FrostCC team plans to begin testing in the second quarter of 2022.
- Helios-NRG algae for CO_2 utilization—Testing of this process for converting CO_2 to algae biomass is planned for the second quarter of 2022.
- Texas A&M algae for CO_2 utilization—Preparations are underway for testing the Texas A&M algae-based technology at the site in 2023.

Other projects that are scheduled for testing include:

- State University of New York at Buffalo bench-scale membrane
- Ohio State University bench-scale membrane
- Membrane Technology & Research bench-scale membrane
- Gas Technology Institute bench-scale membrane
- State University of New York at Buffalo bench-scale sorbent
- Southern States Energy Board bench-scale solid-amine absorption/desorption contactor
- Susteon ionic liquid catalyst
- Electric Power Research Institute/Pacific Northwest National Laboratory/RTI International water lean solvent

The following site modifications projects were underway during BP6:

- Natural gas flue gas infrastructure—The first fire of the natural gas boiler was achieved in December 2020, and the system operated during BP6 to support testing.
- CO_2 utilization infrastructure study—The study of infrastructure additions that would support future testing was completed.
- Increased natural gas flue gas flow through the PSTU—Evaluations were underway for increasing the flue gas flow rate for solvent technology developers.
- Install moisture measurement on the natural gas boiler flue gas header—An instrument to provide real-time moisture data was identified and will be installed in BP7 to support technology developers.

- Restoration work at the former gasification/pre-combustion site—Final restoration activities were completed, and the project was closed. The site is ready for future projects.
- Sump and waste handling improvement— Installation of the new system, which will include a new tank and associated equipment to allow the separation of rainwater and process fluids, will be completed in BP7.
- PSTU solvent filter improvement—This project was initiated to prevent leaks and enhance personnel protection, with completion planned for the next budget period.
- Control system modification for lock-out test/try— The function will reduce the time and effort required for the lock-out process and reduce worker exposure to hazardous voltage during the verification process. Completion of the project is planned in BP7.
- Instrument air improvements—This project will be completed in BP7 to improve the reliability of this critical utility.
- SSTU modifications and MEA baseline testing—Modifications were made to the SSTU to upgrade instrumentation, minimize process bottlenecks, and improve accessibility and functionality for operations and maintenance. Baseline testing with MEA solvent performed after the changes were complete demonstrated a marked improvement in operation as demonstrated by lower regeneration energy requirements compared to previous operation.