National Carbon Capture Center

Topical Report
Budget Period 8

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Disclaimer

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 management technologies. Bridging the gap between laboratory research and large-scale demonstrations, the center evaluates novel 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 8 (BP8) reporting period, spanning from October 1, 2022, through September 30, 2023, efforts at the NCCC effectively advanced post-combustion carbon capture, conversion, and removal technology development. Testing was conducted with membrane, solvent, and sorbent technologies during three test runs, and the site conducted its first algae conversion and direct air capture tests. During BP8, several improvements were made to the site to enhance testing capabilities.

To date, the NCCC has accumulated nearly 150,000 hours of post-combustion testing for over 75 technologies from more than 50 developers originating from six countries in addition to the USA: Canada, Germany, India, Japan, Norway, and the UK.

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Table of Contents

Disclaimer ii
Abstract iii
Acknowledgement iv
List of Figures and Tables vii
List of Abbreviations viii
1.0 Executive Summary 1
1.1 Project Partnerships 1
1.2 Reporting Period 1
1.3 Test Facilities 1
1.4 Accomplishments 2
1.5 Future Test Plans 6
2.0 Test Facilities and Support 8
2.1 Test Site 8
2.2 Support Staff 9
2.3 Analytical Support 10
3.0 Technical Progress 12
3.1 CO_2 Capture Projects 12
3.1.1 UT-Austin PZAS Process 12
3.1.2 Carbon America FrostCC Process 15
3.1.3 EPRI/Pacific Northwest National Laboratory/RTI International Water-Lean Solvent 17
3.1.4 KC8 Capture Technologies UNO MK 3 Solvent Process 17
3.1.5 SRI International Mixed-salt Process Solvent 17
3.1.6 GTI Energy Rotating Packed Bed Solvent Process 18
3.1.7 CORMETECH Sorbent 19
3.1.8 Altex Technologies Sorbent Process Intensification 20
3.1.9 NETL Membrane Materials 20
3.1.10 NETL Fiber Optic-based Sensors 21
3.1.11 Ohio State University Membrane 21
3.1.12 Precision Combustion Microlith Sorbent Technology Testing 22
3.1.13 GTI Energy Graphene Oxide-Based Membrane 23
3.1.14 Helios-NRG Membrane 24
3.2 CO_2 Conversion Projects 24
3.2.1 UCLA CarbonBuilt Concrete 24

3.2.2 Helios-NRG Algae 25

3.3 Carbon Reduction Technologies 25

3.3.1 SSEB/Aircapture Sorbent-Based Direct Air Capture 25

3.4 Site Modifications 27

3.4.1 Sump and Waste Handling Improvement 27

3.4.2 Control System Modification for Lock-Out Test/Try 27

3.4.3 PSTU Steam Condensate Flow Meter Improvements 27

3.4.4 Natural Gas Reliability Upgrades 28

3.4.5 Computer Modeling of Flue Gas and Solvent Systems 29

4.0 Conclusions and Lessons Learned 30

List of Figures and Tables

Figure 1. Photographs of Post-Combustion Carbon Capture Test Facilities 8
Figure 2. Schematic of Flue Gas Distribution at NCCC Test Facilities 9
Figure 3. PSTU Analysis Capabilities 10
Figure 4. University of Oslo's Proton Transfer Reaction-Time of Flight Mass Spectrometer 13
Figure 5. Ammonia Emissions During PZAS Testing 14
Figure 6. Solvent Samples from CCR Reclaiming Test 15
Figure 7. Carbon America FrostCC Process Diagram 15
Figure 8. Carbon America installation progress, September 2023 16
Figure 9. Simplified ROTA CAP Flow Design 18
Figure 10. CORMETECH Sorbent Process Flow Diagram 19
Figure 11. NETL Membrane Test Equipment 20
Figure 12. OSU Membrane Test Skid Installed in LSTU 22
Figure 13. PCI Sorbent Skid Installed in LSTU 22
Figure 14. GTI Energy Graphene Oxide-Based Membrane Test Skid Installed in LSTU 23
Figure 15. Flow Diagram of Helios-NRG Algae System 25
Figure 16. Aircapture Concept Drawing 26
Figure 17. Aircapture DAC Equipment Installed at the NCCC 26

Table 1. Projects Tested and Under Development During Budget Period 8 2
Table 2. PSTU Gas Analyzers 11
Table 3. PSTU Liquid Sampling Locations 11
Table 4. Test Matrix Parameters for UT-Austin PZAS Test Campaign 13

List of Abbreviations

AFS	Advanced Flash Stripper
BP7	Budget Period 7
BP8	Budget Period 8
BP9	Budget Period 9
CO_2	Carbon dioxide
DAC	Direct air capture
DOE	Department of Energy
GPU	Gas permeation unit
LSTU	Lab-Scale Test Unit
MEA	Monoethanol amine
NCCC	National Carbon Capture Center
NETL	National Energy Technology Laboratory
NO_2	Nitrogen dioxide
OSU	Ohio State University
PCI	Precision Combustion Inc.
PO-13	Post-Combustion Run 13
PO-14	Post-Combustion Run 14
PO-15	Post-Combustion Run 15
PSTU	Pilot Solvent Test Unit
SO_3	Sulfur trioxide
SRII	SRI International
SSEB	Southern States Energy Board
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 carbon management technology solutions. Bridging the gap between laboratory research and large-scale demonstrations, the NCCC evaluates carbon capture, conversion, and removal processes from third-party developers, focusing on the early-stage development of the most promising, cost-effective technologies for future commercial deployment.

The NCCC is quickly nearing the mark of 150,000 hours of testing, successfully advancing a wide range of technologies toward commercial scale while improving their performance and reducing cost. The NCCC testing of over 75 technologies from more than 50 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 reduction.

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 carbon capture 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 (DAC).

Since the NCCC is a cost-shared collaborative 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 8 (BP8) of the NCCC's second cooperative agreement with DOE, DE-FE0022596, covering October 1, 2022, through September 30, 2023.

1.3 Test Facilities

The NCCC provides test facilities and wide-ranging support to researchers developing low-cost carbon management technologies. 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/natural gas unit and from a dedicated natural gas boiler.

The site accommodates solvent testing with the Pilot Solvent Test Unit (PSTU) and the bench-scale Slipstream Solvent Test Unit (SSTU) and provides pilot bays, bench-scale bays, and the Lab-Scale Test Unit (LSTU) to site technology developer test equipment.

1.4 Accomplishments

During the reporting period, the NCCC operated for three test runs, supporting carbon capture and conversion projects, as well as the NCCC's first DAC demonstration.

- Run PO-13 started in BP7 on August 1, 2022, and ended on January 12, 2023.
- Run PO-14 was conducted from February 15, 2023, through July 31, 2023.
- Run PO-15 started on August 1, 2023, and will continue into Budget Period 9 (BP9).

Table 1 lists the technology developer projects tested during the reporting period, as well as those currently being developed for testing in 2024. New projects that are planned for testing in 2024 or later but are not yet in the NCCC's engineering support phase are listed in Section 1.5.

Table 1. Projects Tested and Under Development During Budget Period 8

	Location/ Scale	*Tested in Run PO-13*	*Tested in Run PO-14*	*Tested in Run PO-15*	*Planned for 2024*
CO_2 Capture Projects					
University of Texas at Austin (UT-Austin) PZAS™ process	PSTU	✓	✓	✓	
Carbon America FrostCC™ process	Pilot-scale				✓
EPRI/Pacific Northwest National Laboratory/RTI International water-lean solvent	PSTU				✓
KC8 Capture Technologies UNO MK 3 solvent process	Pilot-scale				✓
SRI International (SRII) mixed-salt solvent	Pilot-scale				✓
GTI Energy ROTA-CAP™ rotating packed bed solvent process	Bench-scale	✓	✓		
CORMETECH sorbent	Bench-scale				✓
Altex Technologies sorbent process intensification	LSTU				✓
NETL membrane materials	LSTU	✓	✓	✓	✓
NETL fiber optic-based sensors	SSTU				✓
Ohio State University (OSU) membrane	LSTU	✓			
Precision Combustion Inc. (PCI) Microlith® sorbent	LSTU		✓		
GTI Energy graphene oxide-based membrane	LSTU			✓	✓

	Location/ Scale	Tested in Run PO-13	Tested in Run PO-14	Tested in Run PO-15	Planned for 2024
Helios-NRG membrane	LSTU				✓
CO_2 Conversion Projects					
UCLA CarbonBuilt concrete	Bench-scale				✓
Helios-NRG algae	Bench-scale	✓			✓
Direct Air Capture Projects					
Southern States Energy Board (SSEB)/Aircapture sorbent-based DAC	Bench-scale		✓	✓	✓

Highlights of the current technology developer projects are described below.

UT-Austin PZAS Process

Since performing previous successful test campaigns at the site with the PZAS process featuring the Advanced Flash Stripper (AFS) and piperazine solvent in the PSTU, UT-Austin conducted another test campaign focused on degradation and oxidation studies, as well as mitigation measures. The test campaign also featured use of University of Oslo's Proton Transfer Reaction-Time of Flight Mass Spectrometer to analyze emissions and CCR's solvent reclaiming technology. Operation entailed over 5,800 hours and collected solvent degradation, emissions, and corrosion data, which are being analyzed for final results.

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. Minimum objectives for this field test include achieving 90% CO_2 capture at a rate equivalent to 500 metric tons per year and 100 continuous hours of operation. Beyond the minimums, nominal target goals for this test are 99% CO_2 capture at a rate of 1,000 metric tons per year and 1,000 hours of continuous operation. The Carbon America team plans to begin testing in the first quarter of 2024.

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. Commissioning of the modifications is targeted for the first quarter of 2024, with testing to begin immediately thereafter.

KC8 Capture Technologies UNO MK 3 Solvent Process

KC8 Capture Technologies is developing the UNO MK 3 solvent process which uses a novel catalytically enhanced precipitating solvent technology for natural gas combined-cycle application. Under Phase I of this ARPA-E FLECCS-funded program, KC8 Capture Technologies proved the potential for the process to be retrofitted to gas turbines to produce low-emissions, low-cost power in a highly variable renewable penetration grid and was awarded to proceed to field demonstration at the NCCC in Phase II. KC8 Capture Technologies plans to deliver modular skids to the NCCC for installation in the pilot bay area to demonstrate capture of 5 to 10 tonnes of CO_2 per day. Testing is planned to begin in the second or third quarter of 2024.

SRI International Mixed-salt Process Solvent

SRII is developing a novel mixed-salt solvent-based technology that combines potassium and ammonium salts as the solvent with unique process configurations without chilling the solvent to efficiently capture CO_2 from flue gas. The solvent mixture is non-precipitating, non-degradable, inexpensive, and readily available and it can be regenerated at elevated pressure. It minimizes the volatility of the pure ammonia-based solvent and thus chilling requirements, and it improves the kinetics of the slow potassium carbonate reaction with ammonium salts as the promoter. In this project, SRII plans to deliver modular skids to the NCCC's pilot bay area to demonstrate capture of 5 to 10 tonnes of CO_2 per day. Engineering work was underway, and testing is planned in the second half of 2024.

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. 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. After completing a test campaign at the NCCC in June 2022, GTI made modifications to bring the test skid back to its original design capacity. Testing was conducted from April through July 2023, confirming that the modifications significantly improved the solvent performance and brought the unit rating close to the original design.

CORMETECH Sorbent

CORMETECH is developing a sorbent monolith carbon capture system for bench-scale testing at the NCCC. The project team, which includes Global Thermostat Operations, Middle River Power, Southern Company, and Zero Carbon Partners, will develop, optimize, and test a novel integrated process technology for point-source capture of CO_2 from natural gas combined-cycle flue gas. The process employs multiple beds of monolithic amine contactors to capture CO_2 by adsorption and then regenerate via thermal desorption. The bench-scale test will target at least one month of continuous operations demonstrating 95% CO_2 capture with 95% purity of the CO_2 product stream. Testing is slated for 2024.

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 2024.

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 NETL team returned the automated membrane test skid to operation with new materials in October 2022. Since then, the skid was used to test three different bulk films composed of a proprietary NETL material, samples of thin-film composite membrane materials, and a thin-film membrane sample developed by University at Buffalo and Helios-NRG. NETL also performed initial screenings on five additional thin-film composite membranes. These samples will be evaluated during NCCC's BP9 into the spring of 2024.

NETL Fiber Optic-based Sensors

NETL is developing an optic sensor technology for online monitoring of solvent degradation and CO_2 concentration in flue gas. NETL plans to test their sensor technology using monoethanol amine solvent in the SSTU. Testing is targeted to start in the first quarter of 2024.

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 (N_2) selectivity at 77°C. Flue gas testing started in November 2022 using undiluted natural gas flue gas. The skid was then operated with diluted natural gas flue gas having a 4.4% CO_2 concentration. OSU completed the test campaign in December 2022, achieving 530 hours of continuous operation. Overall, the membrane performance was stable under the test conditions, with a CO_2 recovery of around 90% and CO_2 purity of more than 95% on dry basis.

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 briefly at the NCCC in 2020 and in 2022, and conducted a third test campaign in April 2023, completing 45 hours of operation with 18 adsorption and desorption cycles. PCI demonstrated sorbent performance and durability in the presence of water and other common contaminants of the flue gas stream. The sorbent was rapidly thermally regenerated at low temperature (70 to 90°C) and was stable under all test conditions. Data acquired at the NCCC was utilized to refine PCI's computational fluid dynamics models for CO_2 sorption-desorption kinetics and refine of the techno-economic analysis for a full-scale unit.

GTI Energy Graphene Oxide-Based Membrane

GTI is developing a graphene oxide-based membrane technology expected to achieve at least 90% CO_2 capture from natural gas- or coal-derived flue gas using GO-1 and GO-2 membranes in a two-stage configuration (GO^2 process) to demonstrate its performance. The GO 1 membrane has high CO_2 permeances up to 1,200 GPU with close to 700 CO_2/N_2 selectivity, and the GO-2 membrane has permeance as high as 2,500 GPU. Testing at the NCCC commenced in August 2023. About 460 testing hours were completed in BP8, and testing will continue through the end of the year.

Helios-NRG Membrane

Helios-NRG is collaborating with the University at Buffalo to develop thin-film composite membrane technology using CO_2-philic block copolymers with intrinsic microporosity for post-combustion CO_2 capture. The membrane, which consists of rubbery polyethylene oxide and a polymerizable metal-organic framework, has achieved CO_2 permeance of 4,500 GPU and CO_2/N_2 selectivity of 40 at 35 to 60°C in laboratory testing. The current efforts are to scale up membrane fabrication and validate resistance to flue gas contaminates through long-term testing at the NCCC with flue gas. The Helios-NRG/University at Buffalo team secured funding for Phase 2A, and they plan to test improved membranes in 2024.

UCLA CarbonBuilt Concrete

UCLA is working to further improve their CarbonBuilt process to maximize CO_2 valorization and process economics from their 2021 test campaign for a suite of CarbonBuilt products that are compliant with best-in-class industry standards. Based on process modeling results, UCLA is modifying the concrete curing reactor and process control on the existing skids to improve mineralization performance. The process will be demonstrated again at the NCCC in 2024 using real flue gas with products to meet/exceed industry standards.

Helios-NRG Algae for CO_2 Conversion

Helios-NRG is developing a novel algae technology to capture CO_2 from fossil fuel power plants and then use the produced algae to make revenue-producing products. The upcoming test will demonstrate an improved version of the multi-stage continuous flow system that was previously tested at the NCCC in 2022. The system will be upgraded with controls for better operability and enhanced gas dissolution, with the expected benefits of increased algae productivity and reduced costs. The test campaign is scheduled to begin in the summer of 2024.

SSEB/Aircapture Sorbent-Based Direct Air Capture

SSEB is leading a project team to demonstrate decreased costs of DAC through testing of existing materials in integrated field units to produce CO_2 of at least 95% purity. The DAC technology provider, Aircapture, has designed a DAC system that utilizes waste heat typical of that available in power generation and industrial facilities. Testing at the NCCC began in April 2023, and through September 2023, the DAC skid achieved 1,343 hours of operation and confirmed production of CO_2 from air. Testing will continue through the end of the year. Through this testing, Aircapture has demonstrated it can meet its targets of more than 50% capture efficiency, greater than 95% CO_2 gas purity and 95% liquefaction efficiency, 99.9% liquid CO_2 purity, desorption temperatures of 80 to 100°C, and unattended DAC operations. In the coming NCCC budget period, Aircapture will add integrated CO_2 liquefaction to the demonstration test and complete a third test campaign with that as the focus.

Site Modifications

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

- Sump and waste handling improvement
- Control system modifications for lock-out test/try
- 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 2024 or later include:

- Texas A&M algae for CO_2 conversion
- University at Buffalo sorbent
- Clean Energy Research Institute solvent in the PSTU
- University of Sheffield monoethanol amine (MEA) solvent in the PSTU

2.0 TEST FACILITIES AND SUPPORT

Located at Alabama Power's E.C. Gaston power plant, the NCCC provides test facilities and wide-ranging support to researchers developing low-cost carbon management technologies.

2.1 Test Site

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 Plant Gaston's Unit 5, which is fired with pulverized coal or natural gas, and from the NCCC's natural gas testing infrastructure. The flue gas can be conditioned to suit specific technology developer needs.

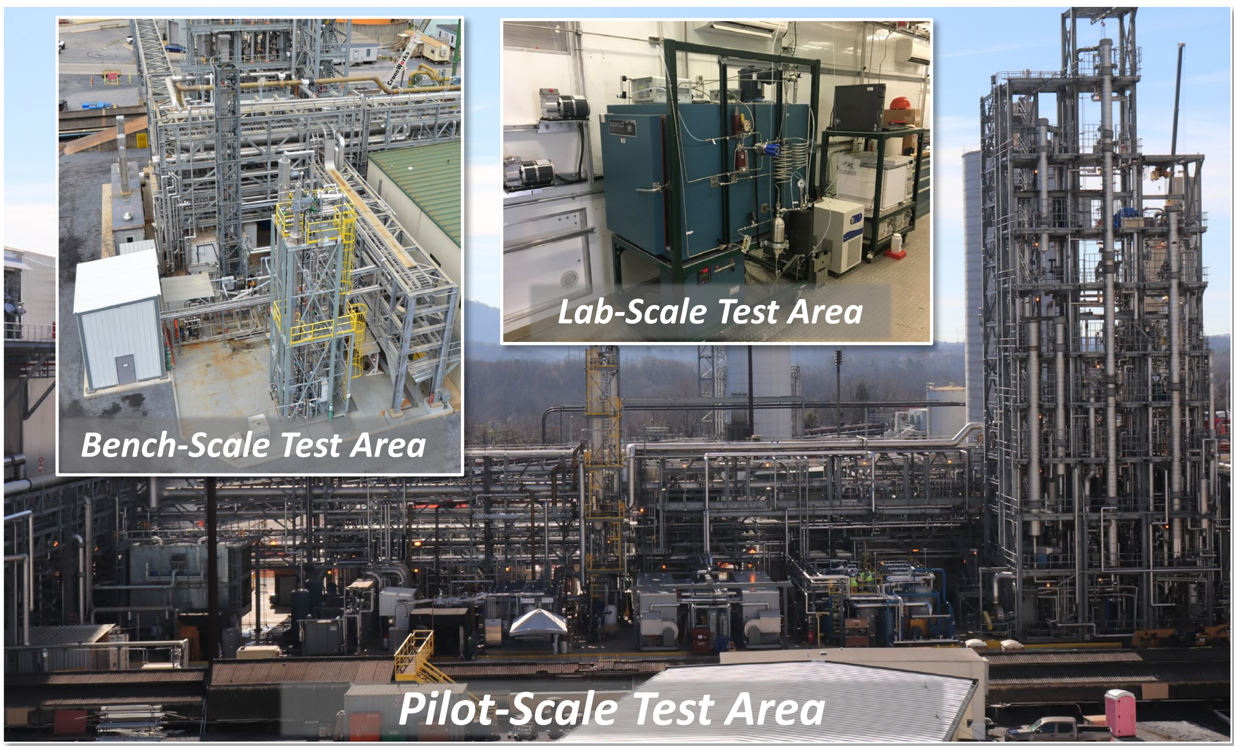

Figure 1. Photographs of Post-Combustion Carbon Capture Test Facilities

Plant Gaston Unit 5 meets all environmental requirements through state-of-the-art controls, and thus the flue gas extracted for testing is fully representative of commercial conditions. While Unit 5 was designed as a supercritical coal-fired unit, it now has the capability to operate using 100% natural gas, a mixture of natural gas and coal, or 100% coal.

The NCCC's dedicated natural gas-fired boiler, commissioned in early 2021, allows the NCCC to simulate flue gas from a conventional natural gas combined-cycle plant, and with process adjustments, from coal-fired or industrial sources. The natural gas test system also creates operational independence from Plant Gaston, increases operational flexibility and available testing time, and supplies a flue gas source with minimal contaminants.

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.

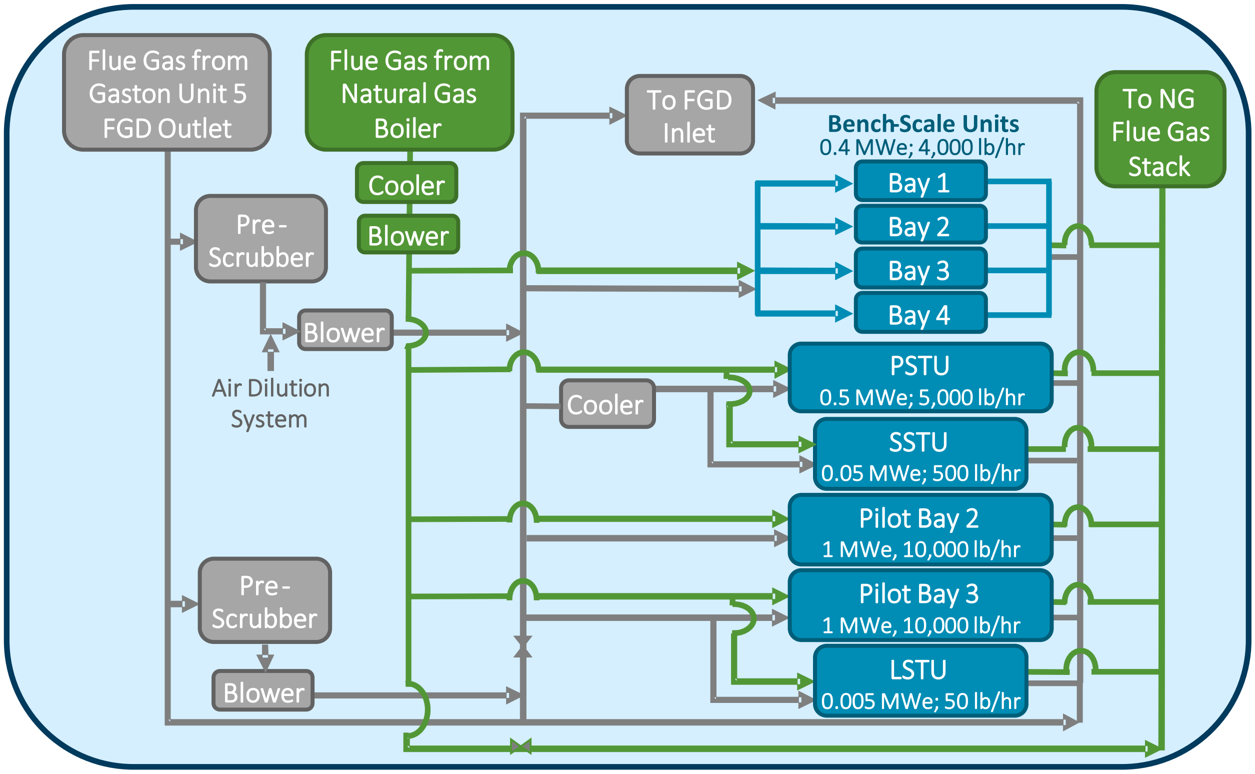

Figure 2. Schematic of Flue Gas Distribution at NCCC Test Facilities

The NCCC design provides the flexibility to test not only carbon capture processes, but also CO_2 conversion, DAC, and hybrid concepts. Flue gas composition can be modified, for example through air dilution and bottle gas injection, to simulate various flue gas sources.

2.2 Support Staff

The NCCC offers a highly experienced staff who aid developers in moving their technologies forward:

- Design engineers with proficiency in technology scale-up and process and infrastructure modifications to test new projects
- Operations and maintenance staff with in-depth knowledge of project execution
- Research engineers that collect and analyze data, and report on technology performance and design improvements
- Support staff to develop contracts and other measures to protect developers' intellectual property

2.3 Analytical Support

The NCCC test site includes on-line process gas analyzers and an on-line process titrator for solvent measurements. These instruments, housed in dedicated laboratory space, include gas chromatographs for analysis of gas streams, a nitrogen dioxide low-level (parts per billion) analyzer, and an Electrical Low Pressure Impactor (ELPI+) manufactured by Dekati. Sampling ports for the ELPI+ are located on the PSTU inlet (untreated flue gas), the SSTU inlet (following SO_2 removal and cooling within the PSTU process units), and the SSTU wash tower outlet.

Liquid sampling systems are also available for analysis of amine degradation products. To assist with solvent corrosion studies, corrosion coupons holders are located in the PSTU and SSTU.

The NCCC offers a system for adding nitrogen dioxide (NO_2) to the flue gas as a method for testing technologies requiring NO_2 concentrations higher than that of the supplied flue gas. Also available is a system for adding SO_3 in flue gas slipstreams to study aerosols and solvent emissions.

The current analytical capability for gas and liquid analysis is shown in Figure 3 for the PSTU. The yellow boxes show what gas constituents are analyzed or the sampling location and what type of sampling takes place at the location. The green boxes are liquid analysis and sampling locations. Red text indicates what type of emission control was provided for testing during the UT-Austin oxidation studies (see Section 3.1.1) and can be used in future testing. As seen in Figure 3, SO_3 and NO_2 addition after the blower are NCCC capabilities that are also offered to developers. NCCC will work with developers to develop and supply the analytical support needed for their testing.

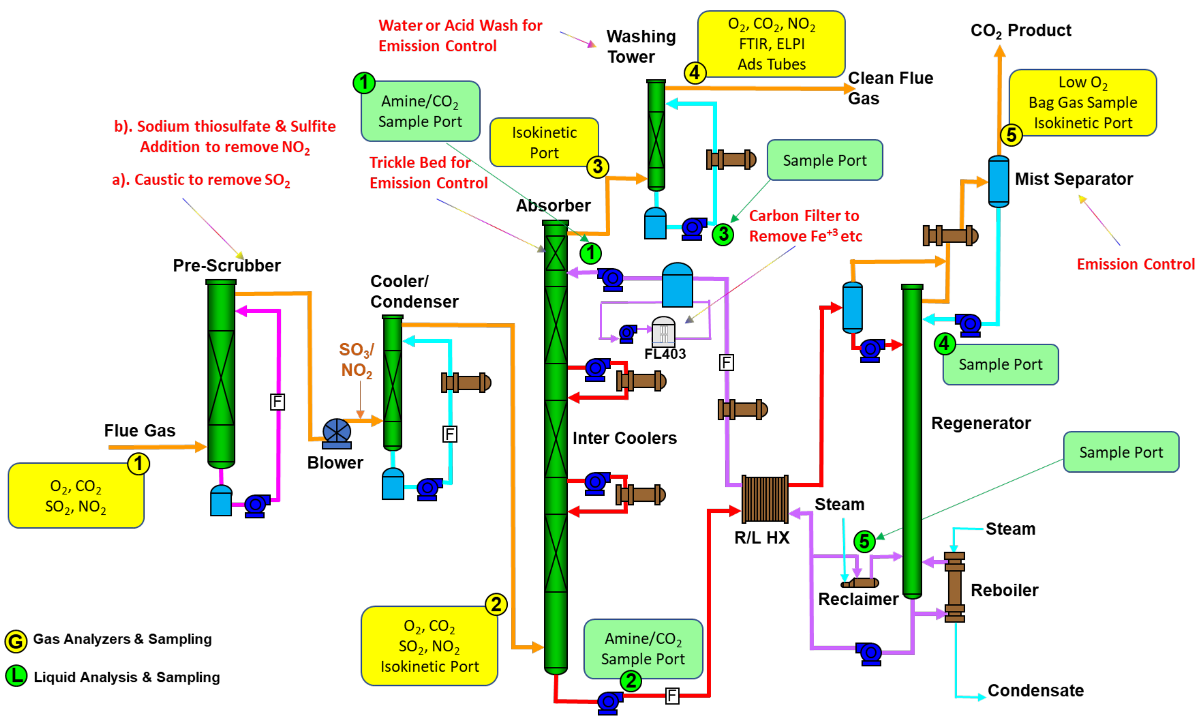

Figure 3. PSTU Analysis Capabilities

Table 2 provides the locations of PSTU gas analyzers along with information on the analysis. In addition to the commercially established techniques listed, the NCCC developed an impinger train for analysis of amine and degradation products in the flue gas exiting the absorber.

Table 2. PSTU Gas Analyzers

On Figure 3	*Stream*	*Species*	*Technique*
Yellow box #2	Absorber inlet	CO_2 Oxygen Sulfur dioxide	NDIR Paramagnetic Ultraviolet
Yellow box #4	Absorber outlet	Oxygen CO_2 Nitrogen oxide NO_2	Paramagnetic NDIR NDIR NDIR
	Regenerator outlet	CO_2	By difference

Liquid samples are extracted from the four locations indicated in Table 3. An auto-titration system is used to determine the solvent concentration and CO_2 loading, taking a sample automatically every 30 minutes at each location.

Table 3. PSTU Liquid Sampling Locations

On Figure 3	*Stream*	*Temperature, °F*	*Description*
Green box #5	Regenerator outlet	230	Hot-lean
Green box #1	Absorber inlet	110	Cool-lean, same composition as hot-lean (5)
Green box #2	Absorber outlet	130	Cool-rich
Green box #4	Regenerator inlet	215	Hot-rich, same composition as cool-rich (2)

3.0 TECHNICAL PROGRESS

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

- Run PO-13, starting in Budget Period 7 (BP7) on August 1, 2022, and ending January 12, 2023
- Run PO-14, beginning February 15, 2023, and concluding on July 31, 2023
- Run PO-15, starting August 1, 2023, and continuing into BP9

The following sections describe the current projects at the site.

3.1 CO_2 Capture Projects

3.1.1 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 test campaign, which was supported by DOE, EU LAUNCH, and private companies, entailed a study of solvent degradation and oxidation, as well as mitigation measures. In addition, the test demonstrated that the solvent can process hot flue gas directly from a natural gas combined-cycle plant without cooling.

The NCCC completed several modifications to accommodate the testing, including the addition of a heater to heat the flue gas to 110ºC (230ºF), 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.

Design and construction work to support this project were completed in October 2022, and water commissioning began in November. Key achievements from the commissioning included:

- Commissioning the flue gas heater, demonstrating heating to the desired temperature
- Reaching an 8,000 lb/hr flow rate of natural gas boiler flue gas that was not achievable previously
- Demonstrating a flue gas CO_2 concentration of 4.4% using air injected at the PSTU blower, which adds flexibility in the natural gas boiler operation
- Commissioning the new water wash configuration using the third absorber bed as part of a two-stage wash

Several test conditions were completed to measure the heat loss around the AFS before solvent operation in the PSTU began in December. Natural gas flue gas was introduced once solvent circulation reached steady state. Initial operation focused on unloading fresh solid piperazine from six drums into the PSTU and achieving a uniform solvent concentration. A special process to soften the solid piperazine employed a slipstream of rich solvent from the PSTU circulation loop to carry the softened piperazine back to the PSTU solvent circulation loop.

After a site outage was completed, the solvent test campaign began with used solvent from previous campaigns in February 2023 (the fresh solvent from the drums was used as makeup). The test plan consisted of five test matrices with various control mechanisms to evaluate solvent performance, emissions, and degradation. These control mechanisms and parameters are shown in Table 4.

Table 4. Test Matrix Parameters for UT-Austin PZAS Test Campaign

Control Parameters	***Purpose***
Reduce NO_2 to < 1 ppm and measure	Use sulfite/thiosulfate in pre-scrubber to remove NO_2
Nitrogen sparging in the absorber sump	Test efficacy of dissolved oxygen stripping in the absorber sump
Remove iron (as chelates) with carbon bed	Test impact of removing oxidation catalysts over slipstream range 1 – 5 gpm
Water wash configured as acid wash loop	Ammonia control
Adding corrosion coupons	Monitor corrosion simultaneous with oxidation

The first five-week test matrix included all the degradation mitigation methods: adding thiosulfate and sulfite in pre-scrubber, sparging nitrogen at the bottom of the absorber and having carbon filters online. The second five-week test matrix was conducted with no nitrogen sparging and with new corrosion coupons installed. During the third five-week period, no chemicals were added to the pre-scrubber to reduce nitrogen dioxide in the flue gas. For the fourth test matrix, the carbon bed was bypassed, and for the fifth test matrix, all degradation mitigation methods were turned back on. Various water wash configurations were also evaluated for emissions control during this period, including a trickle bed wash, third absorber bed water wash, water and acid wash in the wash tower, and combinations of these. All the test conditions were completed in late August.

During the test campaign, UT-Austin used a specialized analyzer, the Proton Transfer Reaction-Time of Flight Mass Spectrometer, shown in Figure 4, from University of Oslo to collect emission data on cleaned flue gas leaving the absorber and wash tower at below 1 ppm concentration range. The analyzer operated from July until the end of test campaign in October.

Figure 4. University of Oslo's Proton Transfer Reaction-Time of Flight Mass Spectrometer

During the test campaign, UT-Austin requested an extension of testing time for an added scope of evaluating CCR's solvent reclaiming technology and verify solvent performance post reclaiming. For the added scope, the NCCC worked expeditiously with CCR and the UT-Austin team to develop siting and layout, design to accommodate the CCR mobile unit, etc. Beginning in September, a slipstream of lean solvent from the PSTU was fed to the CCR unit, and the reclaiming test was concluded after a volume equal to three times the PSTU solvent inventory was processed. Solvent, as well as residual waste samples were collected for analysis during the three-day reclaiming test.

Overall, the test campaign entailed over 5,800 hours of operation and collected solvent degradation, emissions, and corrosion data, which are being analyzed for final results. A preliminary assessment demonstrated the effectiveness of nitrogen dioxide reduction in the flue gas with chemical addition to pre-scrubber, nitrogen sparging in absorber sump to reduce dissolved oxygen in the solvent, and use of the carbon bed to remove corrosion and degradation products from the solvent. The acid wash proved to be effective in controlling ammonia emissions, as shown in Figure 5. In addition, solvent reclaiming reduced ammonia emissions by removing degradation products.

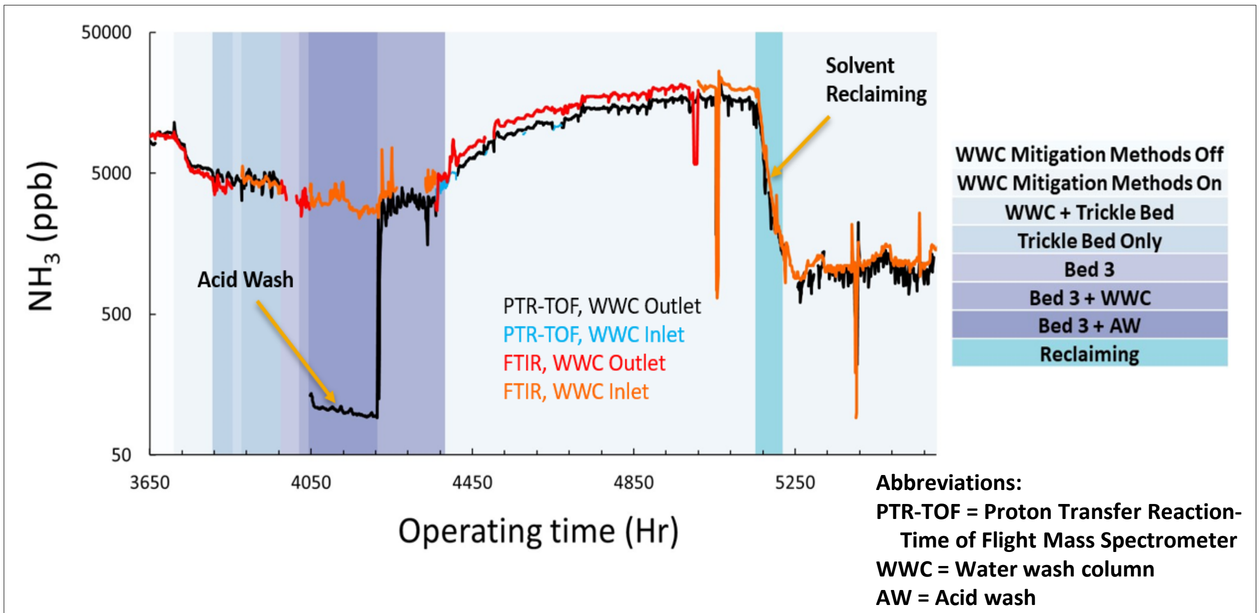

Figure 5. Ammonia Emissions During PZAS Testing

Solvent reclaiming was successfully demonstrated based on the solvent color progression from dark brown to almost clear over three days, as shown in Figure 6. Testing also demonstrated that the piperazine solvent can achieve a CO_2 capture rate of over 95% with a minimal increase in energy penalty from the 90% capture case. Additional analysis is ongoing, and final results will be published in a subsequent report.

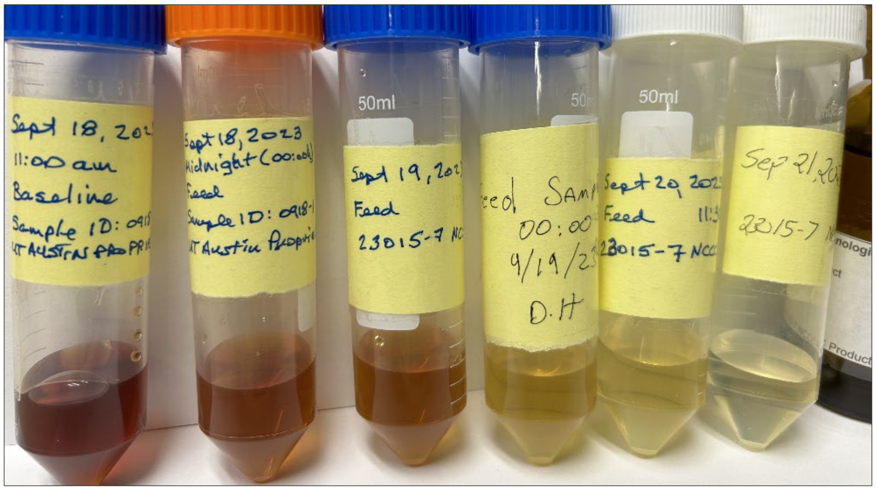

Figure 6. Solvent Samples from CCR Reclaiming Test

3.1.2 Carbon America FrostCC Process

Carbon America has developed the FrostCC process for point-source carbon capture applications. FrostCC separates CO_2 from a flue gas stream by compressing and cooling the stream to conditions that facilitate the solidification of the CO_2. Importantly, no external refrigerant is used to achieve this cooling. Cryogenic conditions are achieved through compression, atmospheric cooling, gas stream expansion, and heat integration. While the process centers on a newly developed heat exchanger for CO_2 solidification (or "frosting"), the peripheral steps take advantage of existing technologies. Figure 7 outlines the steps of the FrostCC process and how CO_2 is separated.

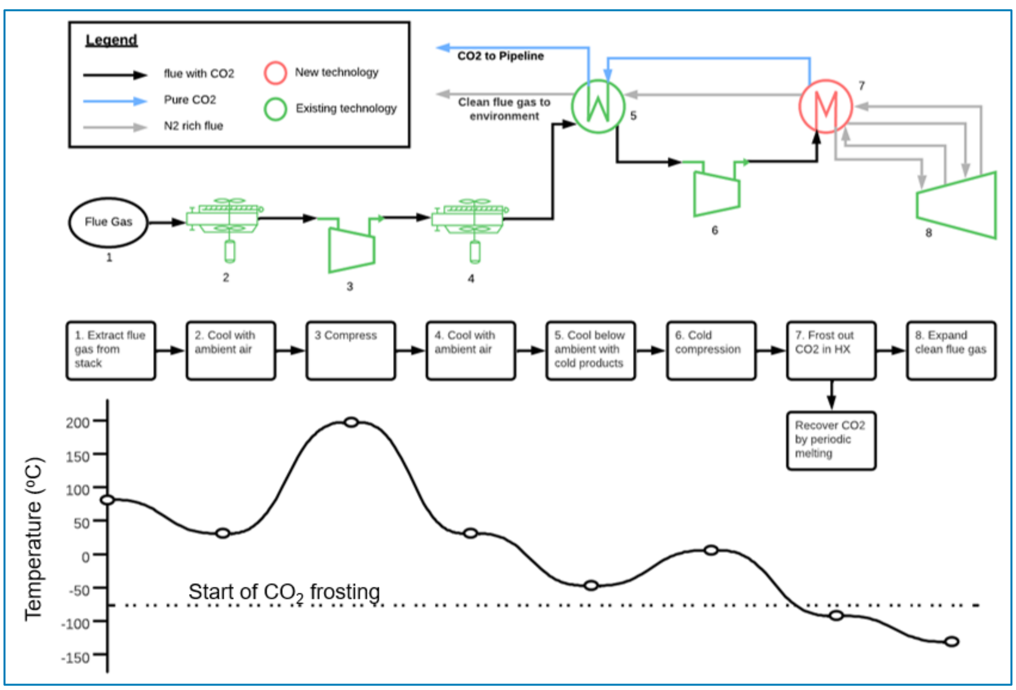

Figure 7. Carbon America FrostCC Process Diagram

To date, testing of the component processes of the FrostCC system have occurred at Carbon America's facilities in Colorado. The upcoming pilot field test at NCCC will represent the first combined, continuous demonstration of carbon capture (frosting) and production (melting).

NCCC and Carbon America personnel worked together throughout Budget Period 8 to prepare for the field test. NCCC engineers developed packages for the installation of Carbon America's equipment in the pilot bay and issued those to construction in early 2023. Meanwhile, Carbon America worked with external vendors and their internal fabrication team to acquire and prepare skids for shipment to the NCCC. Initial delivery and placement of the compression, pre-cooling, and electrical skids occurred in March 2023. NCCC construction personnel then completed all connections between the NCCC infrastructure, and the Carbon America skids while Carbon America personnel completed internal system connections.

Carbon America experienced delays in obtaining the Frost heat exchangers from external vendors, but work continued to prepare the supporting processes for testing. In July and August NCCC construction personnel prepared the foundations to support the liquid CO_2 and Frost heat exchanger structures, as shown in Figure 8. Meanwhile, Carbon America personnel onsite commissioned the gas compressor, dryer, and expander systems. Once the equipment commissioning was complete, Carbon America personnel embarked upon a test plan to obtain pressure and temperature data to validate the thermodynamic models used to design and predict the FrostCC process. In September, the liquid CO_2 pumphouse, liquid CO_2 tank, and Frost heat exchanger tower base steel were installed.

Figure 8. Carbon America installation progress, September 2023

Next steps for the project in Budget Period 9 will include final installation of the Frost heat exchanger towers and liquid CO_2 piping. Carbon America will then go through full-system commissioning and then begin executing the test plan. Minimum objectives for this field test include achieving 90% CO_2 capture at a rate equivalent to 500 metric tons per year and 100 continuous hours of operation. Beyond the minimums, nominal target goals for this test are 99%

CO_2 capture at a rate of 1,000 metric tons per year and 1,000 hours of continuous operation. The data collected during the test will be critical to confirm thermodynamic modeling and inform future process development and scale-up.

3.1.3 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.

Three major scopes identified in this project include (a) flue gas cooling to 60 to 70ºF, which will require a 60-ton rental chiller and buffer tank and two new heat exchangers, (b) use of a GE CSTR skid steam heater in lieu of the PSTU reboiler for larger heat transfer surface areas, and (c) replacing absorber packing with an equivalent plastic version. Design and construction were underway throughout the budget period. Commissioning of the modifications is targeted for the first quarter of 2024, with testing to begin immediately thereafter.

3.1.4 KC8 Capture Technologies UNO MK 3 Solvent Process

KC8 Capture Technologies is developing the UNO MK 3 solvent process, which uses a novel catalytically enhanced precipitating solvent technology for natural gas combined-cycle application. Under Phase I of this ARPA-E FLECCS-funded program, KC8 Capture Technologies proved the potential for the process to be retrofitted to gas turbines to produce low-emissions, low-cost power in a highly variable renewable penetration grid and was awarded to proceed to field demonstration at the NCCC in Phase II. KC8 Capture Technologies plans to deliver modular skids to the NCCC for installation in the pilot bay area to demonstrate capture of 5 to 10 tonnes of CO_2 per day. Testing is tentatively scheduled to begin in the second or third quarter of 2024.

3.1.5 SRI International Mixed-salt Process Solvent

SRII is developing a novel mixed-salt solvent-based technology that combines potassium and ammonium salts as the solvent with unique process configurations without chilling the solvent to efficiently capture CO_2 from flue gas. The solvent mixture is non-precipitating, non-degradable, inexpensive, readily available, and can be regenerated at elevated pressure. It minimizes the volatility of the pure ammonia-based solvent and therefore chilling requirements, and it improves the kinetics of the slow potassium carbonate reaction with ammonium salts as the promoter. In this project, SRII plans to deliver modular skids to the NCCC's pilot bay area to demonstrate capture of 5 to 10 tonnes of CO_2 per day.

Engineering work has been underway, including the NCCC design of a new medium-pressure steam supply line that will be needed for skid operation, preparations for medium- and low-pressure steam supply, sulfuric acid and anhydrous ammonia and their delivery systems, and chiller design and chilled water delivery. SRII will conduct a process hazard analysis in October 2023 with the NCCC's participation. Testing is targeted to begin in the third or fourth quarter of 2024.

3.1.6 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.

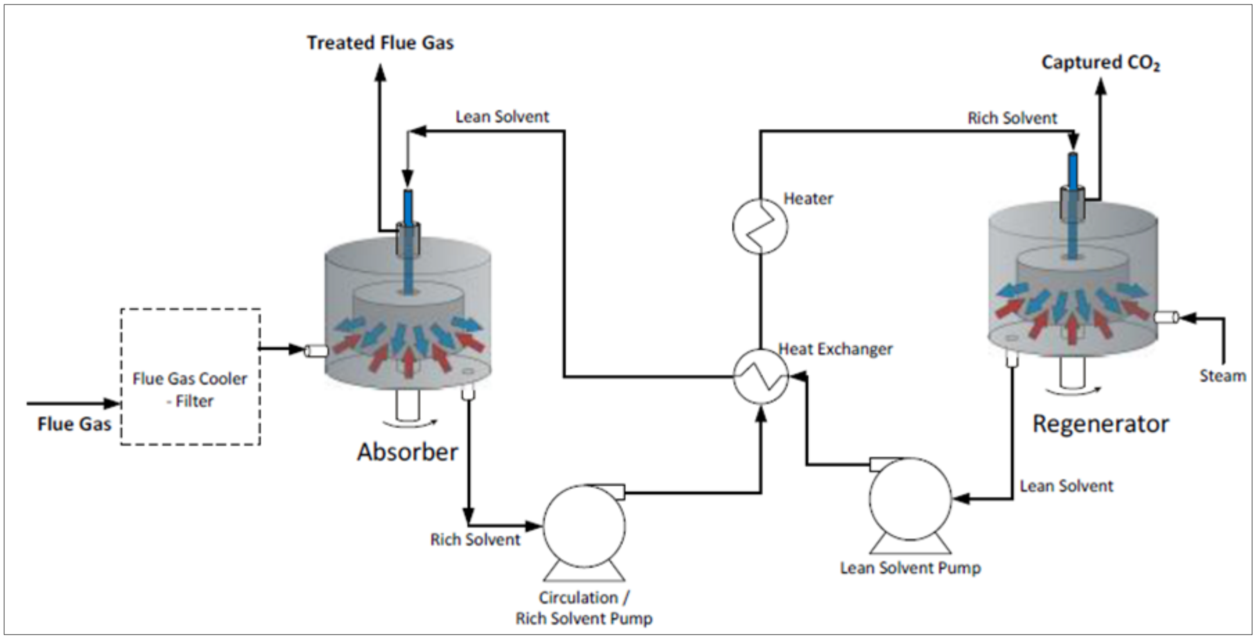

Figure 9. Simplified ROTA CAP Flow Design

After completing a test campaign at the NCCC in August 2022, GTI made modifications to bring the test skid back to its original design capacity. The first change was to increase the size of the rich/lean crossflow heat exchanger, and the second was to replace the original stripping packing to full size packing. These modifications were designed to increase the temperature of the hot-rich solvent entering the stripper and solvent residence time in the stripper.

GTI returned to the NCCC, completed the proposed modifications, and conducted testing from April 21 through July 10, 2023. During this time, in addition to verifying the performance improvements from those modifications, GTI tested different solvents at various concentrations. They also tested a higher flue gas CO_2 concentration achieved by injecting CO_2 to simulate industrial flue gas conditions.

The performance showed that the modifications significantly improved the solvent performance and brought the unit rating close to the original design. GTI completed a total 1,802 hours of operation since the skid was commissioned in October 2021. The NCCC also operated the Slipstream Solvent Test Unit with GTI's solvent for 1,604 hours to serve as a baseline with conventional column operation to compare to the GTI ROTA-CAP configuration.

3.1.7 CORMETECH Sorbent

CORMETECH is developing a sorbent monolith carbon capture system for bench-scale testing at the NCCC. The project team, which includes Global Thermostat Operations LLC, Middle River Power, Southern Company, and Zero Carbon Partners LLC, will develop, optimize, and test a novel integrated process technology for point-source capture of CO_2 from natural gas combined-cycle flue gas. As shown in Figure 10, the process employs multiple beds of monolithic amine contactors to capture CO_2 by adsorption and then regenerate via thermal desorption. The bench-scale test will target at least one month of continuous operations demonstrating 95% CO_2 capture with 95% purity of the CO_2 product stream. Testing is slated for 2024.

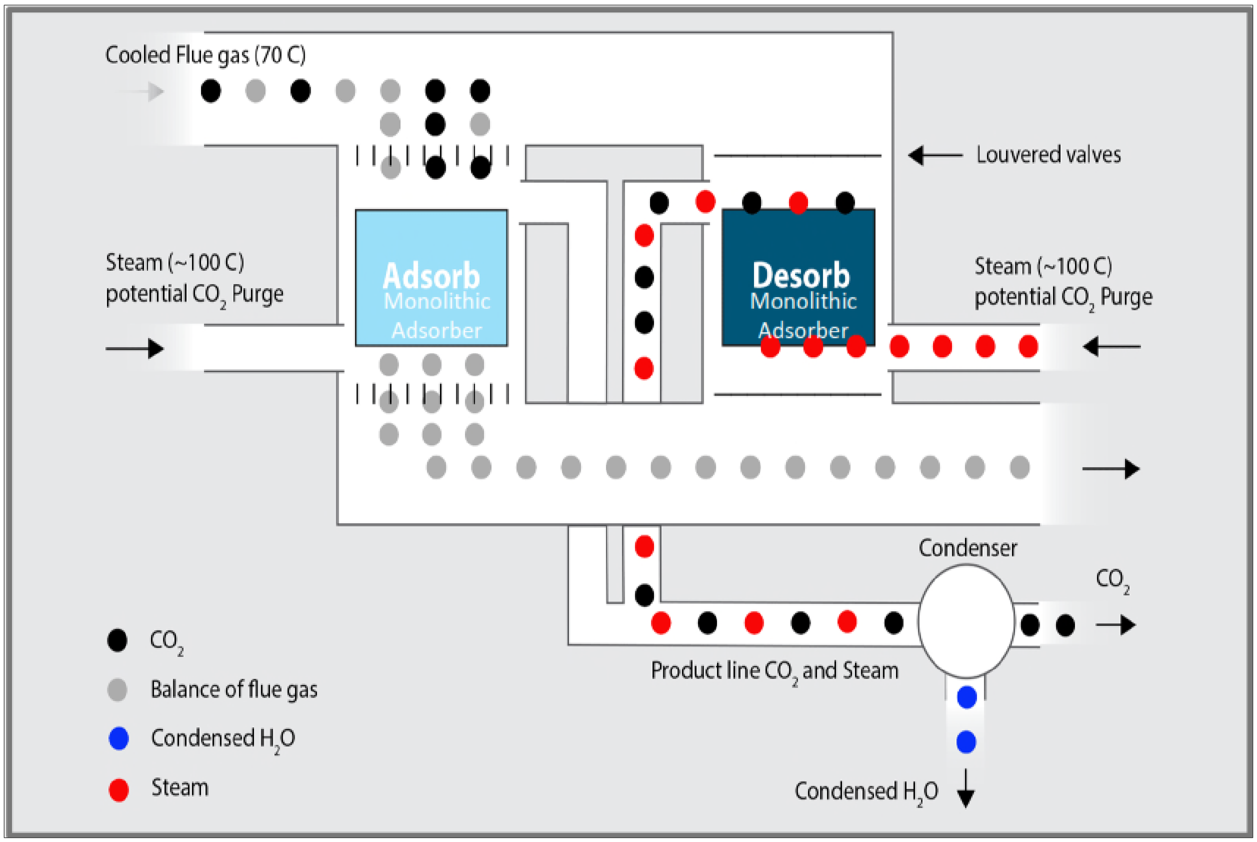

Figure 10. CORMETECH Sorbent Process Flow Diagram

Active collaboration between NCCC and CORMETECH personnel kicked off in May 2023 with a site visit to discuss integration of the bench-scale test skid and begin the development of the technology collaboration agreement. The engineering teams then held a series of hazard review meetings in June and July to identify any adjustments to the skid design before fabrication. CORMETECH has provided NCCC with skid information so that a project scope document and initial layout design has been completed. Next steps for the project teams in Budget Period 9 will include final skid fabrication by CORMETECH and detailed design package creation by NCCC.

3.1.8 Altex Technologies Sorbent Process Intensification

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 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.

In March 2023, Altex completed coating the sorbent on the adsorber and installed it in the test skid. Once the skid was complete, Altex began testing with simulated flue gas to determine the stability of the sorbent coating. Some technical issues were identified requiring resolution before shipping the skid to the NCCC. Testing is currently planned to begin in March 2024.

3.1.9 NETL Membrane Materials

NETL continues to pursue transformational carbon capture technologies through its Carbon Capture Program. One area of this effort focuses on the development of new membrane materials for the purpose of carbon dioxide separation and capture. Computational approaches such as atomistic modeling inform the development and synthesis of materials for experimentation in the automated test skid at the NCCC (Figure 11). The skid offers the opportunity for NETL to obtain performance data on real flue gas for these new materials in the early stages of development and with a very small amount of membrane required.

Figure 11. NETL Membrane Test Equipment

The NETL team returned the automated membrane test skid to operation with new materials in October 2022. From then until May 2023, the skid was used to test three different bulk films composed of a proprietary NETL material (NETL P15 polymer). These tests spanned 2,790 hours and demonstrated stable CO_2/N_2 separation performance that exceeded Robeson's upper bound. Testing then shifted to focus on samples of thin-film composite membrane materials. Three NETL samples that also contained NETL P15 polymer were tested for 600 to 700 hours each and demonstrated stable performance. Overall, these tests demonstrated that the P15 polymer has high CO_2 permeability (>850 Barrer), high CO_2/N_2 selectivity (>40), non-aging behavior, and long-term stability in flue gas conditions.

NETL and NCCC staff evaluated another membrane material in August 2023. University at Buffalo and Helios-NRG have developed a thin-film membrane sample under DOE funding, and it was tested for 695 hours in the automated membrane test skid. NETL personnel then visited the NCCC in September 2023 to review skid performance and perform initial screenings on five additional thin-film composite membranes. These samples will be evaluated during NCCC's Budget Period 9 into the spring of 2024.

3.1.10 NETL Fiber Optic-based Sensors

NETL is developing an optic sensor technology for online monitoring of solvent degradation and CO_2 concentration in flue gas. NETL plans to assess their sensor technology using monoethanol amine solvent in the SSTU.

A project kickoff meeting was held in August 2023 to review the technology, sensor installation configurations, test, and schedule. NETL proposed to install four CO_2 gas sensors and four liquid sensors to test sensor performance under various process conditions. A follow-up call was held in September to discuss issues raised based on NCCC's initial review of sampling locations. It was agreed that the gas sensor locations will be reduced to two, while liquid sensors remain at four. All the sensors will be installed on slipstreams of process lines. The NCCC will provide the proposed locations and stream information to NETL. Testing is targeted to start in the first quarter of 2024.

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/N_2 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. Following flue gas testing at the NCCC, a techno-economic analysis will be completed to verify the technology's ability to achieve a 70% CO_2 capture rate at less than $30/tonne CO_2.

The OSU test skid was delivered to the NCCC in October 2022 and was installed in the LSTU, as shown in Figure 12. Flue gas testing started in November using undiluted natural gas flue gas. The skid was then operated with diluted natural gas flue gas having a 4.4% CO_2 concentration. OSU completed the test campaign on December 20, achieving 530 hours of continuous operation. Overall, the membrane performance was stable under the test conditions, with a CO_2 recovery of around 90% and CO_2 purity of more than 95% on dry basis.

Figure 12. OSU Membrane Test Skid Installed in LSTU

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 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 13) at the site in 2020 with bottle gases and returned in 2022 for flue gas testing.

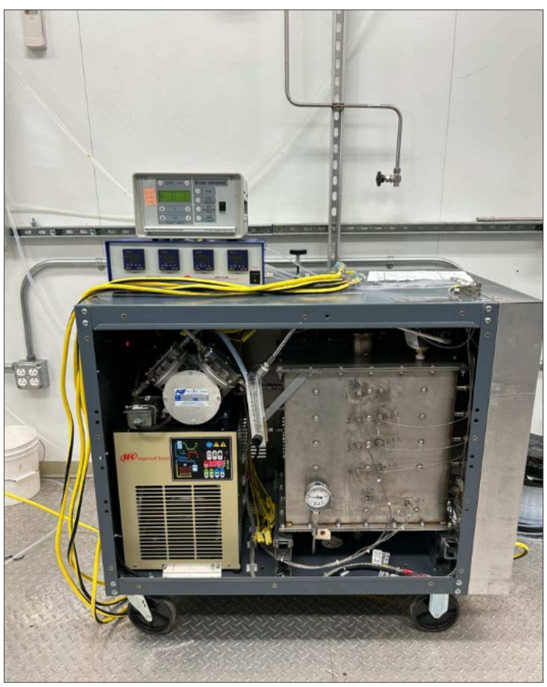

Figure 13. PCI Sorbent Skid Installed in LSTU

PCI returned for a third test campaign in April 2023. The NCCC completed the installation and connections, and flue gas testing was completed on April 23, with 45 hours of operation with 18 adsorption and desorption cycles. The test objective was to gain additional performance data from an improved reactor design.

From these three test campaigns, PCI demonstrated sorbent performance and durability in the presence of water and other common contaminants of the flue gas stream. The sorbent was rapidly thermally regenerated at low temperature (70 to 90ºC) and was stable under all test conditions. Data acquired at the NCCC was utilized to refine PCI's computational fluid dynamics models for CO_2 sorption-desorption kinetics and refine of the techno-economic analysis for a full-scale unit. Based on the modeling results, this technology can meet the DOE cost targets for carbon capture by 2035.

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 permeance as high as 2,500 GPU. In this project, GTI designed and operated a skid combining 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.

The skid was delivered and installed in the LSTU in August 2023 (see Figure 14). GTI engineers completed the initial skid commissioning with flue gas. The NCCC assisted GTI in resolving issues with excess moisture in a permeate stream and flue gas flow restrictions.

Figure 14. GTI Energy Graphene Oxide-Based Membrane Test Skid Installed in LSTU

GTI began testing in September. In support of this test, the NCCC provides natural gas flue gas with CO_2 enrichment from a cylinder to achieve a typical coal flue gas CO_2 concentration. The

NCCC also provides GTI with chillers to remove excess moisture in the flue gas and gas analyzers to measure gas compositions. About 460 testing hours were completed in BP8, and testing will continue through the end of 2023.

3.1.14 Helios-NRG Membrane

Helios-NRG is collaborating with the University at Buffalo to develop thin-film composite membrane technology using CO_2-philic block copolymers with intrinsic microporosity for post-combustion CO_2 capture. The membrane, which consists of rubbery polyethylene oxide and a polymerizable metal-organic framework, has achieved CO_2 permeance of 4,500 GPU and CO_2/N_2 selectivity of 40 at 35 to 60°C in laboratory testing. The current efforts are to scale up membrane fabrication and validate resistance to flue gas contaminates through long-term testing at the NCCC with flue gas.

The project kicked off in November 2022 to define the project scope. Biweekly calls were established in April 2023 with the Helios-NRG/University at Buffalo team to discuss the project status, test plan and schedule, and skid design. The team worked to finalize the P&ID, review skid modification needs, and schedule a process hazard analysis with the NCCC. The Helios-NRG/University at Buffalo team secured funding for Phase 2A, and they plan to test improved membranes in 2024.

3.2 CO_2 Conversion Projects

3.2.1 UCLA CarbonBuilt Concrete

This project is a continuation of UCLA's effort to further improve their CarbonBuilt process to maximize CO_2 valorization and process economics from their 2021 test campaign for a suite of CarbonBuilt products that are compliant with best-in-class industry standards. In this effort, process models will be developed to inform the scale-out of the process to produce diverse precast concrete components. Based on the modeling results, UCLA will modify the concrete curing reactor and process control on the existing skids to improve mineralization performance. The process will be demonstrated again at the NCCC using real flue gas with products to meet/exceed industry standards.

UCLA will modify the original skids for the new test based on lessons learned from the previous test campaign. The primary modifications will include a new 40-foot curing chamber trailer with new gas distribution internals and a higher flue gas flow rate. UCLA's skids were shipped to the skid fabricator in February 2023 for modifications. A factory acceptance test is to be completed prior to shipping the skids to the NCCC for reinstallation.

A project kickoff meeting was held in August 2023 with UCLA and their skid designer and fabricator, AirClean, to review changes from the previous test. In addition to the size increase on the flue gas supply and return lines, UCLA added a diesel boiler for steam generation that will be used for curing, a water softener skid for water treatment and storage for boiler operation, and a small knockout drum to remove flue gas condensate. Design work began on new low-pressure steam and condensate lines. In addition, new power feeds are required for the boiler and reactor gas distribution fans. A process hazard analysis was held in September. Skid delivery is planned for the fourth quarter of 2023, with testing to begin in January 2024.

3.2.2 Helios-NRG Algae

Helios-NRG previously tested a novel algae technology to capture CO_2 from fossil-fueled power plants at the NCCC in 2022. In a new DOE-funded project, Helios-NRG will test a scaled-up version of the technology at the NCCC. The multi-stage continuous flow capture system will be upgraded with controls for better operability and enhanced gas dissolution. Expected benefits include increased algae productivity and reduced costs. Figure 15 illustrates the process.

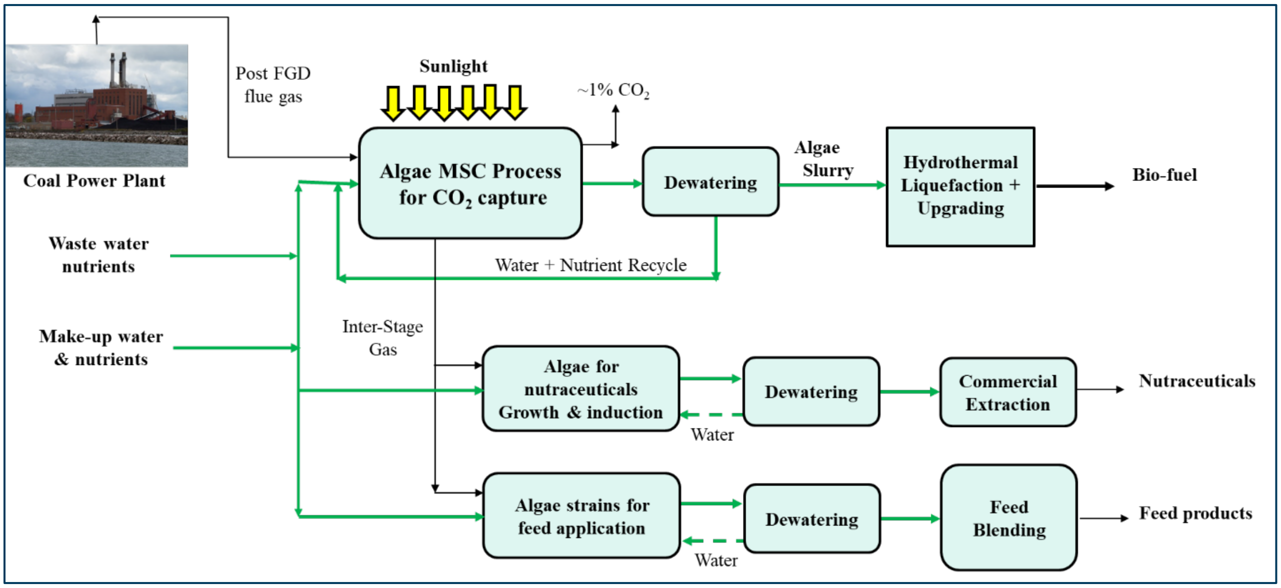

Figure 15. Flow Diagram of Helios-NRG Algae System

Helios-NRG and NCCC kicked off the project in August 2023 and are targeting summer 2024 for operations. Next steps for the project team will include establishing the technology collaboration agreement and identifying a high-sunlight area at the NCCC to locate the test equipment.

3.3 Carbon Reduction Technologies

3.3.1 SSEB/Aircapture Sorbent-Based Direct Air Capture

SSEB is leading a project team to demonstrate decreased costs of DAC through testing of existing materials in integrated field units to produce CO_2 of at least 95% purity. The DAC technology provider is Aircapture. Using sorbent materials provided by Global Thermostat in a monolithic contactor, Aircapture has designed a DAC system that utilizes waste heat typical of that available in power generation and industrial facilities. The monolith materials are rotated through absorption and desorption steps within the DAC test skid, as described in Figure 16. The NCCC field test will demonstrate capture and production of CO_2, including liquefaction. Target metrics include demonstrating capture efficiency of more than 50%, greater than 95% CO_2 gas purity and 95% liquefaction efficiency, 99.9% liquid CO_2 purity, desorption temperatures of 80 to 100°C, and unattended DAC operations.

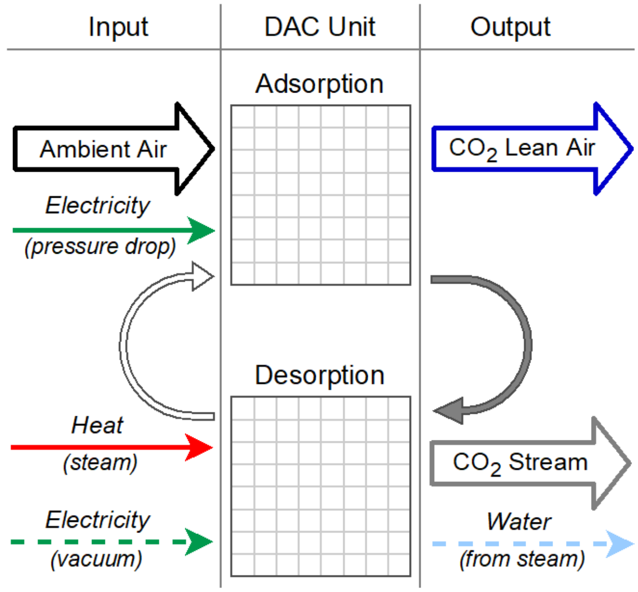

Figure 16. Aircapture Concept Drawing

Many major milestones were achieved during the current NCCC budget period. The technology collaboration agreement was established in October 2022, and engineering teams then worked to prepare packages to integrate the test equipment with the existing NCCC infrastructure. Aircapture delivered the DAC and heat recovery skids in March 2023 (see Figure 17). The NCCC installed interconnections and commissioning then began in May 2023.

Figure 17. Aircapture DAC Equipment Installed at the NCCC

Aircapture began executing their operations test plan in June 2023 and continued to test throughout the remainder of the NCCC budget period. This was executed in two sequential test campaigns. The first test campaign focused on identifying and addressing any issues with operating the equipment in an outdoor environment. This effort was successful and greatly increased operational robustness. A second test campaign immediately followed the first and shifted the focus of the test to optimizing system efficiency. Through this testing, Aircapture has demonstrated it can meet its targets for capture efficiency, CO_2 gas purity, desorption temperature, adsorption/desorption cycle time, and unattended operations.

Through September 2023, the DAC skid achieved 1,343 hours of operation and confirmed production of CO_2 from air. In the coming NCCC budget period, Aircapture will add integrated CO_2 liquefaction to the demonstration test and complete a third test campaign with that as the focus. Next steps for the project team will focus on the addition of this equipment. For SSEB and Aircapture, this technology will also be part of the front-end engineering design for the Southeast DAC Hub, which is negotiating with DOE's Office of Clean Energy Demonstrations following selection as part of a funding opportunity made possible by the Bipartisan Infrastructure Law.

3.4 Site Modifications

3.4.1 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 and environmentally harmful 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 includes a new tank and associated equipment to allow the separation of rainwater and process fluids, was completed in the previous budget period. The project design and installation were completed in July 2022, and the system was commissioned and put into service in May 2023.

3.4.2 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. The modifications were installed in spring and summer 2023 as allowed by working around ongoing long-term test project operations. The modifications will be tested and commissioned in November 2023 as part of a planned plant electrical outage.

3.4.3 PSTU Steam Condensate Flow Meter Improvements

This project improved 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.

The project replaced the air-cooled condensate cooler with a larger-capacity water-cooled condensate cooler and added an additional Coriolis-type flow meter in series with the existing higher-range integral orifice type flow meter. The Coriolis-type flow meter provides a lower flow measurement range at higher accuracy than the existing flow meter. The larger-capacity water-cooled condensate cooler (cooled by site cooling water) ensures that the steam condensate is sub-cooled enough to prevent formation of any gas bubbles that might interfere with the Coriolis-type flow meter operation. The piping and valves for the condensate weighing system were also rearranged for better operational ergonomics and easier access. The larger-capacity water-cooled condensate cooler also helps ensure that the condensate to the weighing system is at a lower temperature providing for safer possible operator exposure when utilizing the condensate weighing system.

The modifications were implemented and commissioned in 2022 and were tested during the UT-Austin PZAS test campaign in 2023. Steam flow measurements from the new lower-flow-range steam flow meter showed agreement within 8 to 10% of mass-based (gain in weight) steam condensate measurement calibration methods above 600 lb/hour. This compares to 15% measurement difference with the older existing steam flow meter. The measurement agreement range was 10 to 20% for lower flow ranges between 400 and 600 lb/hr. The system has not been fully vetted over a range of operational conditions, so more tests will be needed (preferably when using MEA or another well-understood solvent) to better understand the measurement deviations over the full range of PSTU operating conditions. The system will be utilized for future technology testing in the PSTU, and it is expected to provide more accurate results for the solvent regeneration equipment.

3.4.4 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. Work completed in BP8 included:

- Installation of a new feedwater tank level transmitter to provide resiliency
- Installation of a wind curtain on the boiler floor to prevent freezing of exposed piping during extreme cold weather events, as was experienced in December 2022
- Enlargement of the condensate drain from the flue gas header to remove excess water buildup
- Relocation of the cooling water control valve on the flue gas cooler from the supply to the return side to allow for optimization of cooling
- Installation of flue gas cooler inspection ports
- Addition of boiler water level gauge pre-fill valves to allow safe filling of transmitter legs after outage

Work will continue in BP9 on the following scope items:

- Completing installation of redundant demineralized water pump

- Installing an electric hoist to allow easier access of heavier equipment replacements on the upper floors of the structure
- Performing a final review of an equipment cross-reference guide

3.4.5 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. Work on the project was paused in 2023 and will resume in 2024.

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-13, starting in BP7 on August 1, 2022, and ending January 12, 2023
- Run PO-14, beginning February 15, 2023, and concluding on July 31, 2023
- Run PO-15, starting August 1, 2023, and continuing into BP9

Active projects during the budget period are listed below.

- UT-Austin PZAS Process—UT-Austin conducted further testing at the site with a test campaign of more than 5,800 hours of operation. The test campaign provided solvent degradation, emissions, and corrosion data, which are being analyzed for final results, as well as demonstration of a solvent reclaiming technology.
- Carbon America FrostCC Process—The FrostCC cryogenic CO_2 removal process is designed to compress and expand the flue gas stream with proper heat integration, producing near-pure solid CO_2. Testing will begin in early 2024.
- 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 using the PSTU. The test campaign is scheduled for 2024 and will use both coal- and natural gas-derived flue gases.
- KC8 Capture Technologies UNO MK 3 Solvent Process—KC8 Capture Technologies is developing the UNO MK 3 solvent process, which uses a novel catalytically enhanced precipitating solvent technology for natural gas combined-cycle application. KC8 Capture Technologies plans to deliver modular skids to the NCCC for installation in the pilot bay area to demonstrate capture of 5 to 10 tonnes of CO_2 per day. Testing is tentatively scheduled to begin in the second or third quarter of 2024.
- SRI International Mixed-salt Process Solvent—SRII is developing a novel mixed-salt solvent-based technology that combines potassium and ammonium salts as the solvent with unique process configurations without chilling the solvent to efficiently capture CO_2 from flue gas. In this project, SRII plans to deliver modular skids to the NCCC's pilot bay area to demonstrate capture of 5 to 10 tonnes of CO_2 per day. Testing is planned in the second half of 2024.
- 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 a test campaign at the NCCC in August 2022, GTI made modifications to bring the test skid back to its original design capacity. Testing was conducted testing from April 21 through July 10, 2023, confirming that the modifications significantly improved the solvent performance and brought the unit rating close to the original design.
- CORMETECH Sorbent—CORMETECH is developing a sorbent monolith carbon capture system for bench-scale testing at the NCCC. The process employs multiple beds of monolithic amine contactors to capture CO_2 by adsorption and then regenerate via

thermal desorption. The bench-scale test will target at least one month of continuous operations demonstrating 95% CO_2 capture with 95% purity of the CO_2 product stream. Testing is slated for 2024.

- 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 2024.
- 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.
- NETL Fiber Optic-based Sensors—NETL is developing an optic sensor technology for online monitoring of solvent degradation and CO_2 concentration in flue gas. NETL plans to test their sensor technology using monoethanol amine solvent in the SSTU.
- Ohio State University 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 GPU and more than 140 CO_2/N_2 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 was completed in December 2022, achieving 530 hours of continuous, stable operation.
- 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 April 2023, PCI conducted a test campaign with rapid thermal regeneration at low temperature. 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 began testing 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. Operation began in September 2023 and will continue through the end of the year.
- Helios-NRG Membrane—Helios-NRG is collaborating with the University at Buffalo to develop thin-film composite membrane technology using CO_2-philic block copolymers with intrinsic microporosity for post-combustion CO_2 capture. The current efforts are to scale up membrane fabrication and validate resistance to flue gas contaminates through long-term testing at the NCCC with flue gas. The Helios-NRG/University at Buffalo team secured funding for Phase 2A, and they plan to test improved membranes in 2024.
- UCLA CarbonBuilt Concrete— UCLA is working to further improve their CarbonBuilt process to maximize CO_2 valorization and process economics from their 2021 test campaign for a suite of CarbonBuilt products that are compliant with best-in-class

industry standards. Based on process modeling results, UCLA is modifying the concrete curing reactor and process control on the existing skids to improve mineralization performance. The process will be demonstrated again at the NCCC in 2024 using real flue gas with products to meet/exceed industry standards.

- Helios-NRG Algae for CO_2 Conversion—Helios-NRG is developing a novel algae technology to capture CO_2 from fossil fuel power plants and then use the produced algae to make revenue-producing products. The upcoming test will demonstrate an improved version of the multi-stage continuous flow system that was previously tested at the NCCC in 2022. The test campaign is scheduled to begin in the summer of 2024.

Other projects that are scheduled for testing include:

- Texas A&M algae for CO_2 conversion
- University at Buffalo sorbent
- Clean Energy Research Institute solvent in the PSTU
- University of Sheffield MEA solvent in the PSTU

The following site modifications projects were underway during BP8:

- Sump and waste handling improvement
- Control system modifications for lock-out test/try
- PSTU steam condensate flow meter improvements
- Natural gas system reliability upgrades
- Computer modeling of flue gas and solvent systems