NATIONAL CARBON
CAPTURE CENTER

Budget Period 9 Topical Report

Reporting Period: October 1, 2023 – September 30, 2024

Project Period: June 6, 2014 – September 30, 2025

DOE Cooperative Agreement
DE-FE0022596

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Abstract

Sponsored by the U.S. Department of Energy (DOE), the National Carbon Capture Center (NCCC) is a cornerstone of U.S. innovation in the research and development of cost-effective, technically viable carbon management technologies. Bridging the gap between laboratory research and large-scale demonstrations, the center evaluates novel processes from technology 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 9 (BP9) reporting period, spanning from October 1, 2023, through September 30, 2024, 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 cryogenic point-source capture and direct air capture tests. During BP9, several improvements were made to the site to enhance testing capabilities.

To date, the NCCC has accumulated more than 157,000 hours of post-combustion testing for over 80 technologies from more than 50 developers originating from six countries in addition to the USA: Canada, Germany, India, Japan, Norway, and the UK.

Acknowledgement

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List of Abbreviations

AFS	Advanced Flash Stripper
BP8	Budget Period 8
BP9	Budget Period 9
BOP	Balance-of-plant
CMU	Concrete masonry unit
CO_2	Carbon dioxide
DAC	Direct air capture
DOE	Department of Energy
EEMPA	N-(2-ethoxyethyl)-3-morpholinopropan-1-amine
ELPI	Electrical Low Pressure Impactor
FGD	Flue gas desulfurization
GPU	Gas permeation unit
GTI	GTI Energy
LLNL	Lawrence Livermore National Laboratory
LSTU	Lab-Scale Test Unit
MEA	Monoethanol amine
MHI	Mitsubishi Heavy Industries
NCCC	National Carbon Capture Center
NETL	National Energy Technology Laboratory
NO_2	Nitrogen dioxide
PNNL	Pacific Northwest National Laboratory
PSTU	Pilot Solvent Test Unit
PTR-TOF MS	Proton Transfer Reaction-Time of Flight Mass Spectrometer
RH	Relative humidity
RPI	Rensselaer Polytechnic Institute
SCR	selective catalytic reduction
SO_3	Sulfur trioxide
SRW	Segmental retaining wall
SSEB	Southern States Energy Board
SSTU	Slipstream Solvent Test Unit
TRL	Technology readiness level
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 technology developers, focusing on the early-stage development of the most promising, cost-effective technologies for future commercial deployment.

The NCCC has surpassed 157,000 hours of testing, successfully advancing a wide range of technologies toward commercial scale while improving their performance and reducing cost. The NCCC's testing of over 80 technologies from more than 50 developers has already confirmed the reduction of the projected cost of CO_2 capture by more than 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 and Carbon Management'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 9 (BP9) of the NCCC's second cooperative agreement with DOE, DE-FE0022596, covering October 1, 2023, through September 30, 2024.

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-15 started in BP8 on August 1, 2023, through December 19, 2023.
- Run PO-16 was conducted from January 8, 2024, through June 30, 2024.
- Run PO-17 started on July 1, 2024, and will continue into Budget Period 10 (BP10).

Table 1 lists the technology developer projects tested during the reporting period, as well as those currently being developed for testing in 2025.

Table 1. Projects Tested and Under Development During Budget Period 9

	Location/ Scale	*Tested in Run PO-15*	*Tested in Run PO-16*	*Tested in Run PO-17*	*Planned for 2025*
CO_2 Capture Projects					
University of Texas at Austin (UT-Austin) PZAS™ process	PSTU	✓			
ExxonMobil/Mitsubishi Heavy Industries (MHI) solvents	PSTU		✓		
EPRI/Pacific Northwest National Laboratory (PNNL)/RTI International (RTI) water-lean solvent	PSTU			✓	
Carbon America FrostCC™ process	Pilot-scale		✓		
SRI mixed-salt solvent	Pilot-scale				✓
KC8 Capture Technologies UNO MK 3 solvent process	Pilot-scale				✓
CORMETECH sorbent	Bench-scale			✓	✓
NETL membrane materials	LSTU	✓	✓	planned	✓
NETL fiber optic-based sensors	SSTU		✓	✓	✓
Lawrence Livermore National Laboratory (LLNL) structured packing	SSTU				✓
GTI Energy (GTI) graphene oxide-based membrane	LSTU	✓	✓		
Rensselaer Polytechnic Institute (RPI)/State University of New York at Buffalo (SUNY Buffalo) sorbents	LSTU				✓
Helios-NRG membrane	LSTU				✓

	Location/ Scale	Tested in Run PO-15	Tested in Run PO-16	Tested in Run PO-17	Planned for 2025
NETL Proton Transfer Reaction-Time of Flight Mass Spectrometer (PTR-TOF MS)	PSTU				✓
CO_2 Conversion Projects					
University of California, Los Angeles (UCLA) CO_2Concrete™	Bench-scale		✓		
Texas A&M University algae	Bench-scale				✓
CO_2 Removal 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

After 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 solvent degradation, corrosion studies, and mitigation methods. A PTR-TOF MS from University of Oslo was installed for measurements of solvent emission and degradation products in clean flue gas. The NCCC completed several modifications to accommodate the testing, including the addition of a flue gas heater, acid wash, a new hot-rich bypass on the AFS skid, and carbon filter upgrades. The test campaign concluded on October 20, 2023, after the completion of an extended test to verify solvent performance following three days of solvent reclaiming. More than 5,800 hours of performance data were collected during the entire testing, which entailed three test periods beginning in December 2022.

ExxonMobil/MHI Solvents

ExxonMobil and MHI tested two MHI solvents in the PSTU to collect data on emissions and energy consumption. The KS-21™ solvent was tested for about 590 hours, and the second solvent, Solvent B, was tested for more than 850 hours. Solvent emission data was collected continuously using a Fourier transform infrared spectrometer, the University of Oslo's PTR-TOF-MS, and a manual impinger and sorbent sampling train.

EPRI/PNNL/RTI Water-Lean Solvent

EPRI is working with PNNL and RTI International to scale up the EEMPA (N-(2-ethoxyethyl)-3-morpholinopropan-1-amine) water-lean solvent for CO_2 capture. The solvent is water-miscible with low viscosity and low surface tension for better wettability. In this project, the NCCC worked with EPRI and its team to modify the PSTU design to achieve the desired process conditions for operation with the solvent. Three major scopes in this project include the use of a rental chiller and chilled water loops to control flue gas moisture, an extended PSTU platform to site the chiller, and installation of new heat exchangers. Testing with coal flue gas began on August 22, marking the start of the test campaign, which is expected to continue into 2025.

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 heat integration to facilitate CO_2 removal via phase change and produce pure liquid CO_2. The Carbon America team completed testing in the second quarter of 2024, meeting performance targets with over 1,000 hours of flue gas operation, up to 99% capture efficiency, and CO_2 product purity of 99.97%. The test campaign validated physics-based model predictions with good data fits and confirmed the co-capture of pollutants like NOx, SOx, and heavy metals in flue gas. The robust operation achieved is expected to advance the FrostCC technology readiness level.

SRI Mixed-Salt Process Solvent

SRI 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 September 2024, SRI’s modular skids were delivered to the NCCC and installed in the pilot bay area for demonstration of 5 to 10 tonnes of CO_2 capture per day. The test campaign is expected to begin in early 2025.

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 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 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 2025.

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 began in September 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. NETL finished evaluating a series of thin-film composite membranes in June 2024, having accumulated 2,888 hours of operation since September 2023. The NCCC managed the testing and transmitted data to the NETL team. In November 2024, NETL will begin a test campaign with their new rubbery thin-film composite membrane coupons inside a 3-D printed permeation cell.

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, with two gas sensors and four liquid sensors. Solvent circulation began in September 2024, and the test campaign is expected to continue into 2025.

LLNL Structured Packing

LLNL has developed advanced structured packings based on additively manufactured geometries. These packings improve the mass transfer rate with minimum tradeoffs on pressure drop and maximum liquid loading. LLNL has demonstrated the performance of these packings in the lab and will scale the packings and further validate their performances in the SSTU using monoethanol amine (MEA) solvent. Testing is planned for 2025.

GTI 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 gas permeation units (GPUs) with close to 700 CO_2/N_2 selectivity, and the GO-2 membrane has permeance as high as 2,500 GPU. This project concluded after GTI completed a test campaign in June 2024 with the GO^2 process. A total of 1,500 hours of testing was achieved since the project was commissioned in August 2023.

RPI/SUNY Buffalo Sorbents

RPI is developing a transformational molecular layer deposition tailor-made, size-sieving sorbent developed by SUNY Buffalo and using a pressure swing adsorption process developed by University of South Carolina for CO_2 capture. The sorbent is designed to have high CO_2 adsorption capacity and excellent stability in the presence of water vapor. The technology will be tested in the LSTU beginning in early 2025.

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 contaminants 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 2025.

NETL PTR-TOF

NETL will install and operate their PTR-TOF MS during PSTU operation. Use of the NETL instrument at the NCCC will provide a real-world field test opportunity for NETL to familiarize themselves with the instrument and better understand its application to other CO_2 capture process sites. NETL plans to use this instrument as part of a mobile emissions and performance testing system that will be deployed at various CO_2 capture sites and projects to provide highly accurate and independently verified performance data. The instrument will be used to collect data during PSTU operation planned for early 2025.

UCLA CO_2Concrete

UCLA is working to further improve their CO_2Concrete process to maximize CO_2 valorization and process economics from their 2021 test campaign for a suite of CO_2Concrete products that are compliant with best-in-class industry standards. In May 2024, UCLA completed its second test campaign at the NCCC with an ultra-low-carbon concrete production process using CO_2 from flue gas. For this campaign, UCLA modified their process based on the previous operation and process simulations, incorporating a new reactor with internal fans for better gas distribution. Carbonization of the concrete products—masonry units, segmental retaining wall units, and wet-cast manholes—was conducted on three sets of each type from late April through the end of May 2024.

Texas A&M Algae

Texas A&M AgriLife Research has received DOE funding to integrate sorbent-based CO_2 capture with algae technologies to produce value-added products and biomass with ultra-high yield. Testing at the NCCC will begin in 2025.

SSEB/Aircapture Sorbent-Based Direct Air Capture

SSEB's project demonstrating Aircapture's sorbent-based DAC technology was designed to utilize low-grade waste heat at industrial facilities. DAC operation began in 2023, and DAC with integrated CO_2 liquefaction began in March 2024. The final test campaign concluded in July, with 3,384 hours of operation achieved over four campaigns. The project demonstrated equipment robustness under a wide variety of weather conditions and greater than 90% availability, excluding planned maintenance.

Site Modifications

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

- PTR-TOF MS installation—Purchase and installation of the NCCC's own PTR-TOF MS for measurements of solvent degradation products in the PSTU flue gas outlet for operation beginning in December 2024
- SSTU flowmeter improvement—Improvements to the SSTU flue gas flow measurements to be commissioned and evaluated during SSTU operation planned for the remainder of 2024
- Natural gas system reliability upgrades—Enhancements to the natural gas flue gas system to improve reliability, including upgrading flue gas condensate drain operation, enabling easier instrumentation calibration during startup, and accommodating operations feedback on piping and instrumentation diagram layouts
- Installation of dew point sensor at instrument air offtake from Plant Gaston

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 NCCC facilities accommodate a range of equipment sizes and operating conditions and provide commercially representative settings that promote technology readiness. Natural gas flue gas used for testing is derived from the NCCC's natural gas boiler and is representative of that from a natural gas combined-cycle power plant, with varying process conditions available. Coal flue gas for testing comes from an electric generating unit, Plant Gaston Unit 5.

The site hosts 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, shown in Figure 1. The site includes an independent control room, electrical infrastructure, and a balance-of-plant (BOP) area containing utilities and chemical storage/handling facilities

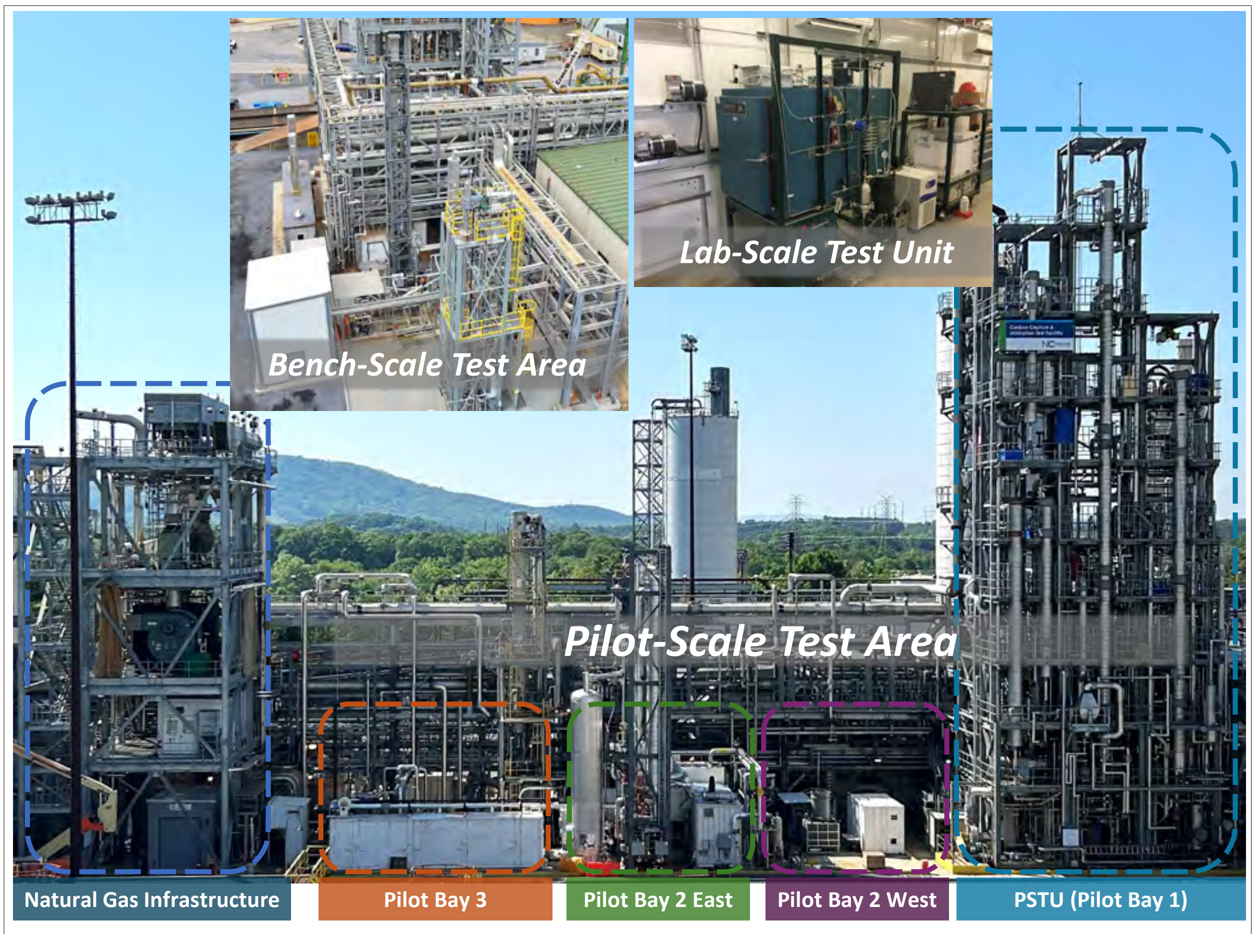


Figure 1. Photographs of Post-Combustion Carbon Capture Test Facilities

The site accommodates several tests at multiple scales simultaneously, with optionality for natural gas- or coal-derived flue gas delivered to each test location (see Figure 2).

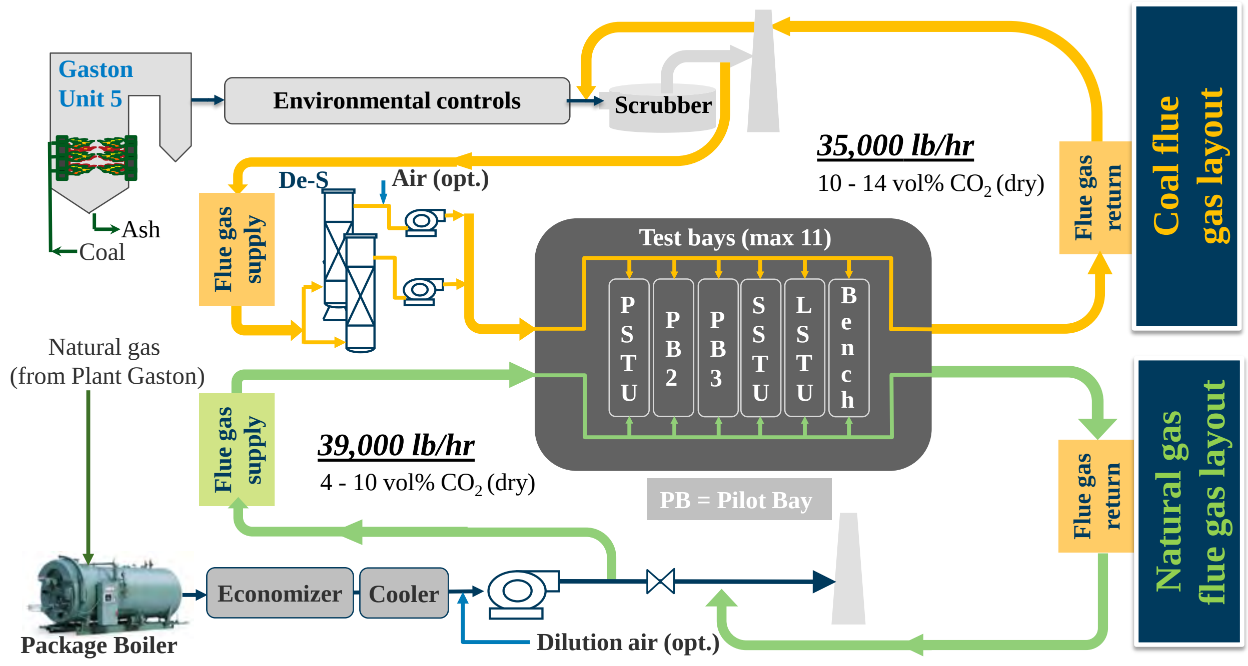


Figure 2. Schematic of Flue Gas Distribution at NCCC Test Facilities

Natural Gas Flue Gas Source Description. The natural gas-fired boiler system provides flue gas and steam for NCCC testing irrespective of power plant operation. NCCC staff maintain full oversight of the system. The CO_2 concentration of the flue gas can be modulated either by adjustments to the firing rate or by the addition of dilution air to mimic natural gas-based generating units or even low CO_2-containing boiler flue gases, providing maximum flexibility.

The natural gas system, shown in Figure 3, includes a package boiler, flue gas cooler, blower, steam condenser, and supporting systems for water cooling and treatment. The package boiler, a 1,100-boiler HP system from Cleaver Books, can produce 36,700 lb/hr of 150 psig saturated steam and 39,000 lb/hr of flue gas for developer testing. The boiler features a built-in economizer on the flue gas exit to recover some of the combustion heat energy, producing an outlet gas temperature in the range of 310ºF to 330ºF. The downstream heresite-baked, phenolic-coated, finned-tube flue gas cooler cools the gas to around 110ºF for flue gas moisture control. The subsequent 120-HP blower can move up to 10,000 actual cubic feet per minute to developer test bays.

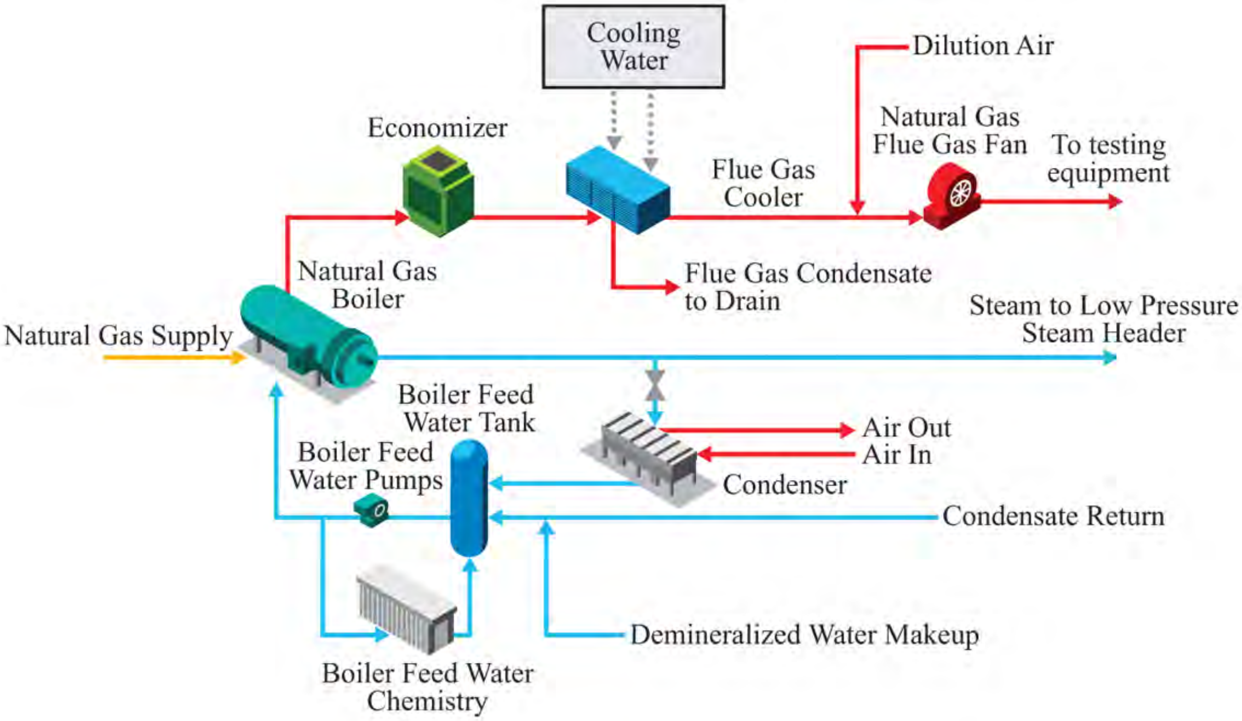


Figure 3. Schematic of Natural Gas Boiler System

Coal Flue Gas Source Description. The commercial unit supplying coal-derived flue gas, Plant Gaston Unit 5, began operation in 1974. It is a supercritical boiler with a nameplate generation capacity of 880 MW and meets all environmental requirements through state-of-the-art controls. These include an (SCR) unit to decrease nitrogen oxides, sodium bicarbonate injection to control SO_3 emissions, hot-side electrostatic precipitators, a baghouse for particulate and mercury control, and a wet flue gas desulfurization (FGD) unit to control SO_2 emissions. Unit 5 has the capability to co-fire natural gas with coal or combust only natural gas up to half the nameplate load. The unit is expected to convert to natural gas-only operation by January 2027.

Up to 35,000 lb/hr of flue gas is extracted from downstream of the Unit 5 FGD unit and is utilized for testing. Flue gas passes through one of two pre-scrubbers having a total capacity of about 29,000 lb/hr to remove residual SO_2. The actual extraction flow rates are adjusted via the use of blowers to satisfy the demand of each test unit. Flue gas to the PSTU passes to a direct-contact cooler, with 5,000 lb/hr of coal-derived flue gas or up to 8,000 lb/hr of natural gas flue gas available to the PSTU and 500 lb/hr of coal-derived flue gas or 800 lb/hr natural gas flue gas available to the SSTU.

Flue Gas Composition and Conditions. Table 2 lists the composition and conditions (after SO_2 scrubbing in coal-derived case) of site-supplied flue gases for typical operation.

Table 2. Average Values of Flue Gas Composition and Conditions

	CO_2, vol%	O_2, vol%	H_2O, vol%	NO, ppmv	NO_2, ppmv	SO_2, ppmv	Temp., °F	Press., psig
Coal-fired flue gas	12.1	7.1	7.6	41	2	1	155	2
Simulated natural gas flue gas	4.2	16.1	5.4	13	<1	<1	155	2
Natural gas flue gas*	4 - 9.2	2.5 - 14	4 - 17.2	15 - 30	<4.5	<1	120 - 180	0 - 2

*Dependent on dilution factor

CO_2 concentrations above the values given in Table 2 can be achieved with CO_2 product recycle or injection from a CO_2 storage medium (e.g., cylinder, Dewar, tank) at the capture unit to simulate various industrial conditions such as exhaust gas recirculation and industrial applications (cement, iron/steel, chemical). Additionally, high-purity CO_2 product from PSTU and SSTU operation can be made available for CO_2 conversion technology evaluation.

Flue Gas Additive Systems. An important way the NCCC supports the unique requirements of technology developers is by augmenting specific flue gas component concentrations for individual test campaigns. The installed additive systems, which are currently available for technology developer use, include nitrogen dioxide, sulfur trioxide, ammonia, and CO_2 systems. More additive systems may be installed for projects incorporating emissions and degradation studies.

2.2 Solvent Test Units

Pilot Solvent Test Unit. The PSTU was designed to achieve 90% CO_2 capture from coal-derived flue gas using a 30 wt% aqueous monoethanol amine (MEA) solution. MEA is used as the baseline solvent for comparing other tested solvents. The PSTU is operationally flexible to accommodate a range of solvent properties, processing up to 5,000 lb/hr of coal-derived flue gas and up to 8,000 lb/hr of natural gas-derived flue gas.

The major subsystems of the PSTU are (1) a cooler/condenser unit that cools the flue gas to appropriate reaction temperatures and reduces/controls flue gas moisture; (2) an absorber to promote efficient gas-liquid contacting to remove CO_2 from the flue gas; (3) a wash tower that cools the CO_2-depleted flue gas, removing trace amounts of entrained solvent; (4) and a regenerator to release the CO_2 from the solvent. For solvent regeneration, three options are available: the conventional packed bed column regenerator with external reboiler; a continuous stirred tank reactor (CSTR), a one-stage separation unit with reduced space requirements compared to conventional regenerator columns; and an AFS, which recovers the stripping steam heat through cold and warm rich bypasses.

The PSTU contains space where additional regeneration technologies or process improvement equipment can be located, such as a chiller to further cool the incoming flue gas or a steam heater to heat incoming flue gas passing to the absorber. Critical equipment, such as the steam flow measurement devices, employ redundant meters and manual measurement options to validate important reportable data.

Figure 4 provides a simplified process flow diagram of the PSTU using the conventional regeneration configuration. The process requirements for the major columns are specified in Table 3.

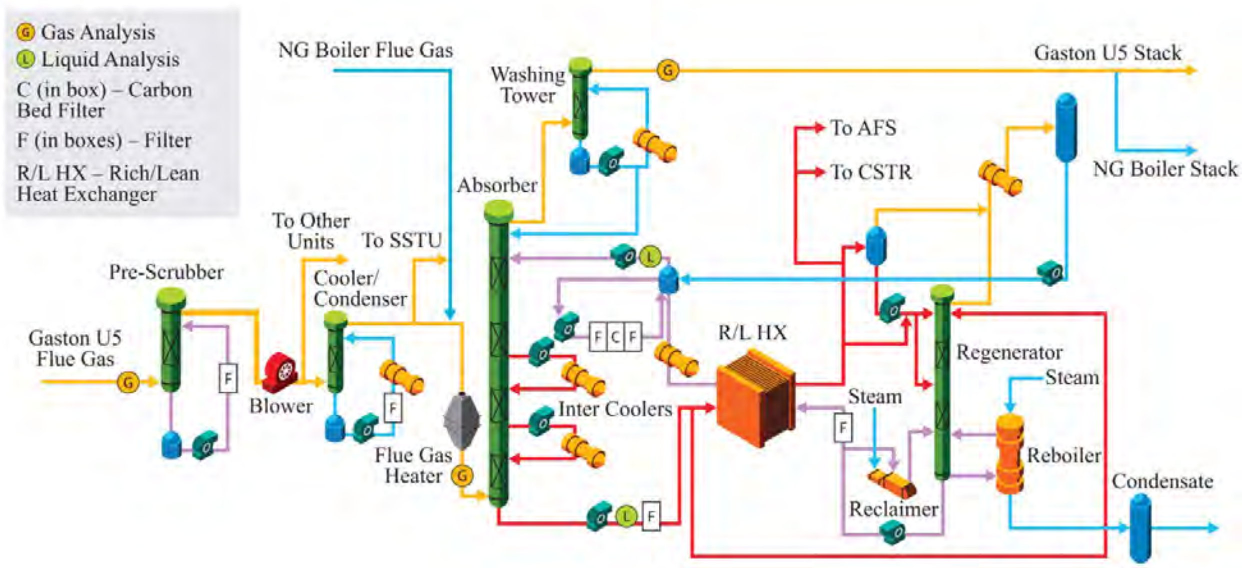


Figure 4. PSTU Process Flow Diagram

Table 3. PSTU Column Characteristics

Equipment	Cooler/ Condenser	Absorber	Wash Tower	Regenerator
Outside diameter, inches	24	26	24	24
Number of beds (height)	1 (10 ft)	3 (20 ft) + 1 (10 ft)	1 (10 ft)	2 (20 ft)
Max. operating temp., °F	200	300	200	400
Max. operating pressure, psig	15	15	15	200
Mist eliminator	Yes	Yes	Yes	Yes
Viewing ports	Yes	Yes	Yes	Yes

Slipstream Solvent Test Unit. The SSTU, shown in Figure 5, is a solvent-based CO_2 absorber/regenerator system with the ability to test innovative CO_2 capture solvents under a variety of conditions using up to 500 lb/hr of coal-derived flue gas and 800 lb/hr natural gas-derived flue gas. The unit requires a nominal solvent inventory of 400 gallons or less, making it ideal for evaluation of advanced solvents where only small quantities are available. The SSTU is optimized for validating lab-based results under industrial conditions for vetting solvents for further pilot-scale testing or commercialization.

Figure 5. Photographs of Slipstream Solvent Test Unit

As shown in Figure 6, the major subsystems of the SSTU are (1) an absorber to promote efficient gas-liquid contacting to remove CO_2 from the flue gas; (2) a wash tower that cools the CO_2-depleted flue gas, removing trace amounts of entrained solvent; and (3) a regenerator to release the CO_2 from the solvent utilizing a kettle-style reboiler. Table 4 lists the major components of the unit along with their operational capabilities.

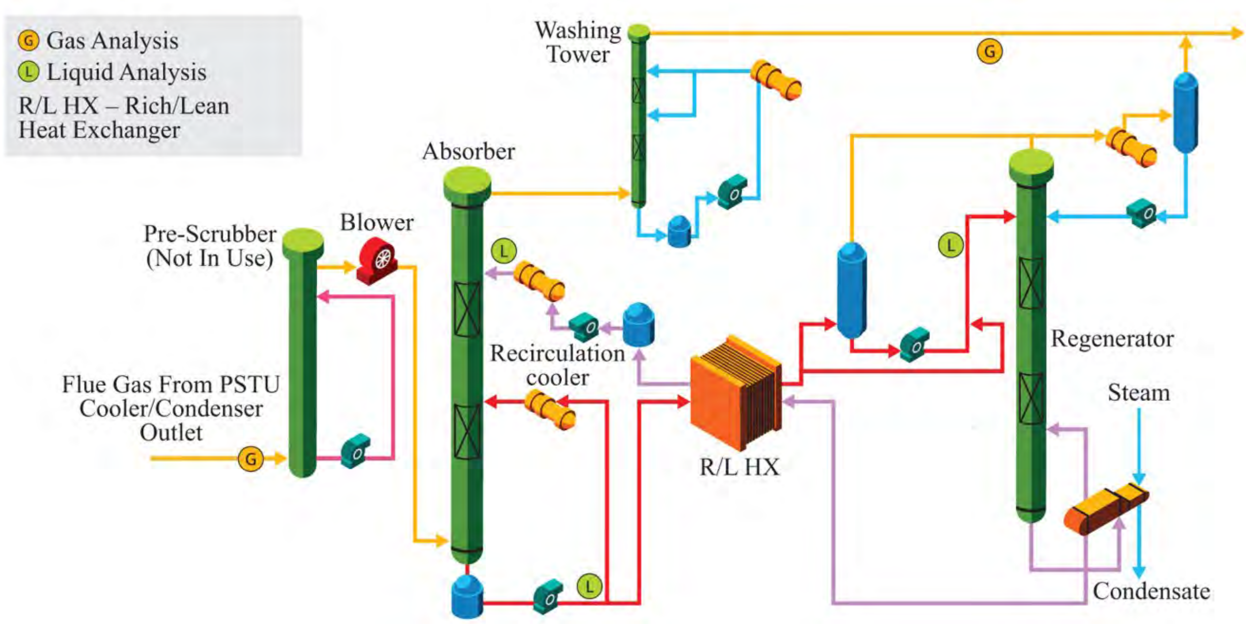


Figure 6. SSTU Process Flow Diagram

Table 4. SSTU Equipment and Operational Capability

Component	Absorber	Wash Tower	Regenerator
Liquid turndown ratio	3:1	3:1	3:1
Gas turndown ratio	2:1	2:1	2:1
Column height, ft	19	30	19
Column diameter, in	10	12	6
Number of beds	2	2	2
Maximum operating pressure, psig	12	10	45
Maximum operating temperature, °F	190	300	350

2.3 Test Areas for Developer Skids and Equipment

Pilot Bays 2 and 3. Two pilot bays located next to the PSTU are intended for projects up to 30 tonnes per day (TPD). Flue gas for Pilot Bays 2 and 3 is provided by the PSTU's pre-scrubber or the Pilot Bay 3 pre-scrubber via a flue gas crossover header that provides redundancy. Each of the foundations is designed for a wide range of equipment weights and column/steel moments. Pilot Bay 2 has curbs and sumps for containment and collection of solvents or other liquids and can be further divided into smaller bays (Pilot Bay 2 East and Pilot Bay 2 West) to host multiple, yet smaller, simultaneous developer tests.

Bench-Scale Test Area. Developer test skids that are sized at less than 2 TPD are installed in an area designed to accommodate as many as four skids, depending on footprint. Flue gas is supplied from a blower to a common header to which test skids are connected. A dedicated utility bridge provides ready access to flanged connection points for flue gas supply/return and utilities. It is curbed for containment and equipped with a sump and pumps for management of liquids.

Lab-Scale Test Unit. The LSTU provides an indoor space for small-footprint, non-weatherized lab-scale test skids at pounds per day CO_2 capacity and supplies utilities needed for flue gas testing. It provides general gas analysis and houses additional backup gas analyzers.

2.4 Analytical Support

The test center employs state-of-the-art gas and liquid analytical and sampling equipment maintained and operated by on-staff chemists. Samples are extracted for determination of untreated flue gas composition, gas and liquid streams in the PSTU (see Figure 4 on page 12) and SSTU (see Figure 6 on page 13), process gas in the LSTU, and treated flue gas streams. The center houses two analytical labs that contain analytical equipment, sample storage (ambient and refrigerated), reagent storage, packaging supplies, etc.

2.4.1 Standard Gas and Solvent Analysis

Process gas analyzers are available for the PSTU, SSTU, and LSTU. The PSTU is equipped to monitor gas composition at three primary sample points (see Figure 4 on page 12). An array of sample probes and five extractive analyzers provide accurate data on a continuous basis. Backup systems are in place to minimize downtime. Five specialized Nafion probes are used to sample low-level, soluble components such as SO_2 and NO_2. Standard condensing chillers are used for other points. A total of five Emerson XStream process analyzers are used to monitor components of interest using the analysis methods indicated: CO_2--non-dispersive infrared; oxygen--paramagnetic; SO_2--ultraviolet; nitrogen oxide--tunable diode laser; nitrogen dioxide--ultraviolet (ppm) and tunable diode laser (ppb).

The SSTU is equipped to monitor gas composition at three primary sample points (Figure 6 on page 13). The unit has its own Nafion dryer and process gas analyzers (CO_2, O_2, SO_2, NO_2). The LSTU provides process gas analysis with several XStream systems and six process gas chromatographs. An ambient air quality measurement and a low-level analyzer (about 30 to 1,000 ppm CO_2) are available for DAC processes.

Solvent Concentration and Loading Measurements. Liquid sampling systems are available for solvent analysis in the PSTU and SSTU. A lab gas chromatograph is available to analyze most components of single or blended amine solvents. An auto-titrator can be used to determine the solvent concentration and CO_2 loading. The auto-titrator takes a sample automatically every 30 minutes at each location. To determine the CO_2 loading, the samples are titrated with potassium hydroxide and sulfuric acid to determine the solvent concentration. Auto-titration analyses of the solvent CO_2 loading are cross-checked using periodic total inorganic carbon analyses. Cross checks for the solvent concentrations are performed using gas chromatography.

An online gas chromatograph was added in 2024 to measure the concentration of solvents (single amines or blends) and CO_2. This system can analyze a sample every 5 to 10 minutes, depending on the chemistry.

Total Nitrogen Measurement. The facility also houses a Shimadzu total nitrogen analyzer capable of several analysis techniques, but its main use is for total nitrogen analysis, an excellent marker when trying to distinguish carbon capture solvents from other hydrocarbons like machine oils or alcohols. When sampling sump contents in real time, operators can be notified immediately in the event of a solvent spill or equipment leak. In NCCC operation, a constant flow of sample is delivered to the instrument, and if the amount of nitrogen detected exceeds solvent concentration discharge limit setpoints, the instrument triggers an alarm, and the process equipment is assessed for solvent leaks.

2.4.2 Analysis of Solvent Emissions, Solvent Degradation, and Corrosion

Impinger Train for Measurements of Carryover of Amine and Degradation Products. The NCCC developed an impinger train for analysis of amine and degradation products in the flue gas exiting the PSTU absorber. An ice bath removes both droplets and condensable liquids from the samples in an EPA Modified Method 5 sample system.

Fourier Transform Infrared Analyzer. This instrument is used for measurements of ammonia and solvent carryover.

Electrical Low Pressure Impactor (ELPI+). The ELPI+, manufactured by Dekati, is used for aerosol sampling for solvent emissions studies. Sampling ports for the ELPI+ are located on the PSTU inlet (untreated flue gas), absorber outlet, wash tower outlet, and on the SSTU.

Offsite Analysis. NCCC lab specialists collect and ship samples to offsite labs for analysis of solvent components not available at the site, such as the heat-stable salts, formate and acetate.

PTR-TOF Mass Spectrometer. The NCCC is currently procuring an Ionicon Analytik PTR-TOF MS, which is expected to be delivered and installed in December 2024. This instrument provides simultaneous, real-time monitoring of volatile organic compounds without requiring any sample preparation and can detect compounds at very low concentrations (ppb - ppt range). The H_3O^+ proton transfer is non-reactive with air constituents, thus eliminating interference with the sampling matrix, but it reacts readily with hydrocarbon molecules. The NCCC will use this instrument to detect and quantify solvent carryover and degradation products using a heated sample probe and heated sample line. The NCCC will supply the equipment data to test partners as a screening and identification tool for solvent losses and degradation products. The instrument will be primarily connected to gas sample points on the PSTU wash tower outlet and absorber outlets but could be connected to other process sample locations as needed.

Corrosion Analysis. Corrosion coupon holders are located in the PSTU and SSTU for solvent corrosion studies.

2.5 Data Automation for Test Partners

For offsite transfer of real-time process data to test partners, the NCCC uses E-Notification software. The software automatically sends specified data from the plant historian formatted in an Excel spreadsheet at pre-selected frequencies. It also provides electronic communication alerts to process deviations of interest.

3.0 Technical Progress

During the reporting period, the NCCC supported multiple CO_2 capture, conversion, and removal projects (described below) and provided testing opportunities during three test runs:

- Run PO-15 started in BP8 on August 1, 2023, and ended on December 19, 2023.
- Run PO-16 was conducted from January 8, 2024, through June 30, 2024.
- Run PO-17 started on July 1, 2024, and will continue into Budget Period 10 (BP10).

3.1 CO_2 Capture Projects

3.1.1 UT-Austin PZAS Process

UT-Austin continued development of their PZAS process featuring piperazine solvent using the AFS, with the primary goals of studying solvent degradation, oxidation, and mitigation of both. The testing demonstrated that the solvent can operate with hot flue gas, such as that exiting the heat recovery steam generator of a natural gas combined-cycle power plant. To simulate this condition, a flue gas heater was installed to heat the flue gas to 230°F upstream of the absorber. To study the solvent corrosion, new corrosion ports were installed on the PSTU/AFS system.

The test campaign concluded on October 20, 2023, after the completion of an extended test to verify solvent performance after a three-day solvent reclaiming process. More than 5,800 hours of performance data were collected during the entire testing, which entailed three test periods beginning in December 2022. Following the solvent testing and rinsing of the equipment, a final dataset was collected with the PTR-TOF-MS on raw flue gas.

To study solvent degradation, emissions, and mitigation approaches, the operating conditions included the addition of chemicals to the PSTU pre-scrubber for NO_2 removal, nitrogen sparging in solvent to remove dissolved oxygen, solvent filtration with carbon beds, various water and acid wash configurations for emission controls, and thermal reclaiming to recover degraded solvent. Based on the test results, UT-Austin concluded the following:

- Adding sulfite/thiosulfate in the pre-scrubber reduces NO_2 in flue gas from 2.5 ppm to 0.5 ppm. This led to a reduction of the piperazine oxidation rate from 0.6 mol/hr to 0.3 mol/hr, a 50% reduction.
- Sparging nitrogen into the solvent at the bottom of the absorber at a rate of 0.5 SCFM (0.03% of the flue gas flow rate) removed greater than 75% of dissolved oxygen, which resulted in about 0.1 mol/hr piperazine oxidation.
- Filtering solvent through a carbon bed did not appear to have any significant effect on amine oxidation rate.
- Acid washing reduced ammonia emissions from 3,000 to 20 ppb. Water washing alone had no effect on ammonia emissions reduction. For amine emissions, either two stages of

water wash or one stage of water wash followed by an acid wash were effective. Neither water nor acid washing significantly affected the total hazardous air pollutant emissions.

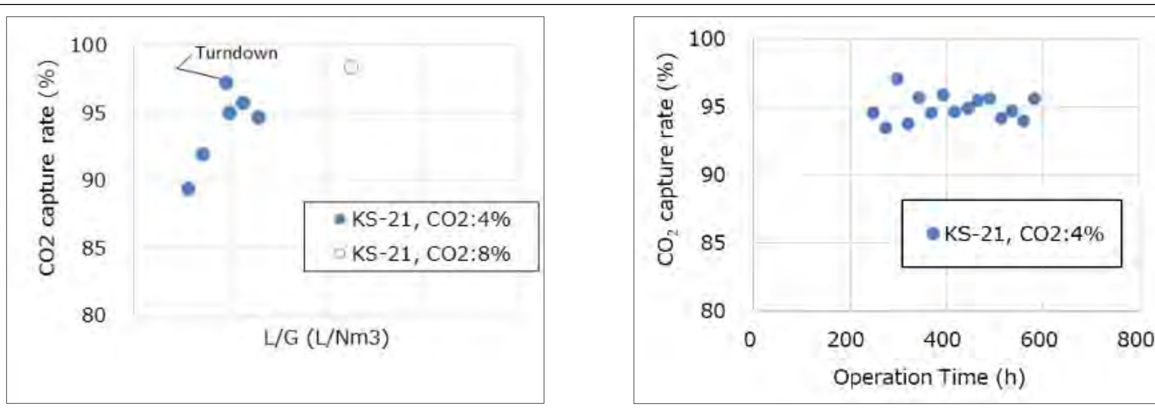
- Thermal reclaiming by vacuum distillation was effective in recovering the piperazine and removing degradation products, as evidenced by ammonia emissions, which decreased from 20 ppm before the reclaiming to 1.5 ppm immediately after the reclaiming. About 90% of the dissolved metals, amino acids, and heat-stable salts were removed.
- With pumping only around the intercooling at the bottom of the absorber for incoming hot flue gas (simulating natural gas combined-cycle flue gas conditions), a 95.5% CO_2 capture efficiency was consistently achieved, with a maximum capture efficiency of 97.7% achieved. The specific reboiler duty was 2.43 GJ/tonne CO_2.

3.1.2 ExxonMobil/MHI Solvents

ExxonMobil and MHI tested two MHI solvents in the PSTU to collect data on emissions and energy consumption. Under an accelerated effort, all preparations were completed in January 2024, water commissioning was conducted, and a heat loss test around the regenerator was performed. The first solvent, KS-21, was tested from February 6 through March 8 for about 575 hours of operation with natural gas boiler flue gas containing 4% CO_2 and 15 hours with flue gas containing 8% CO_2.

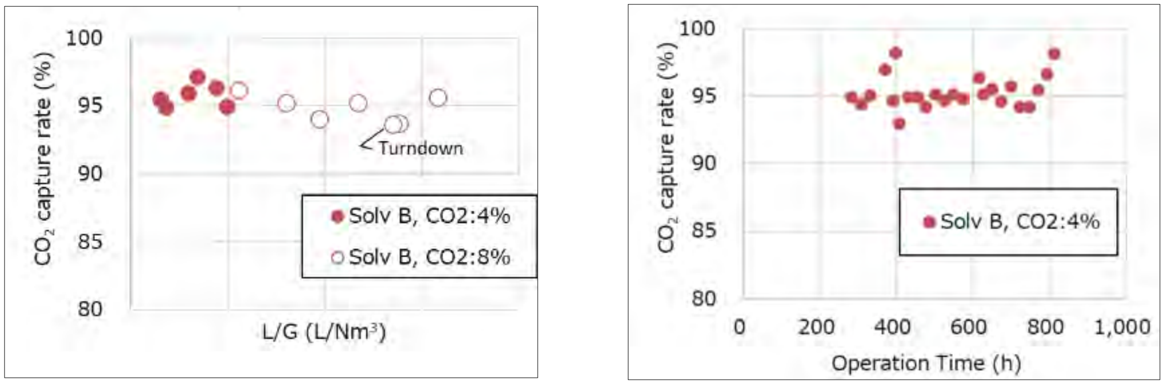
The second MHI solvent, Solvent B, was loaded in the PSTU on March 13 to start parametric testing, which included both 4% and 8% CO_2 in the flue gas. Long-term steady-state solvent degradation testing began on March 29 and concluded on April 24, with over 850 hours of operation for Solvent B. A final heat loss test was completed with water.

During parametric testing of both solvents, the liquid-to-gas (L/G) ratio was varied to evaluate CO_2 capture efficiency, while 95% CO_2 capture efficiency was consistently achieved during long-term steady-state operation for solvent degradation and emission study. Figure 7 and Figure 8 show the results during the parametric testing from both solvents.



Effect of L/G ratio Long-term stability

Figure 7. KS-21 Solvent Performance

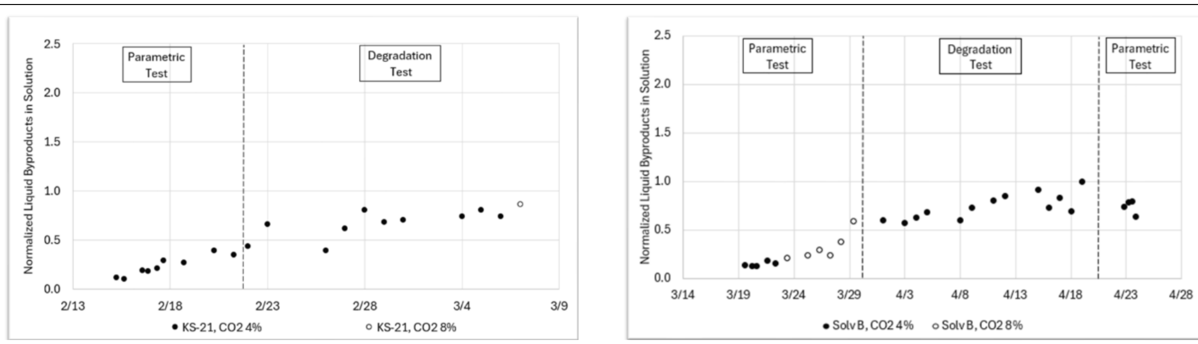


Effect of L/G ratio

Long-term stability

Figure 8. Solvent B Solvent Performance

Solvent emission data was collected continuously using a Fourier transform infrared spectrometer, the PTR-TOF MS, and a manual impinger and sorbent sampling train. Solvent samples were collected daily to determine the degree of degradation. Figure 9 shows the normalized degradation products found in both solvents. ExxonMobil concluded that both solvents were relatively stable during the long-term tests. Some of the higher degradation rates found during the parametric test could be attributed to fluctuations in the flue gas oxygen concentration. Unfortunately, during these solvent tests, the steam consumption values were largely unreliable due to a steam condensate bypass valve being inadvertently left in the open position. Therefore, the specific reboiler duty could not be reported.



KS-21

Solvent B

Figure 9. Solvent Degradation for MHI Solvents

3.1.3 EPRI/PNNL/RTI Water-Lean Solvent

EPRI is working with PNNL and RTI to scale up a water-lean solvent for CO_2 capture. The solvent, developed by PNNL under previous DOE funding, has demonstrated several advantages over traditional amine solvents during lab testing: low viscosity, miscibility with water, low corrosivity, low surface tension, and thermal and chemical stability. In addition, the low water concentration in the solvent reduces energy required to vaporize water during regeneration. In this project, the NCCC worked with EPRI and its team to modify the PSTU design to achieve the desired process conditions for solvent operation. Both coal- and natural gas-derived flue gases will be demonstrated.

Three major scopes in this project include the use of a rental chiller and chilled water loops to control flue gas moisture, an extended PSTU platform to site the chiller, and installation of new heat exchangers. The NCCC completed its design and construction work during the budget period. Prior to loading the water-lean solvent, the PSTU was cleaned with a 0.1-molar sodium hydroxide solution based on PNNL's lab testing and recommendations for reducing the risk of cross-contamination from the previously used solvent.

Flue gas operation began in August 2024, and initial testing was focused on flue gas and solvent temperature and solvent water concentration controls. Parameters were adjusted to reach the lowest temperature possible in the absorber to achieve a high CO_2 capture rate. These parameters included reduced flue gas flow rate, maximized intercooling cooling water flow, and adjustments to the water concentration in the solvent. The Raman spectrometer that was commissioned by PNNL has not been reliable, especially as the solvent turned a black color quickly after testing began. An engineer from University of Oslo came on site on September 10 and set up a PTR-TOF MS for online emissions measurements.

As the testing moved through the test matrix, fog was observed in the regenerator column, which also resulted in solvent carryover in the CO_2 product stream. This issue has been consistent and prevented full execution of the test matrix. Several approaches were taken to reduce the fog and carryover, such as increasing the regenerator pressure, reducing the reboiler solvent recirculation flow rate, returning reflux back to the top of the regenerator, filtering solvent through carbon filters, blinding off the solvent vent line from the reboiler, feeding rich solvent to the middle of the regenerator column instead of the top, and reducing the rich solvent feed pressure. The flue gas flow rate was further reduced to a minimum to reduce the corresponding solvent flow rate. The regenerator sump temperature appeared to play a role, as fog was more prominent with solvent carryover as the temperature increased. The teams will continue to adjust test parameters to understand the root cause of this issue.

3.1.4 Carbon America FrostCC Process

Carbon America has developed the FrostCC process, a novel cryogenic system for CO_2 capture from typical industrial flue gases that separates CO_2 by compressing and cooling the stream to conditions that facilitate the solidification of the CO_2. FrostCC uses a modular design with conventional, well-established equipment in a novel system and process arrangement.

Shown in Figure 10, the FrostCC system consists of heat exchangers, pumps, compressors, expanders, and other BOP components typically found in industrial gas processing operations. The flue gas is compressed, dried, expanded, and cooled as an auto-refrigerant in an open loop cycle to the point where the CO_2 component "frosts" (changes phase from gas to solid, also known as desublimation). The CO_2 deposits as a solid on the heat exchanger surfaces, and the heat exchangers are periodically cycled to melt the solid CO_2 into a liquid. Figure 11 outlines the steps of the FrostCC process and how CO_2 is separated.

Figure 10. Photo of the Carbon America FrostCC System

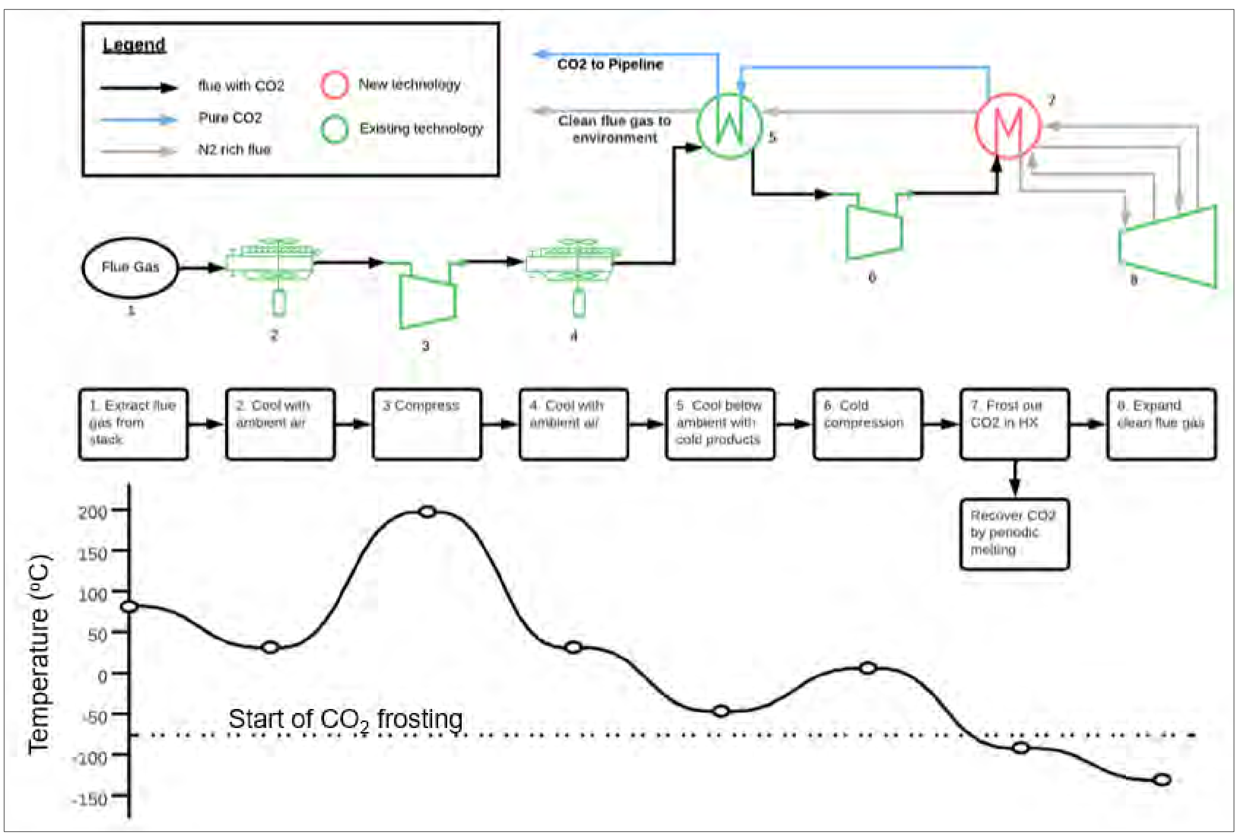


Figure 11. Carbon America FrostCC Process Diagram

Installation of the FrostCC equipment was substantially completed by January 2024, at which time Carbon America began checkouts and conducted a pre-startup safety review. After liquid CO_2 was loaded into the system, a significant dislocation of piping expansion joints in the liquid CO_2 lines connecting the tank and pumps occurred. Carbon America evaluated the cause of the dislocation and thermal expansion/contraction issues observed in the lines and completed a re-design of the affected lines. While the lines were being replaced in mid-February, Carbon America completed successful CO_2 frosting tests inside the system, utilizing both ambient air and boiler flue gas for the CO_2 source.

Carbon America used electrical heaters to remove water over the weeks prior to full system operation utilizing liquid CO_2 and completed commissioning of liquid CO_2 pumps. Carbon America achieved three significant accomplishments during continuous operation in April:

- The first continuous melt cycle on all four exchangers
- The first continuous frost and melt cycle on all four exchangers
- A 36-hour continuous frost and melt test

After beginning full-cycle operation on April 6, Carbon America continued with their planned testing. In April, they completed full-cycle tests of various frost durations along with internal equipment inspections to observe the impact of CO_2 frost operation. They experienced a few short interruptions in flue gas supply but generally operated continuously throughout April.

Throughout May, Carbon America conducted 24/7 test operation with full frost/melt cycles and expansion of the system operating envelope. The NCCC provided two different flue gas CO_2 concentrations along with flue gas analytical composition services to assist with system data collection and operation. Carbon America hosted 36 individuals at the site to view the FrostCC system in operation. The visitors included representatives from electric utilities, industrial emitters, and potential investors.

Carbon America continued operating until June 5, when they began system shutdown due to the planned NCCC site outage starting June 7. The NCCC and Carbon America collaborated to develop a plan and schedule for the end of testing and system removal. The system completed more than 950 hours of operation from April 6 until June 6. The NCCC and Carbon America continued discussions about the feasibility of additional testing at the site in the future.

Key achievements included:

- Operating over 1,000 hours with CO_2 capture from flue gas
- Demonstrating up to 99% capture efficiency
- Reaching capture rates up to 1,500 tonnes per year
- Achieving CO_2 product purity of 99.97% and low O_2 (< 10 ppm on average) concentrations in the CO_2 product

- Validating physics-based model predictions with good data fits
- Confirming the co-capture of pollutants by reducing NOx (NO + NO_2) to < 0.5 ppm, SOx with SO_2 < 2 ppm, and heavy metals in flue gas
- Demonstrating robust expander operations
- Reliably and predictably frosting and melting captured CO_2
- Advancing the FrostCC technology readiness level (TRL) from TRL 5 to TRL 6

The Carbon America team performed a techno-economic analysis for an nth-of-a-kind levelized cost of capture across various CO_2 concentrations with the results shown in Figure 12. The figure also includes levelized cost of capture estimates for amines used in cement plants, with and without FGD and SCR systems. The assumptions can be found in the final report on the NCCC website.

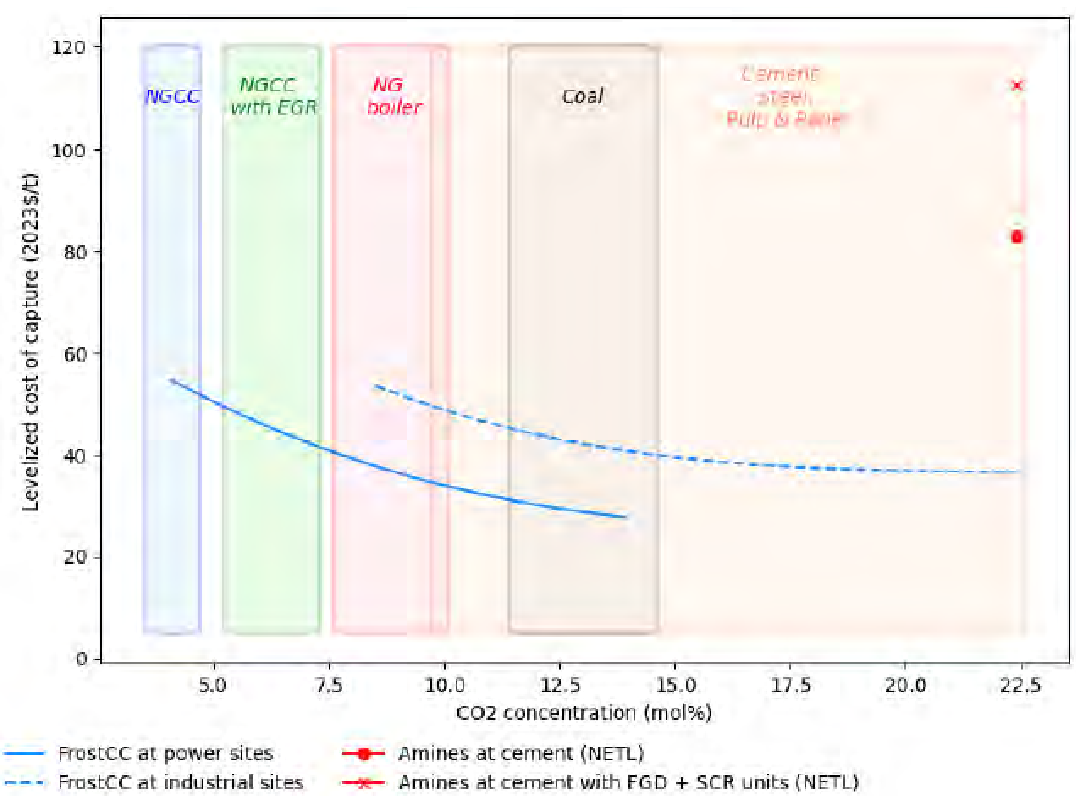


Figure 12. FrostCC LCOC at Industrial and Power Locations at an Estimated 99% Efficiency

After the NCCC pilot, Carbon America plans to demonstrate the first commercial FrostCC module capable of up to 100,000 tonnes per year of CO_2 capture. Once demonstrated, this go-to-market product will be ready for commercial deployment at a variety of emissions sources. Modules will be combined to reach 99% capture of all CO_2 emitted from any point-source emitter. The design of this commercial-scale system is in progress, and the model validations and insights from the NCCC test campaign will provide confidence in the commercial scaled-up design.

3.1.5 SRI Mixed-salt Process Solvent

SRI 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, SRI delivered 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 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. Figure 13 shows the skids, which included four modules, that were installed in September. SRI will conduct a process hazard analysis in October 2023 with the NCCC's participation, and testing is targeted to begin in January 2025.

Figure 13. Installed SRI Modules

3.1.6 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 quarter of 2025.

3.1.7 CORMETECH Sorbent

CORMETECH has developed 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 14, 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.

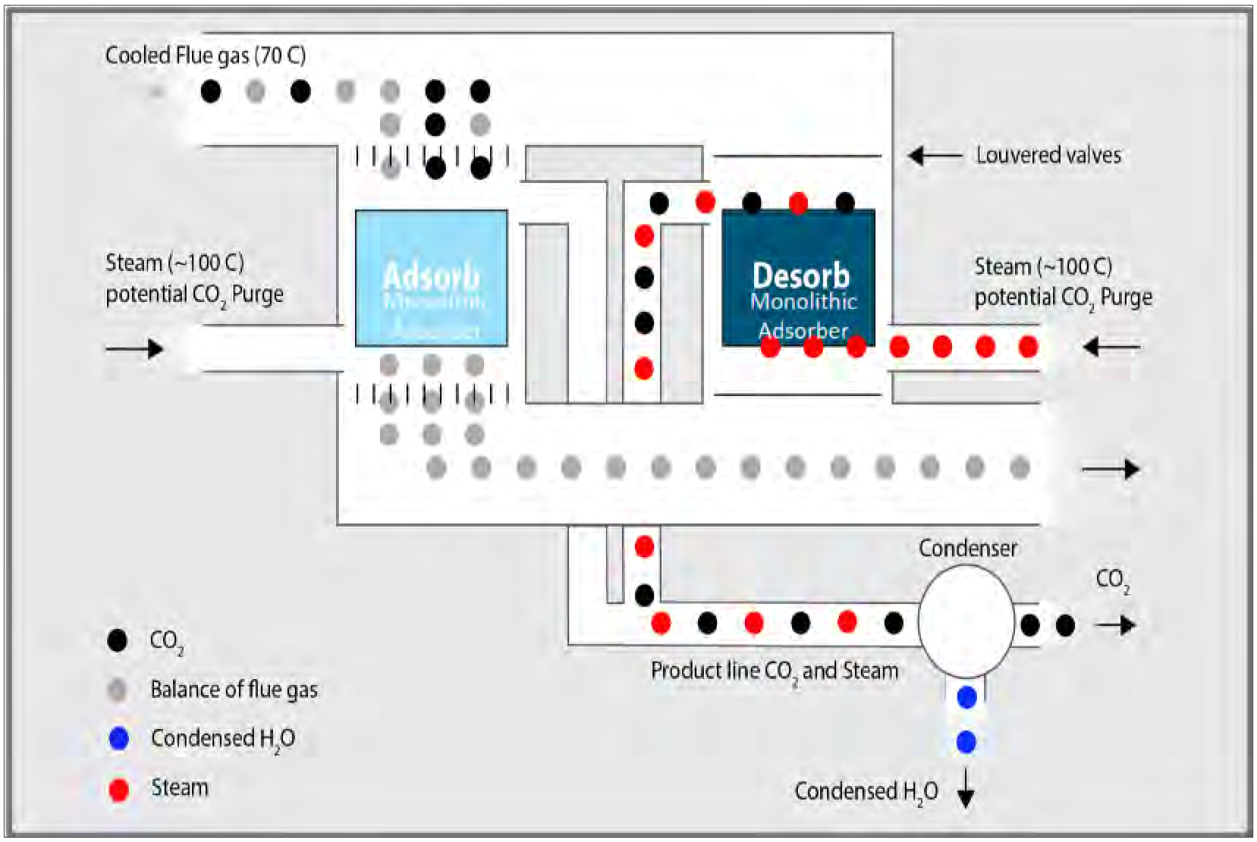


Figure 14. CORMETECH Sorbent Process Flow Diagram

Field construction was completed in July, including mounting and charging a heating, ventilation, and air conditioning unit in their control room and installing a skid roof. The NCCC also completed preparation of ammonia gas injection cabinet and armored tubing installation for ammonia injection line to the CORMETECH mass flow controller. Ammonia will be used for

CORMETECH's SCR operation upstream of the sorbent beds for NOx control. The skid was delivered to the NCCC in May and was installed in the bench-scale area as shown in Figure 15.

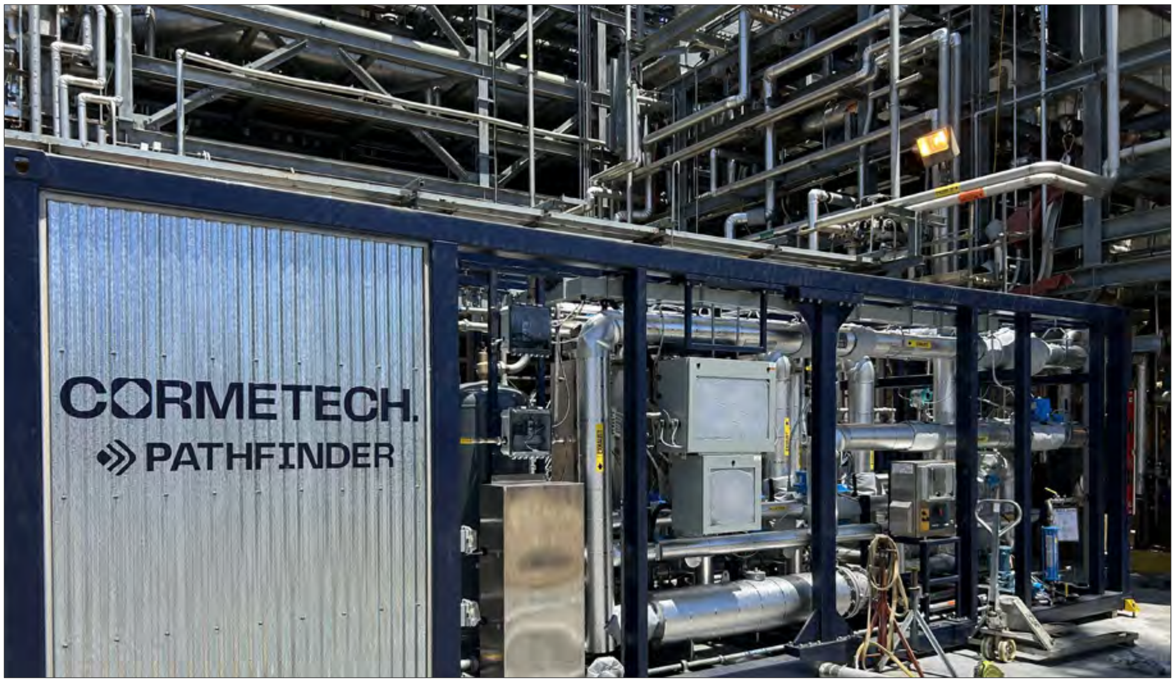


Figure 15. Installed CORMETECH Skid

CORMETECH held a pre-startup safety review in July with NCCC's participation. CORMETECH began skid checkout and commissioning in August. Dummy monolith sorbents were installed in the reactors for the checkout and commissioning. After all issues were resolved, CORMETECH loaded the actual monolith sorbents in one of the three reactors on September 5, and flue gas started to verify preliminary sorbent performance on September 10. Through testing, CORMETECH has identified additional operational issues and will address those and continue their testing through January 2025.

3.1.8 NETL Membrane Materials

NETL continued to pursue transformational carbon capture technologies through its Point Source Carbon Capture Program. One area of this effort focuses on the development of new membrane materials for the purpose of CO_2 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 (see Figure 16). 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. The project objective is to develop a scalable thin-film composite membrane for industrial carbon capture that has a CO_2 permeance greater than 3,000 GPU and CO_2/N_2 selectivity of more than 25.

Figure 16. NETL Membrane Test Equipment

Following the September 2023 visit from NETL personnel to evaluate equipment and material performance, the automated test skid returned to operations in October 2023. Testing continued with multiple new membranes until June 2024, when testing was concluded. This series of thin-film composite membranes accumulated 2,948 hours of operation since October 2023. These membranes were hand-cast, submicron for the selective layer and demonstrated long-term stability in the humid flue gas with particulates.

NETL plans to return in mid-November to resume testing of their new rubbery thin-film composite membrane coupons inside a 3-D printed permeation cell. This cell is a scale-up of a roll-to-roll advanced coating technique used during membrane fabrication, producing machine-coated thin-film composites that are less than 200 nm thick. NETL and NCCC staff have been planning several improvements to the membrane test skid in 2025 to enhance system versability, including adding feed gas humidification and upgrading LabView programming.

In 2025, NETL will perform a first-of-a-kind membrane field test at the U.S. Steel's Edgar Thomson Plant in Braddock, PA. For the demonstration, membrane modules of 1,000 cm^2 are being fabricated for use with blast furnace waste gas of more than 20% CO_2.

3.1.9 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 total of six sensor locations were selected, two for gas and four for liquids. NETL personnel completed the installation for the six sensors with the NCCC's assistance in March 2024. Two gas sensors were temporarily placed in the PSTU flue gas supply and return sampling lines to collect preliminary data while the SSTU was being commissioned with water.

MEA solvent was loaded into the SSTU in late August, and solvent circulation began. Once circulation reached steady state, the sensors were placed online on August 30 to begin collecting data. However, circulation was stopped when leaks were found around sensor assembly package seals caused by using incompatible materials. A leak was later found on a solvent flow meter. The team will continue to work through any issues and complete the sensor testing in February 2025.

3.1.10 LLNL 3D Printed Structured Packing

LLNL has developed advanced structured packings based on additively manufactured geometries. These packings improve mass transfer rate with minimum tradeoffs on pressure drop and maximum liquid loading. LLNL has demonstrated the performances of these packings in the lab and will scale the packings and further validate their performances in the SSTU using MEA solvent.

At the request of LLNL, the NCCC performed a fit test with a single packing layer that LLNL had fabricated as a prototype. The SSTU absorber top was removed, and the packing layer was dropped into place. LLNL may modify the design based on the NCCC's feedback. The NCCC will also procure a different brand of packing to provide LLNL with another comparison point. Testing is planned for 2025.

3.1.11 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 17). 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 17. GTI Energy Graphene Oxide-Based Membrane Test Skid Installed in LSTU

GTI performed their first test campaign at the site from August 2023 through December 2023. In support of this test, the NCCC provided natural gas flue gas with CO_2 enrichment from a cylinder to achieve a typical coal flue gas CO_2 concentration. The NCCC also provided GTI with chillers to remove excess moisture in the flue gas and gas analyzers to measure gas composition.

Preliminary performance data showed good CO_2 separation. Continuous testing indicated some unexpected membrane degradation. GTI identified that improper storage of ionic liquid used in membrane preparation was the root cause for the degradation. New membranes were prepared with fresh ionic liquid and their performances were verified through lab testing.

GTI returned to the NCCC in May 2024 and restarted testing with the new membranes to verify their stability in flue gas. Two initial membranes had issues from either shipping damage or a minor crack in the substrate. Two other membranes were tested until June 6 when GTI concluded their test campaign at the NCCC. A total of 1,500 hours of testing was achieved since the project was commissioned in August 2023.

GTI reported that the two-stage membrane process met the performance targets of greater than 90% capture efficiency and 95% CO_2 product purity. It also demonstrated stable performance for the targeted 200 hours of operation. Parametric test results showed the CO_2 capture performance was impacted by flue gas flow rate and membrane operating temperature. The lower the flow rate and the higher the temperature, the higher the capture efficiency. Table 5 and Table 6 show the results from these parametric tests.

Table 5. Effect of Feed Flow Rate on CO_2 Capture Performance

Test #	Feed flow rate, L/min	CO_2 capture efficiency, %	CO_2 dry-basis purity, vol%
1	1.5	75.8	97.4
2	1.0	83.9	96.8
3	0.9	87.2	96.6
4	0.8	90.6	96.2

Table 6. Effect of Operating Temperature on CO_2 Capture Performance

Test #	Operating temperature, °C	CO_2 capture efficiency, %	CO_2 dry-basis purity, vol%
1	57	66.9	96.4
2	60	78.9	96.6
3	65	83.9	96.8

3.1.12 Rensselaer Polytechnic Institute/SUNY Buffalo Sorbents

RPI and SUNY Buffalo are developing a transformational molecular layer deposition tailor-made, size-sieving sorbent technology with pressure swing adsorption process for CO_2 capture. The sorbent is expected to have high CO_2 adsorption capacity and excellent stability in the presence of water vapor. A skid will be constructed to demonstrate the technology at the NCCC in the LSTU.

SUNY Buffalo held two process hazard analysis meetings in early 2024 with the NCCC's participation. Skid fabrication was completed in August and is scheduled for delivery in December 2024. Testing is planned to last through the first quarter of 2025.

3.1.13 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 contaminants through long-term testing at the NCCC with flue gas. The Helios-NRG/University at Buffalo team secured funding for Phase 2A and plan to test improved membranes in early 2025.

3.1.14 NETL PTR-TOF

NETL recently acquired a PTR-TOF-MS and plans to use the instrument during PSTU operation. This will provide a real-world field test opportunity for NETL to familiarize themselves with the instrument and better understand its application to other CO_2 capture process sites. NETL plans to include this instrument as part of a mobile emissions and performance testing system that will be deployed at various CO_2 capture sites and projects to provide highly accurate and independently verified performance data.

The mass spectrometer will provide real-time measurements of solvent degradation products in the flue gas exiting the PSTU. The instrument will be primarily connected to gas sample points on the PSTU wash tower outlet and absorber outlets and could be reconnected to other process sample points as needed. The instrument will be located in an existing instrument shelter area on the eighth level of the PSTU structure.

In September 2024, NCCC and NETL discussed the project plan and scope and began detailed planning for installation of the instrument and support equipment in October. The project will provide an opportunity for NETL and NCCC personnel to gain experience with this sophisticated instrument and its data processing capabilities, as well as collect data during PSTU operations planned for early 2025.

3.2 CO_2 Conversion Projects

3.2.1 UCLA CO_2Concrete

This project is a continuation of UCLA’s effort to further improve their CO_2Concrete process, aiming to maximize CO_2 valorization and process economics from their 2021 test campaign for a suite of CO_2Concrete products that comply 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 was demonstrated again at the NCCC using real flue gas with products to meet or exceed industry standards.

In this project, up-scaled production was demonstrated for three concrete products—concrete masonry units (CMUs), segmental retaining wall (SRW) units, and wet-cast manholes. The first batch of concrete blocks, SRW units, were delivered on April 30. The concrete mineralization process began using undiluted natural gas flue gas at 8% CO_2 concentration. Three batches of each concrete product carbonatation using undiluted natural gas flue gas for a total of nine batches were completed by May 31. Blair Block provided SRW and CMU blocks, and Alcrete provided the manhole product. NCCC assisted UCLA with loading and unloading these products from trucks and the reaction chamber during the test campaign. Carbonization of the concrete products was conducted on three sets of each type from late April through May.

UCLA reported that 31.3 tonnes of CMU, 51.3 tonnes of SRW, and 40.1 tonnes of concrete manhole were produced and carbonated. They achieved (1) carbonation of three separate concrete products, (2) production of more than 10 tons/day of concrete of each product, (3) absorption of greater than 0.2 g CO_2/g reactant, and (4) compliance of carbonated concrete with industry-standard specifications. Figure 18 shows the CO_2 uptake, conversion efficiency, and

CO_2 uptake per mass of reactants. Figure 19 demonstrates that the compressive strength of each product exceeded industrial standards.

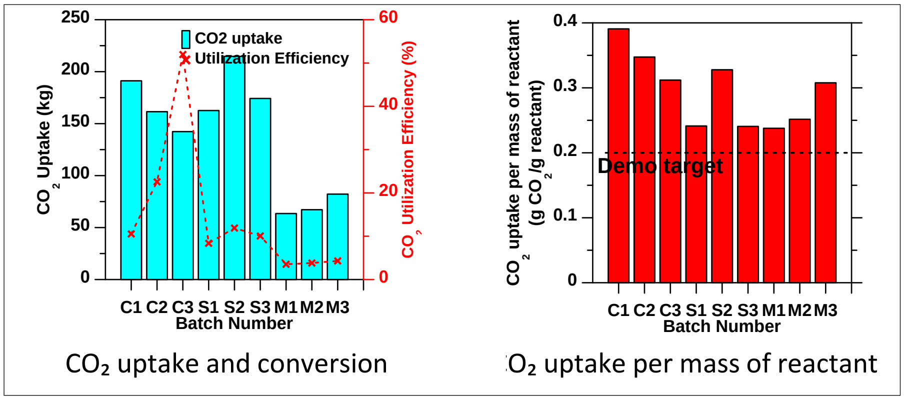


Figure 18. CO_2 Uptake, Conversion Efficiency, and CO_2 Uptake per Mass of Reactants of UCLA CO_2Concrete Process

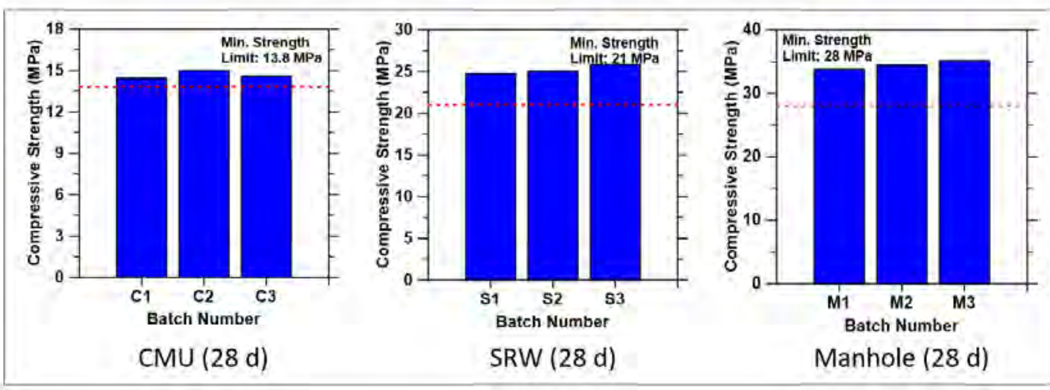


Figure 19. Compressive Strength of Concrete Product from UCLA CO_2Concrete Process

3.2.2 Texas A&M Algae

Texas A&M AgriLife Research is developing an integrated process with sorbent-based CO_2 capture and algae-based technologies to produce value-added products and biomass at ultra-high yield and low costs. The project features (1) a synthetic biology design to trigger auto-sedimentation of algal cells with high solid load for continuous cultivation by periodic auto-cell removal/harvesting, (2) a sorbent that allows CO_2 storage overnight with controlled release during daytime cultures, and (3) hydrogel-based phosphate, ammonia, and bicarbonate-controlled delivery to enhance algae productivity and reduce CO_2 loss from flue gas. The NCCC will help the project team prepare for field testing at the site in 2025.

3.3 CO_2 Removal Projects

3.3.1 SSEB/Aircapture Sorbent-Based Direct Air Capture

SSEB led 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's DAC system utilizes waste heat typical of that available in power generation and industrial facilities. As described in Figure 20, the monolith materials are rotated through absorption and desorption steps within the DAC test skid. The solid-amine contactor exhibits low pressure drop, low thermal mass, high geometric surface area, and Abs/Des: 10:1 (900/90 sec). The NCCC field test demonstrated capture and production of CO_2, including liquefaction. The target metrics were met, including 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.

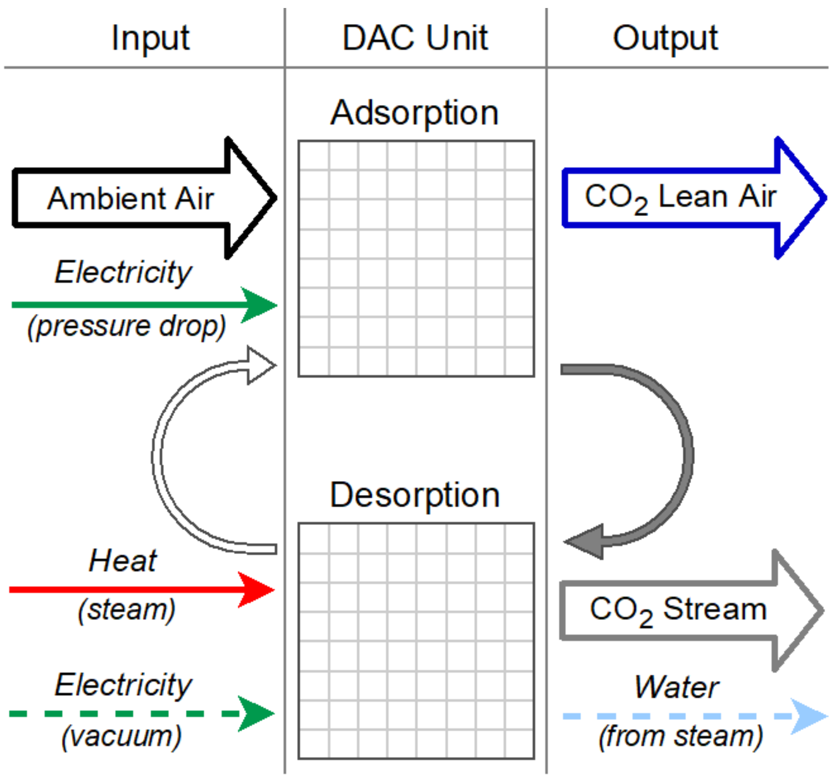


Figure 20. Aircapture Concept Drawing of DAC Process

During this reporting period, Aircapture integrated a CO_2 liquefaction skid to the demonstration test, as shown in Figure 21. Aircapture replaced all the sorbent blocks before the system restarted on March 15, 2024, with the integrated DAC and liquefaction system operation to produce liquid CO_2. The integrated DAC and liquefaction test was completed on April 29, producing liquid CO_2 with a concentration greater than 99.9 mol% CO_2. Total run time of the DAC process at the NCCC was more than 3,300 hours with greater than 90% availability. The DAC RECO$_2$UP project completed five test campaigns over 14 months.

DAC equipment | Integration of liquefaction and DAC equipment

Figure 21. Aircapture Equipment Installed at the NCCC

Table 7 shows performance data as a function of relative humidity (RH) compared to a low humidity baseline, since RH is the main environmental variable affecting performance. For these types of contactors, with steam as the medium for desorption, performance drops as humidity increases. More water remains condensed on the contactor, and since the diffusion coefficient of CO_2 in water is lower than that of CO_2 in air, a performance drop is observed with increasing RH.

Table 7. Results of SSEB/Aircapture DAC Process

DAC Performance	Low RH	Mid RH	High RH
Average production	Baseline	90% of baseline	65% of baseline
Average thermal demand	Baseline	109% of baseline	137% of baseline

At a mid-range RH of 50-60%, the production rate, or simple capacity of the machine, is 90% of the baseline. At high humidity levels greater than approximately 75%, testing shows a more significant drop in productivity to 65% of the baseline. This is an area where more work is needed to find mitigation approaches for the effects of RH. The thermal demand shown in the table is per tonne of CO_2 produced, so as production drops, the thermal demand per tonne of CO_2 increases. A key learning is that exposure of the contactors to high temperature oxygen present in air and the boiler feedwater play a large factor in the lifetime of the contactors.

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 NCCC PTR-TOF Analyzer

The NCCC is purchasing and installing a PTR-TOF mass spectrometer for real-time measurements of emissions in the flue gas exiting the PSTU. This online mass spectrographic technology provides ultra-sensitive, real-time identification and quantification of gas-phase compounds in a gas sample stream. Data on these compounds will provide information on solvent degradation processes and potential air emissions, both important in understanding the operational cost and potential environmental impact of CO_2 capture process operation. Previous and current use of other temporary PTR-TOF-MS instruments at the site have provided valuable data, and a permanently available instrument will be helpful in characterizing future technology tests in the PSTU.

The instrument will be primarily connected to gas sample points on the PSTU wash tower outlet and absorber outlets but could be connected to other process sample locations as needed. The instrument will be enclosed in a new building located on a structural steel platform of the PSTU structure (see Figure 22). Additional new or repurposed instruments will be located in the instrument building. This location places the instruments as close as possible to likely process sample extraction points to provide for the shortest lag time and most accurate samples.

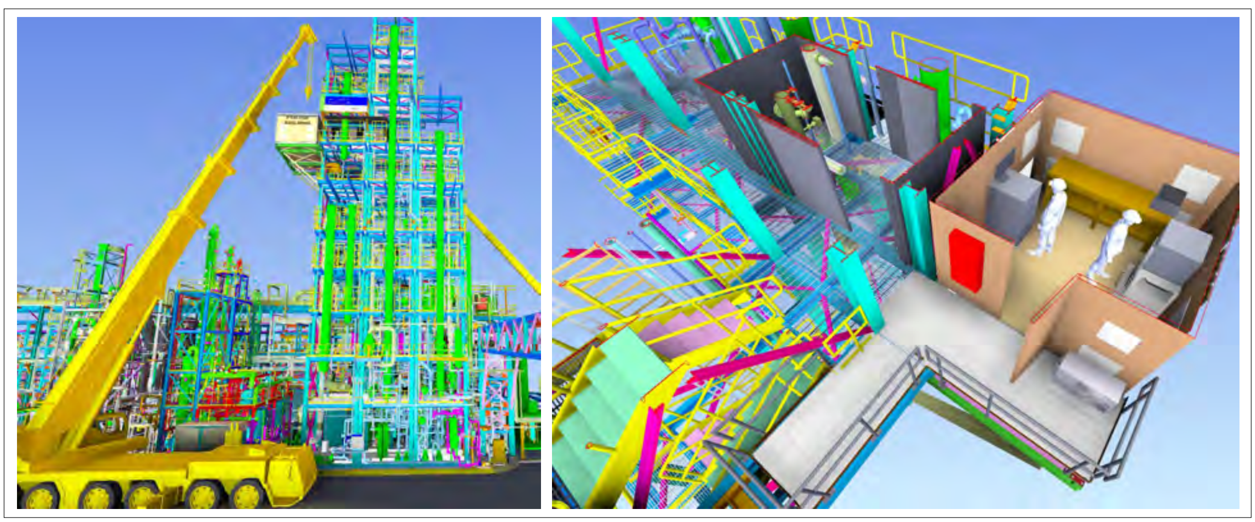


Figure 22. Model View of Installed PTR-TOF MS and Instrument Enclosure Building

The project team completed designs and issued a purchase order for the instrument and enclosure building. The team worked with Southern Company engineering to design the structural support steel needed. Overall project installation is planned for December 2024.

3.4.2 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 focused on the lower condensate flow rate ranges likely to be applicable to CO_2 capture on a natural gas combined-cycle process. The modifications were implemented and commissioned in 2022 and tested during the UT-Austin PZAS test campaign in 2023. PSTU operation utilizing the standard PSTU steam system is planned for Spring 2025, which will provide an opportunity to evaluate the improvements over a range of steam flow conditions.

3.4.3 SSTU Flowmeter Improvement

This project improved the accuracy and repeatability of the SSTU flue gas flow measurement by two different flowmeters. This measurement is the crucial indicator of the overall process flow used in operation of the SSTU. One flowmeter measures the flue gas rate upstream of the absorber, and another measures the flue gas leaving the wash tower outlet leading to the flue gas return header. Accurate and repeatable measurement of flue gas flow is challenging at both locations since the gas is at water-saturated conditions and can contain liquid droplets that interfere with flow measurements.

The modifications were commissioned as part of the SSTU water commissioning in August 2024. The system and flowmeter were partially commissioned during SSTU recommissioning operation in October. Once issues within the overall SSTU system are resolved, full commissioning and test operation of the reconfigured flow measurement system is planned for late 2024.

3.4.4 Natural Gas Reliability Upgrades

This project was initiated to address several reliability issues and provide a more robust operation of the natural gas boiler. The scope of the project evolved to address reliability issues related to ensuring optimal run time for developer testing. This scope addressed items such as human-machine interface optimization and mechanical and electrical design changes to provide more reliable and robust operation of boiler system. Work completed in BP9 included:

- Installation of a redundant demineralized water pump
- Replacement of the original flue gas cooler and addition of a bypass and differential pressure transmitter on the cooler
- Redesign and implementation of new air dilution valves to allow for better operational control
- Installation of electric hoist to allow easier access of heavier equipment replacements on the upper floors of the structure

Work will continue on the following scope items:

- Final review of equipment cross-reference guide for easier maintenance and accessibility to documentation

- Human-machine interface graphic cleanup
- Completion of electric hoist setup with extension of existing monorail

3.4.5 Installation of Dew Point Sensor at Instrument Air Offtake from E.C. Gaston

The instrumentation and controls group explored options for adding a new dew point sensor. Existing sensors that are available were identified and will be evaluated for their suitability.

4.0 Conclusions and Lessons Learned

During the reporting period, the NCCC supported multiple CO_2 capture, conversion, and removal projects and provided testing opportunities during three test runs:

- Run PO-15 started in BP8 on August 1, 2023, and ended on December 19, 2023.
- Run PO-16 was conducted from January 8, 2024, through June 30, 2024.
- Run PO-17 started on July 1, 2024, and will continue into Budget Period 10 (BP10).

Active projects during the budget period are listed below.

- UT-Austin PZAS Process—UT-Austin completed the third of three test campaigns focused on solvent degradation, corrosion studies, and mitigation methods with the PZAS process. Testing demonstrated that with pumping only around the intercooling at the bottom of the absorber for incoming hot flue gas (simulating natural gas combined-cycle flue gas conditions), a 95.5% CO_2 capture efficiency was consistently achieved, with a maximum capture efficiency of 97.7% achieved. The specific reboiler duty was 2.43 GJ/tonne CO_2. More than 5,800 hours of performance data were collected during the three test periods, which entailed beginning in December 2022.
- ExxonMobil/MHI Solvents—ExxonMobil and MHI tested two MHI solvents in the PSTU to collect data on emissions and energy consumption. The KS-21TM solvent was tested for 590 hours, and the second solvent, Solvent B, was tested for more than 850 hours. A 95% CO_2 capture efficiency was consistently achieved during long-term steady-state operation for solvent degradation and emission study. Solvent emission data was collected continuously using a Fourier transform infrared spectrometer, the University of Oslo's PTR-TOF-MS, and a manual impinger and sorbent sampling train. ExxonMobil concluded that both solvents were relatively stable during the long-term tests.
- EPRI/Pacific Northwest National Laboratory/RTI International Water-Lean Solvent—EPRI is working with PNNL and RTI International to scale up the EEMPA water-lean solvent for CO_2 capture. Testing with coal flue gas began on August 22, marking the start of the test campaign, which is expected to continue into 2025. As the testing moved through the test matrix, fog was observed in the regenerator column, which also resulted in solvent carryover in the CO_2 product stream. The fog was more prominent with solvent carryover as the temperature increased. The teams will continue to adjust test parameters to understand the root cause of this issue.
- 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 heat integration to facilitate CO_2 removal via phase change and produce pure liquid CO_2. The Carbon America team completed testing in the second quarter of 2024, meeting performance targets with over 1,000 hours of flue gas operation, up to 99% capture efficiency, and CO_2 product purity of 99.97%. The test campaign validated physics-based model predictions with good data

fits and confirmed the co-capture of pollutants like NOx, SOx, and heavy metals in flue gas. The robust operation achieved is expected to advance the FrostCC TRL from TRL 5 to TRL 6.

- SRI Mixed-Salt Process Solvent—SRI has developed 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 September 2024, SRI's modular skids were delivered to the NCCC and installed in the pilot bay area for demonstration of 5 to 10 tonnes of CO_2 capture per day. The test campaign is scheduled for early 2025.
- 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 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 2025.
- CORMETECH Sorbent—CORMETECH is developing a sorbent monolith carbon capture system for bench-scale testing at the NCCC. 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. Through testing, which began in September 2024, CORMETECH has identified additional operational issues and will address those and continue their testing through January 2025.
- 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. NETL finished testing a series of thin-film composite membranes in June 2024, having accumulated 2,888 hours of operation since September 2023. In November 2024, NETL will begin a test campaign with their new rubbery thin-film composite membrane coupons inside a 3-D printed permeation cell.
- 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, with two gas sensors and four liquid sensors. Solvent circulation began in September 2024. The team will continue to work through any issues and complete the sensor testing in February 2025.
- LLNL Structured Packing—LLNL has developed advanced structured packing based on additively manufactured geometries. LLNL has demonstrated the performance of the packings in the lab and will scale the packings and further validate their performances in the SSTU using MEA solvent starting in March 2025.
- GTI Energy Graphene Oxide-Based Membrane—GTI has developed a graphene oxide-based membrane technology expected to achieve at least 90% CO_2 capture from natural gas- or coal-derived flue gas using a two-stage configuration, the GO^2 process. The project concluded after GTI completed a test campaign in June 2024, for a total of

1,500 hours of testing achieved since the project was commissioned in August 2023. GTI reported that the two-stage membrane process met the performance targets of greater than 90% capture efficiency and 95% CO_2 product purity. It also demonstrated stable performance for the targeted 200 hours of operation. Parametric test results showed the CO_2 capture performance was impacted by flue gas flow rate and membrane operating temperature.

- Rensselaer Polytechnic Institute/SUNY Buffalo Sorbents—RPI is developing a transformational molecular layer deposition tailor-made, size-sieving sorbent developed by SUNY Buffalo and using a pressure swing adsorption process developed by University of South Carolina for CO_2 capture. The technology will be tested in the LSTU in early 2025.
- 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 contaminants through long-term testing at the NCCC with flue gas in 2025.
- NETL PTR-TOF—NETL will install and operate their PTR-TOF MS during PSTU operation. NETL plans to use this instrument as part of a mobile emissions and performance testing system that will be deployed at various CO_2 capture sites and projects to provide highly accurate and independently verified performance data. The instrument will be used to collect data during PSTU operation planned for early 2025.
- UCLA CO_2Concrete—In May 2024, UCLA completed its second test campaign at the NCCC with an ultra-low-carbon concrete production process using CO_2 from flue gas. UCLA reported that 31.3 tonnes of CMU, 51.3 tonnes of SRW, and 40.1 tonnes of concrete manhole were produced and carbonated. They achieved (1) carbonation of three separate concrete products, (2) production of more than 10 tons/day of concrete of each product, (3) absorption of greater than 0.2 g CO_2/g reactant, and (4) compliance of carbonated concrete with industry-standard specifications.
- Texas A&M Algae—Texas A&M AgriLife Research has received DOE funding to integrate sorbent-based CO_2 capture with algae technologies to produce value-added products and biomass with ultra-high yield. Testing at the NCCC will begin in 2025.
- SSEB/Aircapture Sorbent-Based Direct Air Capture—SSEB's project demonstrating Aircapture's sorbent-based DAC technology was designed to utilize low-grade waste heat at industrial facilities. The final test campaign concluded in July2024, with 3,384 hours of operation achieved over four campaigns. The target metrics were met, including 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^{o}C, and unattended DAC operations.
- Site Modifications—Several projects were ongoing for enhancing testing capabilities and improving site conditions:

- PTR-TOF MS installation
- SSTU flowmeter improvement
- Natural gas system reliability upgrades
- Installation of dew point sensor at instrument air offtake from Plant Gaston