FrostCC™ Pilot Testing at National Carbon Capture Center – Summary Report

Executive Summary

Carbon America has successfully completed the operation of a FrostCC™ engineering-scale pilot system at the National Carbon Capture Center (NCCC). This project validated FrostCC's efficacy and reliability at capturing CO_2 from flue gas, advancing the technology from Technology Readiness Level (TRL) 5 to 6.

During the pilot operation, the FrostCC™ system accumulated over 1,000 hours of continuous carbon-capture operation, demonstrating its ability to maintain prolonged performance. The system achieved ultra-high capture efficiencies up to 99%. Carbon dioxide (CO_2) capture productivities reached well over 1,000 metric tonnes per year (TPY). The captured CO_2 had a purity of 99.97%.

The system also effectively removed nitrogen oxides (NO_x) and sulfur oxides (SO_x) from the gas stream, reducing NO_x ($NO + NO_2$) to < 0.5 ppm and $SO_2 < 2$ ppm.

The FrostCC™ pilot was well-instrumented, and data collected during operation were used to further assess the capabilities of the physics-based models used to predict the core capture and recovery steps of the process. The experimental data closely matched model predictions, enhancing confidence in model-based scale-up and the design of larger FrostCC™ systems.

Key results and insights from the FrostCC™ pilot at NCCC will inform the design and operation of a Commercial Demonstration Plant. Scale-up improvements include reduced proportional effect of ambient heat gain, increased available cooling power through multiple stages of compression and expansion, efficiency gains from larger expander sizes, recovery of expander power to drive compressors on a common shaft, higher utilization of the cold from liquid CO_2 for recuperative cooling, and general design enhancements based on pilot learnings.

The successful completion of the FrostCC™ pilot at NCCC marks a significant milestone toward the commercialization of this promising carbon capture technology. With proven performance, robustness, and scalability, Carbon America is positioned to advance FrostCC™ to full-scale deployment, leveraging the insights gained from this pilot to enhance future projects.

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1. Introduction

1.1. Carbon America

Carbon America is a vertically integrated carbon capture and storage (CCS) company with its primary activities focusing on two critical challenges facing CCS: (1) developing a low-cost, robust, environmentally-friendly carbon capture technology in FrostCC™ to accelerate carbon capture deployment across the industrial and power sectors; and (2) developing regional carbon storage hubs in areas that have been neglected by other larger CCS developers. The company's world-class team of engineers, scientists, and developers are working to enable decarbonization of industrial and power sectors, with multiple advanced projects in development.

1.2. FrostCC™

FrostCC™ is a novel cryogenic carbon capture technology designed to remove CO_2 from point sources such as industrial facilities and power plants. FrostCC™ compresses, cools, and expands flue gas to the point where the CO_2 "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 purified, pressurized liquid ready for underground sequestration. The CO_2-lean exhaust gas is circulated back through the system as the auto-refrigerant. Figure 1 shows a simplified process flow diagram (PFD) of the FrostCC™ system. The FrostCC™ engineering-scale pilot plant at the National Carbon Capture Center (NCCC) is FrostCC™'s first end-to-end pilot plant, incorporating all the key process steps to enable it to capture CO_2 continuously from a flue gas.

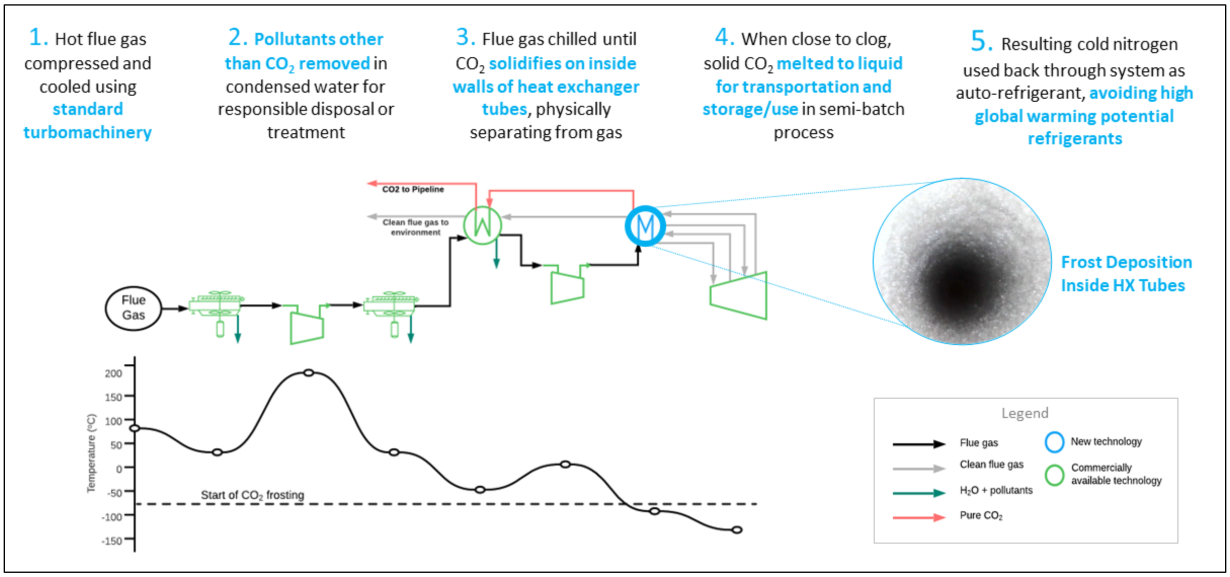

Figure 1 FrostCC™ Process Flow Diagram

1.3. Pilot Plant at the National Carbon Capture Center

Carbon America operated a FrostCC™ engineering-scale pilot system at the National Carbon Capture Center (NCCC) in Wilsonville, AL. The FrostCC™ engineering-scale pilot plant at the NCCC is Carbon America's first end-to-end pilot plant, incorporating compression, cooling, CO_2 frosting, and recovery.

Initial design and operating objectives for this pilot study were defined in 2021. Detailed design progressed through early 2023 in parallel with procurement and fabrication of key sub-systems. The compression, pre-cooling, and expansion sub-systems were commissioned, tested, and model-verified through mid-2023. The fabrication of the Frost towers was completed in late 2023, kicking off final installation and commissioning at NCCC. The pilot was fully commissioned on April 5, 2024, when continuous capture operations began.

In two months of operation, the pilot plant reached a significant milestone by completing 1,000 hours of continuous carbon capture operation, including time and tests outside of the system's design envelope.

Figure 2 FrostCC™ Pilot Plant Installed at the National Carbon Capture Center

1.4. Project Goals

Carbon America's goals for this pilot project were: 1) achieve a minimum of 100 hours of operations, with a target of 1,000 hours; 2) capture a least 500 tpy of CO_2, with a target of 1,000 tpy; 3) attain a minimum capture efficiency (the percentage of CO_2 removed relative to the total amount of CO_2 present in the flue gas feed) of 90%, with a target of 99%; 4) validate physics models; 5) demonstrate co-pollutant capture; 6) evaluate the reliability of the integrated system and key equipment; and 7) advance FrostCC™ to TRL 6.

Carbon America successfully met each of these goals following a rigorous pilot plant test plan. We achieved over 1000 hours of operation, demonstrated capture rates well over 1,000 tpy of CO_2 with efficiencies exceeding 90%. The physics models were validated, non-CO_2 pollutant capture was demonstrated, and the reliability of the integrated system and key equipment was thoroughly evaluated. Consequently, the project advanced the technology to TRL 6, marking a significant milestone in our carbon capture efforts.

1.5. Model-Predicted Performance and Operational Dynamics

Carbon America has developed state-of-the-art modeling capabilities for simulating engineered thermal-fluid systems, validated against hundreds of tests and thousands of operational hours at the laboratory-scale pilot. These coupled multiphysics models were used during the design phase of the project to predict system dynamics and the allowable operating space. This was done across a range of uncertain model input parameters. The uncertainty of these model parameters created a range of potential performance outcomes as we attempted to predict how the system would behave. The modeling results informed the development of the testing strategy. The test plan described in the next section leveraged these modeling results. As operational data were collected, additional modeling studies were conducted to continuously guide the test planning process.

2. Description of Testing Plan and Strategy

The test plan and strategy for the FrostCC™ system were designed to rigorously evaluate its performance under various operating conditions. Key independent variables tested included CO_2 concentration in the flue gas, the concentration of water in the flue gas, the operating parameters in the CO_2 recovery process, and heat exchanger temperature setpoints in the *Pre-cooling Subsection*. The general test plan encompassed continuous operation tests, pollutant tests, and expander tests, each aimed at validating distinct aspects of the system's functionality.

Continuous Operation Tests: The primary goal of these tests was to demonstrate continuous operation under a wide variety of flue gas compositions and internal system states. Independent variables were fixed, and the system was run continuously and uninterrupted for multiple days to capture CO_2. These tests were conducted at varying CO_2 concentrations, using different recovery melt strategies. Steady-state performance was monitored, and data was gathered for transient and steady-state model validation and calibration under varied conditions.

Pollutant Tests: These tests sought to evaluate the FrostCC™ system’s capability to capture sulfur oxides (SO_x) and nitrogen oxides (NO_x) pollutants. Models predicted the formation and removal of pollutants in both the water dropout steps in the process, as well as Frost heat exchangers. Water and liquid CO_2 samples were collected and analyzed for SO_x and NO_x; some tests were performed with coal flue gas where inlet pollutant concentrations were higher.

Expander Tests: The turbo expander’s tolerance to CO_2 in the inlet was tested to determine conditions that may lead to solid particle formation. The control inputs were adjusted to decrease the CO_2 capture rate in the FrostHXs, allowing CO_2 into the expander unit. The goal was to identify conditions that could cause solid CO_2 formation and use the data to further calibrate fundamental models for scaling up the FrostCC™ system. There is limited discussion on this topic in this document due to the proprietary nature of this data.

2.1. Testing Plan Specifics

The FrostCC™ pilot frosting sub-systems operated using an air feed from January to March 2024 to verify and tune all components, including turbomachinery, valves, and sensors. Afterwards, the melting sub-system, which includes the CO_2 tank and pumps, was commissioned. At this time, continuous-mode operation (24/7) using flue gas was initiated, with occasional interruptions due to custom controls software bugs, minor equipment issues, and NCCC boiler shutdowns. The captured CO_2 flow rate and capture efficiency for operating time within the system's design envelope is shown in Figure 3. Seven phases of operation were used and are described in more detail below.

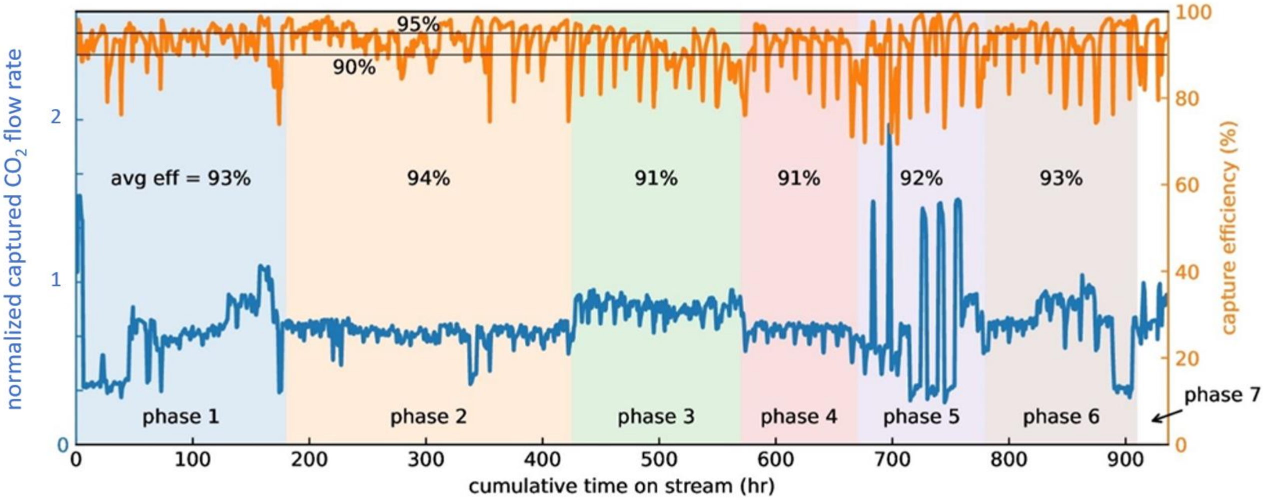

Figure 3 Normalized captured CO_2 flow rate (lower trendline and left axis) and capture efficiency (upper trendline and right axis) for cumulative operating hours within the system's design envelope. The left axis values have been normalized for confidentiality purposes. The weighted average efficiencies for each phase are noted in text in the middle of each colored phase region.

2.2. Testing Phase Descriptions and Key Learnings

Phase 1: The first phase of testing included baseline performance tests to ensure that the system components and controls performed as designed. The tests also explored system operations under a range of conditions. The tests began with a brief period of high CO_2 concentrations. Subsequently, the inlet CO_2 concentration was set lower, starting around 1% by volume, and systematically increased, increasing CO_2 capture productivity until the average capture efficiency dropped below 90%. These initial exploratory experiments mapped out the system limits and guided the subsequent phases of testing.

Phase 2: This phase of testing involved continuous operation at a steady rate of CO_2 capture for ten days. The system performance remained steady over this time, with an average capture efficiency of

94%. During this phase, operations including melting and recooling of the FrostHXs were further tuned to determine which inputs have the largest effect on capture efficiency.

Phase 3: During the third phase of testing, the CO_2 concentration entering the FrostCC™ system was increased to achieve a higher rate of CO_2 capture. Although, the capture efficiency slightly decreased at this higher capture flow, it still averaged over 90%. Larger dips in the capture efficiency were observed between cycles because less coolant was available for recooling the FrostHXs after a melt, as more was being used for the active frosting of CO_2.

Phase 4: In Phase 4, the same nominal capture operation conducted in Phase 2 was repeated to compare system performance. The goal was to determine if any changes had occurred. The average capture efficiency during this phase was 91%, slightly lower than the 94% observed in Phase 2. This decrease was expected due to several factors: warmer ambient temperatures, minor water ice fouling in the precooling heat exchangers (where temperatures are lower than the dryer dew point), and adjustments to the melting cycle timings. These causes of reduced performance are predictable and can be managed in future systems.

Phase 5: After demonstrating continuous system operation, Phase 5 focused on pushing the system to its limits. A series of experiments were conducted with substantially increased CO_2 concentrations, resulting in high capture productivities, peaking at well over 1,000 tpy during short operating periods across multiple test periods. However, sustained operation at these higher concentrations was not possible due to the limited availability of cooling, which is also required for cooling the non-frosting heat exchangers in the batch process. These tests involved temporarily allocating all available cooling to the FrostHXs to demonstrate the system's capability for higher CO_2 capture rates.

Phase 6: After confirming that baseline conditions still resulted in the same capture efficiency and productivity as observed in Phase 2, Phase 6 involved exploratory experiments. These experiments included continuous frosting at higher CO_2 concentrations to test the maximum limits of frost capture per cycle, including near-clog scenarios. The melting process successfully recovered the solid CO_2 during several near-clog cycles, although an extended melt cycle was required after a Frost HX was deliberately fully clogged. Phase 6 also explored intentional frosting post-expander, a technique that could be used in future optimizations.

Phase 7: Phase 7 involved operations on coal flue gas to further characterize pollutant capture with higher inlet NO_x and sulfur dioxide (SO_2) concentrations.

3. Results and Discussion

This section presents the results of the FrostCC™ pilot at the NCCC. The pilot plant successfully reached the project goals, yielding significant insights and achievements. These results, discussed in the following section, underscore the potential of FrostCC™ technology in real-world applications and provide valuable data for future design and operational enhancements.

3.1. Key Results

As discussed previously, some of the significant results generated by the pilot study are the continuous operability, efficient carbon capture, and CO_2 product purity. Overall, Carbon America's goals for this pilot were achieved. Importantly, the cumulative product of these results is change in technology readiness level of FrostCC™ to TRL 6.

Hours of Testing: Fabrication, installation, and commissioning delays narrowed the window for pilot operations, but these delays provided valuable lessons that can be applied to future FrostCC™ designs and operations. Despite the shortened test window, the pilot plant successfully accumulated 1,000 hours of continuous carbon capture operations. Importantly, the system remained cold throughout the testing period, ensuring that disruptions had minimal impact on key insights associated with long-term operation, such as water ice fouling considerations.

Capture Efficiency: During pilot testing, capture efficiencies typically ranged from 90 to 97%, occasionally reaching up to 99%. These variations were influenced by natural temperature fluctuations associated with the cyclical batch process and changing experimental test plans. The average capture efficiency per test phase ranged from 90 to 94%, with many operating hours achieving capture efficiencies of 93 to 97%.

FrostCC™ operates on a cyclical batch process, where capture efficiency occasionally dipped below 90% during the transition between the frosting and melting phases of heat exchanger pairs. This decrease occurred due to the tradeoff between using available cooling to capture frost in the active heat exchanger pair and recooling the other pair after melting. While these brief drops between batches lowered the average capture efficiency, a cumulative average efficiency of 92% was achieved over the entire pilot campaign. Future FrostCC™ systems could mitigate this issue by implementing strategies to increase available cooling and reduce ambient heat gain, both of which will happen naturally as the technology is scaled up in size.

Importantly, brief periods of ultra-high capture efficiency (97-99%) were achieved under ideal operating conditions, typically when the system temperatures were lower. Achieving 99% capture efficiency demonstrates a significant advantage of the FrostCC™ process over traditional capture processes. Reaching this level of performance primarily depends on maintaining sufficient cooling power, which is determined by both the coolant temperature and flow rate into the FrostHXs, given a specific CO_2 concentration. However, limitations on cooling capacity of this pilot plant due to various factors made it challenging to sustain ideal operating conditions for extended periods. The commercial FrostCC™ designs will incorporate known solutions to address these challenges.

CO_2 Capture Rates: The pilot testing demonstrated CO_2 capture well over 1,000 tpy of CO_2. However, most of the testing was performed at lower capture rates of CO_2 where continuous operation was reliably achievable.

CO_2 Product Purity: The pilot demonstrated a CO_2 product purity of 99.97%. After a frosting cycle, the solid CO_2 is melted and pumped into the liquid-CO_2 (LCO_2) tank. LCO_2 samples were sent to an external laboratory for analysis to characterize the CO_2 product. In addition to the 99.97% CO_2 purity,

the analysis showed low O_2 (< 10 ppm on average) concentrations in the CO_2 product. There was some water present in the LCO_2 reservoir, which was attributed to a process upset and maintenance activity which occurred during the commissioning stage and was not easily remedied. This will be avoided in future projects.

Technology Readiness Level: Following the descriptions and assessment protocols of Technology Readiness Levels (TRL) outlined in the DOE G 413.4A, Technology Readiness Assessment Guide, the successful operation of the engineering-scale pilot plant at the NCCC elevated the FrostCC™ technology from TRL 5 to TRL 6. This significant milestone was achieved by demonstrating the FrostCC™ system's performance at pilot scale in a relevant environment, which included operating under realistic conditions simulating actual deployment scenarios. The pilot system used all the key subsystems and unit operations required for the FrostCC™ process, proving the ability to continuously capture CO_2 with electricity as the only energy input to the system, and using the flue gas as an auto-refrigerant. The tests involved prolonged exposure to real-world variables, validating the technology's reliability, scalability, and efficiency in capturing CO_2. As a result, the FrostCC™ system has moved beyond laboratory validation and into the realm of an engineering scale demonstration in an operational environment, thereby meeting the criteria for TRL 6.

3.2. Pollutant Capture

Flue gases contain CO_2, N_2, O_2, water vapor, as well as air pollutants such as SO_x, NO_x, particulates, trace metals, and more. A promising outcome from the pilot testing of FrostCC™ was the verification and quantification of pollutant removal. Measurements confirmed that NO_x and SO_x from the NCCC natural gas-fired boiler flue gases were effectively captured, as evidenced by the on-stream process gas analyzers and other methods. NO_x levels were reduced to less than 1 ppmv, including a reduction of NO by about 90%. Despite the low SO_x concentrations in the boiler flue gas, SO_2 was also captured by the process. Thermodynamic analyses also suggest that FrostCC™ can capture many other pollutants in flue gases that have them.

Pilot testing involved continuous process gas analyzers monitoring flue gas from NCCC. Measurements were taken at several points in the process, including the flue gas supply at the FrostCC™ inlet, diluted flue gas before and after the compressor, and cleaned flue gas returning to NCCC. Additionally, nitrogen and sulfur content in the condensed water streams was measured.

To further assess FrostCC™'s pollutant removal capabilities, coal flue gas with higher pollutant concentrations from E.C. Gaston power plant's Unit 5 boiler was used. NO_x levels at the inlet and outlet of the FrostCC™ pilot, as shown in Figure 4, confirmed FrostCC™'s capability to reduce NO_x levels to below 1 ppmv, even at elevated inlet concentrations.

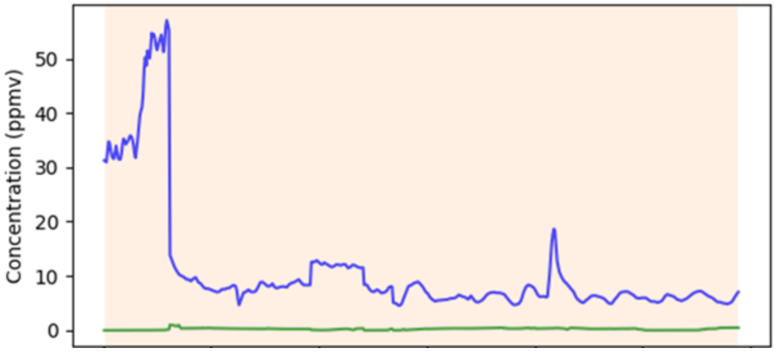

Figure 4 NO_x measurements at FrostCC™ inlet (blue line) and exit streams (green line).

Additionally, FrostCC™ effectively reduced SO_2 concentrations to less than 1 ppmv at the outlet during most of the test period. The system is expected to achieve similar pollutant reductions regardless of the initial concentrations in the flue gas, as removal efficiency is primarily driven by process conditions.

The environmental benefits demonstrated in this pilot testing position FrostCC™ as a highly effective pollutant removal technology. FrostCC™ offers the potential to clean flue gas comprehensively without generating additional emission streams, potentially eliminating the need for separate pollutant control units, and reducing both capital and operational costs compared to other carbon capture solutions.

3.3. Physics-based Model Agreement to Testing Data

The NCCC pilot was equipped with extensive instrumentation, allowing data collected during operation to be used in further assessing the capabilities of our physics-based models, as introduced in the *Model-Predicted Performance and Operational Dynamics* section. These models will support the scale-up and design of a larger system. Figure 5 presents a comparison between the model-predicted results and experimental data for a single frosting period in a pair of Frost HXs. Data-driven boundary conditions were applied to the tube and shell-side inlets of the Frost HXs, with the models predicting the outlet stream temperatures and CO_2 capture efficiency for each heat-exchanger. The results show that our model accurately matches the experimentally recorded data. Relative to the experimental data, the model's tube and shell outlet temperatures have a difference of less than 5 Kelvin (K), and the capture efficiencies have a difference less than 2%.

Figure 6 summarizes the agreement between modeling predictions and experimental results, shown as model "error,", which represents the difference between predictions and actual measurements. This summary focuses on the flue-gas outlet temperature of frosting heat exchangers for more than a hundred frosting cycles across all four Frost HXs. Although the model predictions were systematically higher than the experimental data, the predictions were consistently within a few degrees of the measurements for all frosting cycles. Instances of high intracycle variation, indicated by the error bars on the plot, were correlated with rapid temperature changes at the beginning or end of a frosting cycle. Further refinement of the data-driven boundary conditions is expected to improve model accuracy in these cases.

The models had been previously validated against hundreds of experiments with a 10 tpy-scale FrostCC™ system. The NCCC pilot represented a roughly 100x scale increase in heat exchanger size. The strong agreement between model predictions and experimental data across these scales provides high confidence that the models will also be applicable to the next scale-up, which involves an increase in heat exchanger size from this NCCC pilot to Carbon America's upcoming Commercial Demonstration project. The close agreement between simulation results and NCCC pilot measurements provide high confidence that Carbon America's tools are capable of effectively designing future FrostCC™ systems that can achieve continuous carbon capture at high capture efficiency.

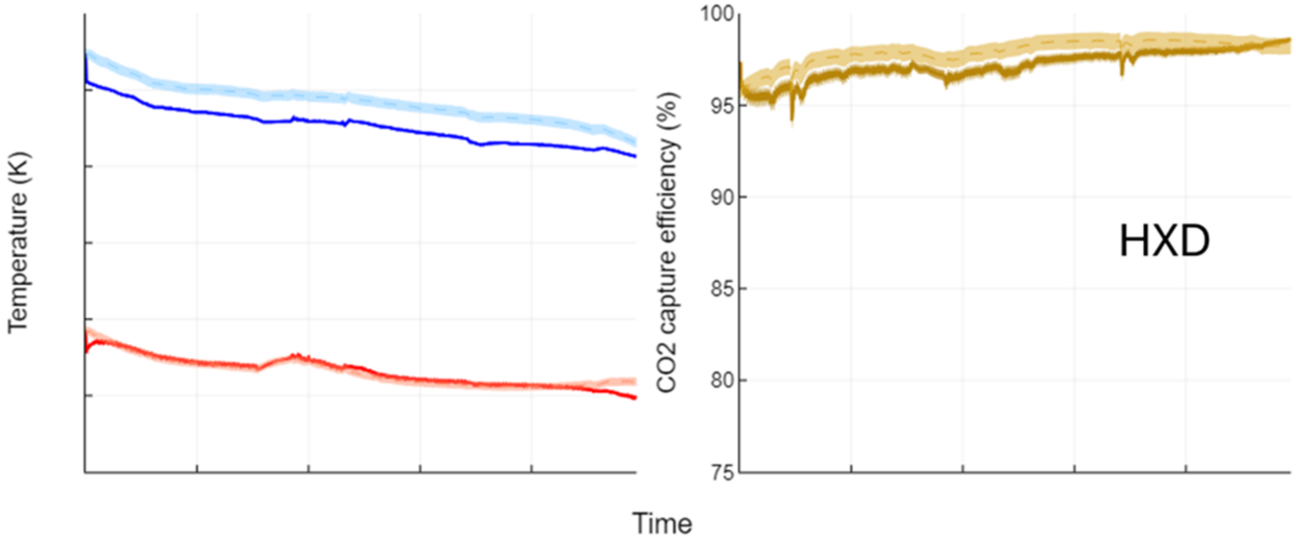

Figure 5 Model predictions (dark solid) and experimental results (light dashed) for frosting operation in the NCCC pilot system for Frost HX -D exit temperatures (left) and capture efficiency (right). The thickness of each line accounts for measurement uncertainties, where thicker lines indicate more uncertainty in the data. Not all numbers are presented for confidentiality reasons.

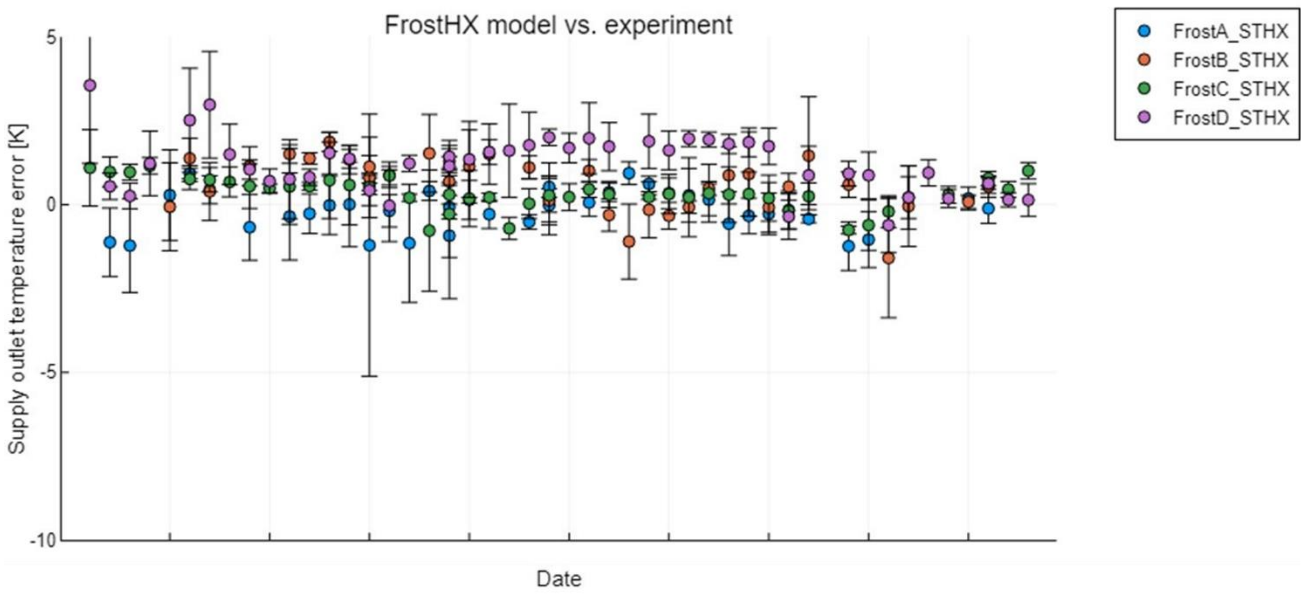

Figure 6 Summary error between simulation results and experimental data for the temperature of the flue outlet during frosting cycles. The error bars are one standard deviation during the time series of each experiment. Specific dates are not included for confidentiality reasons.

3.4. Performance Limitations

The initial target capacity for the NCCC pilot was to capture 1,000 tpy. Although some tests achieved capacities exceeding this target, the system's ability to sustain continuous CO_2 capture required lower CO_2 flow rates. This reduced capacity was primarily due to design and operational compromises at the pilot scale, particularly limited cooling capacity

Several factors contributed to the limited cooling capacity experienced by the pilot plant. First, the pilot was originally designed to operate the LCO_2 tank at lower temperature than was allowed by LCO_2 pumps that were available to procure for this pilot. This adjustment led to a loss of flue gas cooling capacity.

Additionally, the system experienced greater-than-expected ambient heat gain, further reducing total cooling potential. For instance, heat gain in one heat exchanger and surrounding pipes accounted for 10-35% of the total heat exchanger duty. This heat gain was attributed to three compounding factors: the small scale and limited total cooling potential of the pilot project, disproportionally long piping runs, and heat intrusion through insulation defects. To mitigate these issues in future projects, heat gain is expected to be reduced through scale-up, shorter piping runs, and improved insulation.

Lastly, the project went through a late-stage redesign to mitigate the risk of post-expander frosting, a significant concern at the time. This redesign involved reconfiguring process flows and repurposing prefabricated heat exchangers, resulting in off-design operation. While this led to suboptimal performance in the cold recuperation heat exchanger performance due to sizing mismatches and tighter temperature differentials, it significantly decreased the risk of expander degradation.

4. Key Lessons Learned

4.1. No FrostHX Degradation

The FrostCC™ process demonstrated consistent thermodynamic performance, with no degradation in the Frost HXs throughout the pilot testing. Unlike solvent, membrane, and sorbent-based carbon capture systems, which may suffer from thermal, physical, and chemical degradation, FrostCC™ relies on a phase-change separation process within the tubes of the Frost HXs, minimizing degradation over time. The reliability of shell and tube heat exchangers, proven in various industrial applications, supports the durability of the Frost HXs. Specifically designed to handle CO_2 buildup, these heat exchangers undergo a melt step that periodically and completely removes accumulated CO_2, ensuring long-term performance.

4.2. CO_2 Recovery Effectiveness

The melting (CO_2 recovery) process is a core component of the FrostCC™ technology, facilitating continuous carbon capture while CO_2 is deposited into the Frost HXs in a batch process. The melting process was a primary focus of the experimental-scale R&D effort at Carbon America during the 18 months leading up to the engineering-scale pilot at NCCC, proving to be extremely valuable. The pilot testing at NCCC proved a reliable melting process, and the procedure was run autonomously by Carbon America's process-control software. The baseline melting procedure worked successfully from the start, allowing the team to focus on complete system characterization. Over the course of testing, there was only one process upset resulting from the melting process, which occurred while pushing the system’s operational boundaries.

4.3. Opportunities for Improvement

The NCCC pilot revealed several areas for improvement in industrial-scale process equipment, including potential challenges with clathrate hydrates, LCO_2 pump corrosion, insulation performance, valve reliability, and liquid water impacts.

Clathrate hydrates, crystalline phases of CO_2 and water ice, formed under certain conditions, risking equipment damage and efficiency loss. This issue can be addressed through stricter moisture control and equipment modifications, such as eliminating clog-prone liquid-CO_2 pumps.

Rapid corrosion was observed in carbon steel and cast-iron pumps within the LCO_2 subsystem. Corrosion was thought to have been caused by corrosive CO_2 water solutions formed during the frequent start-stop cycles that are characteristic of first-of-a-kind pilot plants. CO_2-saturated liquid water formed upon warming the system when stopped, allowing a corrosive solution to pool in pump bodies. Steel and cast-iron pumps were selected due to a unique combination of hydraulic conditions, schedule, and cost sensitivity for a pilot plant; suitable pumps made of corrosion-resistant materials meeting these needs were not readily available. The risk of corrosion was understood and mitigated by having rebuild kits on-hand to quickly repair deteriorating pumps. However, carbonic acid corrosion in the LCO_2 subsystem is not a characteristic risk of the FrostCC™ process and is easily solved by selecting well-understood, abundant and cost-effective corrosion-resistant materials like austenitic (300-series) stainless steels. Such materials are tolerant of CO_2-water solutions as evidenced by an absence of observed corrosion in the pilot's Type 304L stainless steel LCO_2 piping and process vessels.

Insulation performance on the large vertical FrostHXs was below expectations, largely due to non-ideal installation. Issues included higher ambient heat gain and moisture ingress. Future designs will improve insulation by incorporating larger design margins and enhanced water and rain protection.

Lastly, the pilot encountered significant valve reliability problems, such as poor accuracy in positioned valves, leakage in manual block valves, and binding valve stems due to cold temperatures. These issues have been identified, and corrective measures will be implemented in future projects, such as more appropriate selection of valves and their actuators for certain parts of the system.

5. Application to FrostCC™ Commercial Demonstration Project

The NCCC pilot testing of the FrostCC™ system has provided significant insights and valuable lessons to be applied in the design and operation the Commercial Demonstration project and future large-scale deployments. Improvements to the larger design, some of which are inherently tied to scale-up, include higher utilization of the LCO_2 tank as a cold source for recuperative cooling, increased cooling power capacity by increasing the number of expanders, lower proportional effect of ambient heat gain in a larger-scale system, and the ability to leverage new learnings, such as expansion-related frosting physics, to optimally design the process configuration and equipment.

5.1. Commercial Demonstration Project Module Design

The commercial FrostCC™ product will be designed for deployment as multiple identical trains, each comprising factory assembled and pre-commissioned skids. These trains will be standardized and will be deployed to a wide variety of potential sites using the same design. The number of trains that are deployed will be specified by the total CO_2 flow rate that is being captured for the project. This modular approach provides several significant advantages, detailed in Table 1. The next scale-up demonstration for FrostCC will be the first version of a standard commercial FrostCC™ train.

Table 1 Advantages of FrostCC™ Modularity Strategy

Reduced On-site Construction Time	• The assembling and pre-commissioning of the skids in a controlled environment significantly reduces the time required for on-site construction and commissioning. As a result, the overall project timeline is accelerated. • Multiple identical trains can be constructed and tested simultaneously in the factory, allowing for parallel processing and reducing the total project duration.

Improved Cost Efficiency	• Manufacturing identical units in a factory setting enables bulk purchasing of materials, instruments, etc., and a more efficient use of labor, leading to cost savings. Standardized practices reduce the cost per unit. • On-site construction typically incurs higher labor costs due to the need for specialized skills and the challenges of working in a less controlled environment. Factory assembly allows for a more predictable and streamlined workforce, and allows for advanced manufacturing techniques, such as robotic welding systems. • The incremental train installation offers a significant advantage in optimizing costs and performance of the process and accelerating the learning curve.
Improved Quality Control	• Factory settings offer better control over the construction environment, thus reducing the likelihood of errors, and simultaneously ensuring higher quality standards. The controlled setting allows for more thorough testing and quality assurance before the skids are shipped. Identical trains have uniformity in design and construction, leading to consistent performance.
Simplified Logistics and Installation	• Skid-based modular design simplifies transportation and installation. Pre-assembled skids can be easily transported to the site and assembled with minimal disruption. • The modular approach allows for easy scaling of FrostCC™ installed capacity. Additional trains can be added as needed without significant re-engineering or disruption to existing operations.
Enhanced Flexibility and Adaptability	• Plants can start with a smaller number of trains and gradually scale up based on demand, flue gas variability, and performance; as a result, the investment and operational capacity becomes more flexible than full-sized plant installation. • Retrofitting becomes easier, as modules can be placed at different locations of a site where there is space available.
Enhanced reliability	• Excess trains can be installed for minimal cost increase. In the event of a failure in one train, or unplanned maintenance, a spare train can be brought online to maintain operational continuity. Therefore, overall reliability is enhanced as the plant can continue to operate efficiently without significant downtime. • The modular design facilitates the stocking of critical spare parts such as pumps, valves, and other components. Standardized parts across identical trains mean fewer spare types need to be kept in inventory, simplifying logistics and reducing capital costs.
Risks reduction	• Using identical trains based on a proven design reduces the risk associated with new installations. Each train operates independently, so issues in one train do not necessarily affect the others. • Standardized trains and skids mean that maintenance procedures and training programs can be standardized. Therefore, the complexity and cost of maintaining the system are expected to be reduced.
Faster time to market	• Technology becomes commercially viable once the smaller standard module is proven. • Avoids need for additional scale-up demonstration, which may add several years to commercialization timeline. • Critical to maximizing impact on climate, as soon as possible.

6. Techno-economic Analysis

The FrostCC™ process design has shown significant improvements in capital expenditures, energy efficiency, and reliability, leveraging insights gained from the pilot testing at NCCC. Initial commercial designs highlight these advancements, especially compared to conventional amine systems. A techno-economic analysis (TEA) depicted in Figure 7 shows the nth-of-kind levelized cost of capture

(LCOC) from FrostCC™ designs across various CO_2 concentrations typically found in industrial and power flue gases.

Some of the key assumptions for this NOAK TEA include 85% capacity factor, \$35/MWh electricity price at power site and \$70/MWh price of electricity. Following NETL guidelines[1], a capital cost recovery factor of 0.0709 was used. In all cases, FrostCC™ targets 99% average CO_2 capture efficiency under standard operating conditions, which our models suggest is achievable for the commercial system. Figure 7 also includes LCOC estimates for amines used in cement plants, with and without flue gas desulphurization (FGD) and selective catalytic reduction (SCR) systems, as reported by NETL[2]. Costs have been escalated to 2023 dollars. FrostCC™'s go-to-market strategy aims to target these hard-to-decarbonize sectors in heavy industry where FrostCC™ has the most extreme competitive advantage. FrostCC™ will also expand into broader power and industrial markets to achieve the lowest capture costs across all sectors.

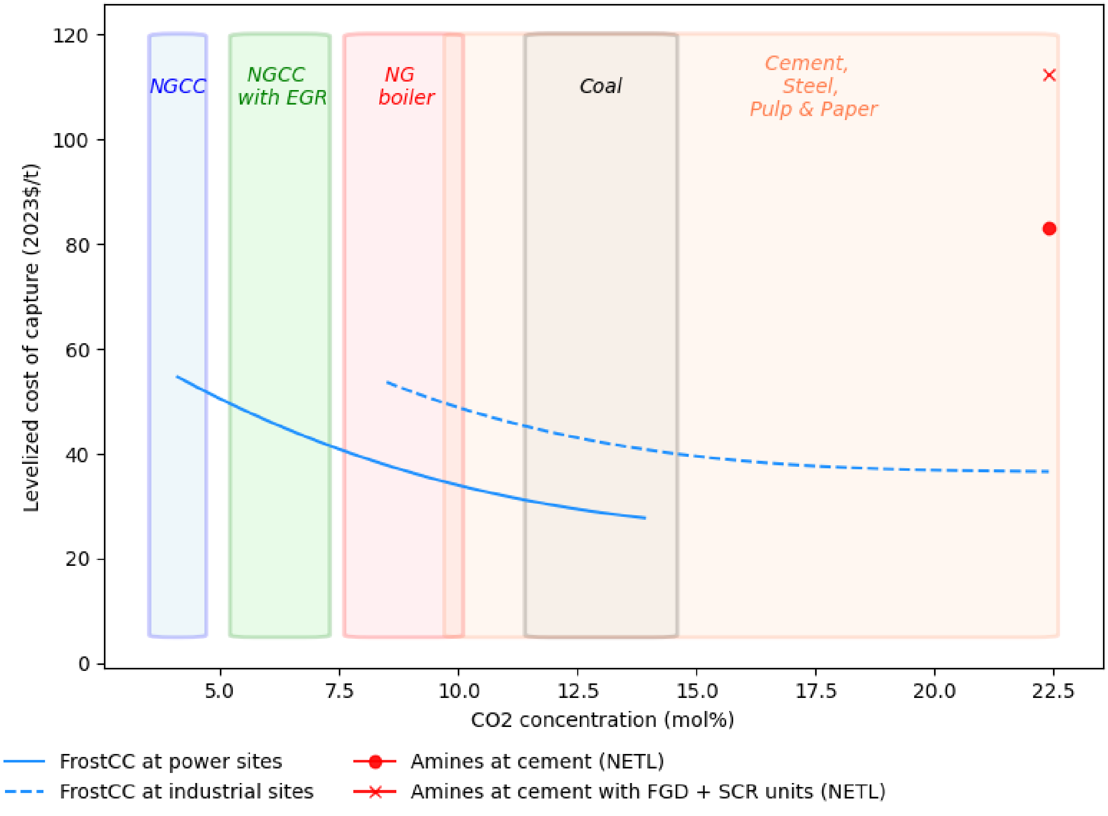

Figure 7 FrostCC™ levelized cost of capture at industrial and power locations at an estimated 99% capture efficiency.

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[1] Theis J. (2021). Quality Guidelines for Energy Systems Studies: Cost Estimation Methodology for NETL Assessments of Power Plant Performance. NETL report. United States. https://doi.org/10.2172/1567736.

[2] Hughes S., Zoelle A. (2022). Cost of Capturing CO2 from Industrial Sources. NETL report. United States. https://doi.org/10.2172/1887586.

FrostCC™ goes beyond cost-effective CO_2 capture by also providing co-environmental benefits through the removal other pollutants, as detailed in the "*Pollutant Capture*" section. Unlike many carbon capture technologies such as solvents, adsorption, chilled ammonia, metal-organic framework (MOFs), and membrane-based systems, FrostCC™ can process unscrubbed flue gases directly. The technology effectively removes key pollutants from flue gas through mechanisms like condensation, dissolution in water, and desublimation as the gas is pressurized and cooled downstream.

In contrast, other technologies often need gas scrubbing systems to avoid challenges like sorbent or membrane degradation and the generation of secondary pollutants, such as nitrosamines; in those cases, additional equipment like desulfurization units (FDU) and selective catalytic reduction (SCR) systems are mandatory. These additional gas scrubbing systems can significantly increase both capital and operational expenditures, costs that are often underestimated in other techno-economic analyses[3]. Managing these pollutants is crucial, as they greatly increase the energy demands and associated costs of CO_2 capture and transport.

A key advantage of the FrostCC™ process is its flexibility; it can be easily adapted to function as a gas scrubber with minimal impact on overall energy consumption. This adaptability not only enhances its environmental benefits but also offers considerable economic potential.

Preliminary analysis of pollutant removal from coal and NGCC flue gases, based on tests at NCCC and in-house thermodynamic calculations, indicates that integrating pollutant capture into the FrostCC™ process design could potentially minimize or eliminate the need for separate desulfurization and SCR units. However, further experiments and detailed process analyses are essential to optimize FrostCC™ for efficient pollutant handling from flue gases.

The potential co-environmental benefits of FrostCC™ could translate directly into cost savings in multiple areas. By reducing or eliminating the need for desulfurization and SCR units, capital expenditures could be lowered, reducing the initial investment required for pollutant control equipment. Additionally, operational costs would decrease due to the absence of additional units, resulting in lower maintenance and operational expenses. These improvements enhance the overall economic viability of the FrostCC™ system.

7. Conclusions

The NCCC pilot project demonstrated the impressive capabilities of Carbon America's FrostCC™ system to capture CO_2 with high efficiency and purity under real world conditions. Across 1,000 hours of carbon capture operation, the pilot achieved up to 99% capture efficiency with an overall average capture efficiency of 92%, demonstrating capture rates well over 1,000 tpy, and a product purity of

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[3] Industry estimates indicate that the additional gas scrubbing systems add at least \$20 per tonne of CO_2 captured to the cost of the carbon capture technology.

99.97%. The pilot successfully validated physics-based models, showing close alignment with experimental data, affirming Carbon America's confidence in scaling up the technology. Key results highlighted the durability of critical components, such as the Frost heat exchangers and the turbo expander, the overwhelming success of the CO_2 recovery process, and the FrostCC™ system's ability to capture co-pollutants like NO_2, NO, and SO_2, proves significant environmental co-benefits.

The successful operation of the NCCC pilot system advanced the FrostCC™ technology from TRL-5 to TRL-6, proving its reliability, scalability, and efficiency in a relevant industrial environment. This milestone underscores the FrostCC™ system's readiness for larger scale implementations.

Challenges during the pilot operation provided valuable insight for future design and operations. The NCCC pilot's ability to maintain high capture efficiency, even under a wide range of operating conditions, highlight's FrostCC™'s potential for widespread application in point-source industrial CO_2 capture. The comprehensive data collected, and the model accuracies achieved will guide the design of the upcoming FrostCC™ demonstration plant for the first iteration of the standard FrostCC™ commercial product.

The FrostCC™ technology offers significant advantages over traditional CO_2 capture systems, particularly in terms of cost effectiveness and pollutant removal. The integrated capture of NO_x and SO_x pollutants, alongside CO_2, provides substantial economic benefits by potentially eliminating the need for separate pollutant control systems. This positions FrostCC™ as a highly competitive solution for emissions reduction in the power and industrial sectors.

In conclusion, the NCCC pilot has validated the FrostCC™ system's performance, reliability, and scalability, paving the way for its commercial deployment. The lessons learned and the successes achieved reinforce the potential of FrostCC™ to significantly reduce CO_2 and other pollutant emissions, contributing to global efforts to combat climate change and enhance air quality. Carbon America looks forward to advancing FrostCC™ with an upcoming FrostCC™ commercial demonstration plant, driving towards a sustainable and cleaner future.