FINAL TECHNICAL REPORT

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"DILUTE SOURCE CO2 CAPTURE: MANAGEMENT OF ATMOSPHERIC COAL-PRODUCED LEGACY EMISSIONS"

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Abstract

This report presents the scientific and technical findings by Carbon Engineering Ltd (CE) resulting from the DOE sponsored research and development project on Direct Air Capture (DAC) process. The work was performed by CE under the Award DE-FE0026861 from the US Department of Energy's (DOE) National Energy Technology Laboratory (NETL). The work plan was centered on advancing the Recipient's DAC technology, developing a better understanding of its performance and cost.

The report outlines the results from two key activities that were performed under this award:

1. Studying the performance characteristics of the DAC plant at both pilot and lab scale
2. Techno-economic analysis (TEA) to study two implementations of CE's proprietary DAC process:

   i) An early commercial DAC process that captures ~1 MT CO_2/year of atmospheric CO_2 (Baseline case), and

   ii) A modified early commercial DAC process that captures 1 MT CO_2/year of flue gas CO_2 downstream of a subcritical PC post-CCS power plant (Case 1 Option C).

Within the first key activity of the project, significant operational improvements and learnings were realized, including for key equipment in the DAC process in addition to the overall system. Learnings included impact of equipment design on the capture, calcination and slaking processes, and operational parameter modifications for optimizing the pelletization process, along with the complex interactions and associated considerations of these on overall system performance. In parallel, benchtop scale equipment was successfully utilized to validate pilot scale data, such as, retention in the pellet reactor, and capture performance parameters of the air contactor. CE continues to conduct core research and development activities; the learnings from this DOE project will contribute to the design, testing and operation activities of CE's fully integrated DAC validation plant, as well as the first commercial DAC plant.

The second key activity incorporated the above learnings, as well as input from vendors and EPC experts, to produce the TEA report. More specifically, the TEA results were based on measured pilot plant performance data for all major unit operations, and on an energy and material balance for the process at commercial scale computed using an Aspen One® process simulation. The cost estimation methodology follows AACE International recommended practices; with an uncertainty range of -15%/+30%. Depending on financial assumptions, energy costs, and the specific choice of inputs and outputs, the levelized cost per ton CO_2 captured from the atmosphere for an early commercial plant for the baseline case ranges from 227 to 304 \$/t-CO_2. And, the levelized cost to capture 98% of the flue gas CO_2 emissions in a subcritical PC power plant (Case 1 Option C) through a combination of Cansolv carbon capture system and a modified DAC system was estimated to range from 109 to 160 \$/MWh of net power generated. Process improvement opportunities identified during this work, in addition to cost reduction opportunities identified during the Value Engineering exercise associated with the Baseline case indicate that significant reductions in capital costs are available as CE scales up and proceeds through deployment of initial facilities.

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1 Technical Progress

1.1 Project Goals

The high-level goals of the project were to cultivate a dilute source carbon dioxide (CO_2) direct air capture (DAC) technology that can be applied to capture from coal-relevant CO_2 streams, such as post-CCS flue gas, or can be applied to re-capture legacy coal-based emissions directly from the atmosphere. The work plan was centered on advancing the Recipient's DAC technology, developing a better understanding of its performance and cost, and codifying these results in a standardized Department of Energy/National Energy Technology Laboratory (DOE/NETL) techno-economic analysis (TEA) format.

In the first budget period, the core objectives focused on gathering and synthesizing experimental results, performance data, and engineering inputs to enhance understanding of the technology. In the second budget period, the core objectives focused on converting the synthesized data from the first budget period into actionable technology developments and propose scale-up strategies to move commercialization of the technology forward.

1.2 Project Management and Planning

1.2.1 Description

This activity encompasses the management activities required for completion of the award deliverables on-time and within the proposed budget.

1.2.2 Progress

The first revision of the project PMP was transmitted to the DOE in Q1 of the project performance period. CE worked with DOE staff to keep the PMP updated with any revisions to the project budget, success criteria or other tracked deliverables, to ensure the project remained on schedule.

CE developed and submitted the DMP to the DOE in Q2 of the project performance period. Data was logged and stored in accordance with the DMP and transmitted as outlined in the document. Improvements to plant instrumentation in Q2 of the project performance period enhanced CE's ability to log specific air contactor data.

Reporting activities proceeded on-time and in compliance with the terms and conditions of the award. CE continued to work with DOE staff to ensure sufficient information was included in briefings and reports transmitted to DOE, and timely receipt of project reporting deliverables.

1.2.3 Conclusions

Project management and planning activities proceeded as planned. CE will continue to work closely with the DOE's program manager and contract officer if any issues with the activities arise.

1.3 DAC Technology Applied R&D: Pilot Operation, Sensitivity Analysis, and Component Optimization

1.3.1 Description

The scope of this work focused on testing and study of the unit operations that comprise CE's dilute source CO_2 capture system at CE's pilot research facility in Squamish, B.C. Investigations into optimization of both equipment design and operating methods were performed, guided by performance of unit operations. This task also included initial investigations and evaluations of alternative equipment and approaches.

1.3.2 Progress

CE spent much of the budget period operating its pilot scale direct air capture facility and conducting lab tests to meet the objectives. In the pilot plant, data was collected for each of the main process equipment (Air Contactor, Pellet Reactor, Calciner, Slaker), which provided valuable insight into the Direct Air Capture pilot performance. The following subsections describe tests performed on the main process equipment.

1.3.2.1 Air Contactor

Pilot Air Contactor

In Q1 of the project reporting period initial testing indicated that the air velocity instrumentation on the air contactor was sensitive to local wind effects, and could not provide reliable results required to validate the mass transfer coefficient (K_L). Engineering staff identified alternative solutions to measure air velocity and procured a screen panel air flow system, which was installed in Q2 of the project performance period (see Figure 1-1).

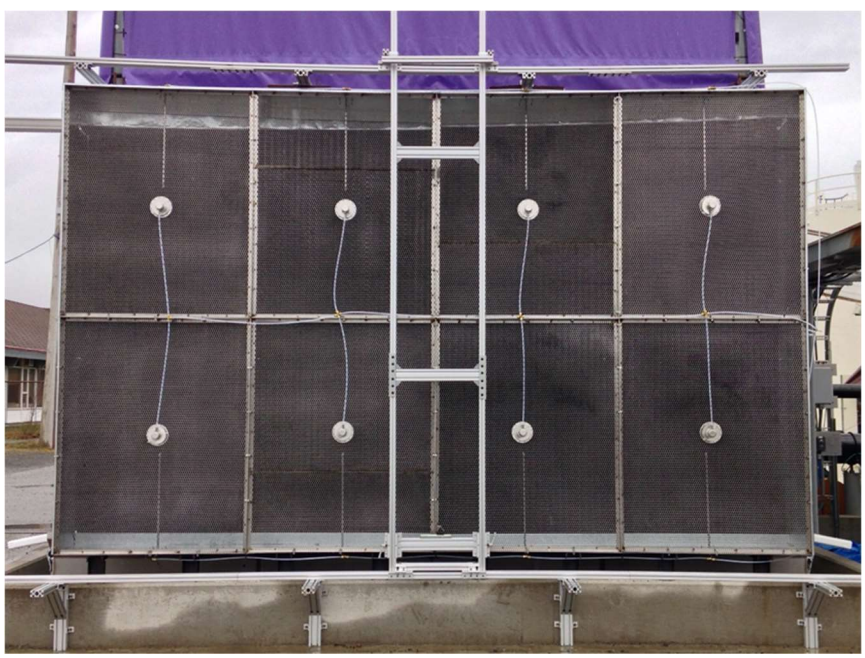

Figure 1-1 CE Screen Panel Air Flow System

Following installation of the air flow system, CE could validate the pressure drop across the system at various air velocities, and confirm it matched the packing vendor specified pressure drop curve (see Figure 1-2).

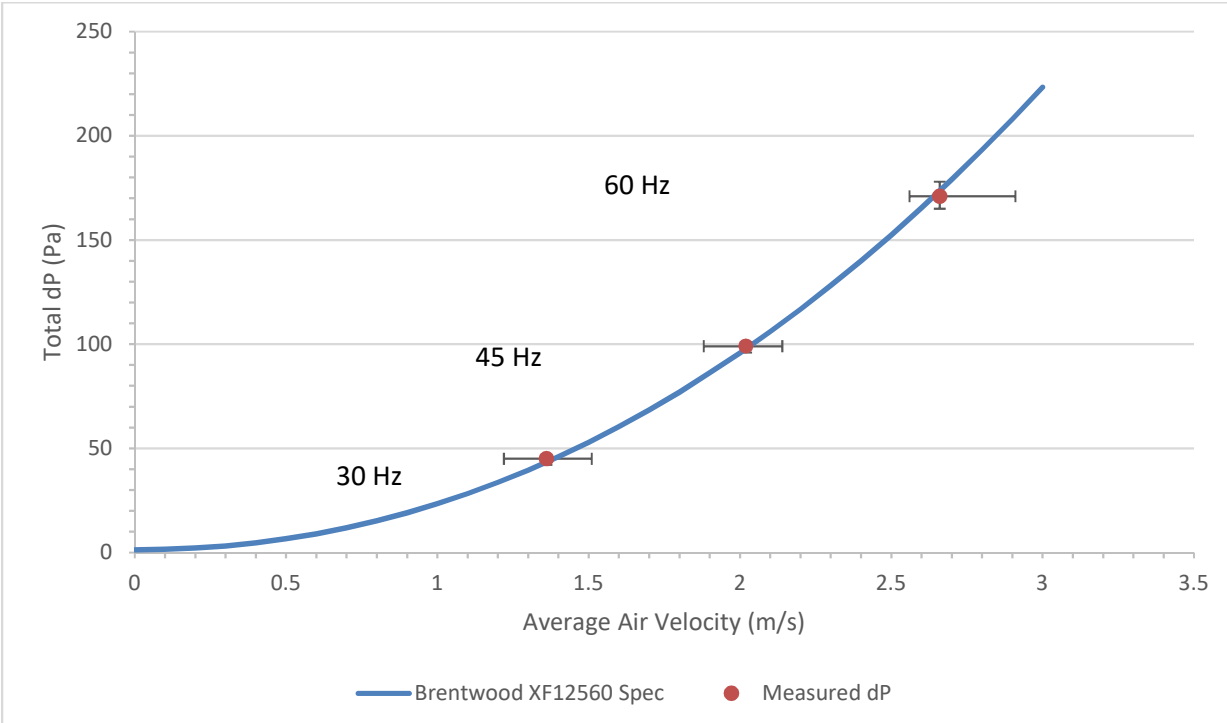

Figure 1-2 Pilot Air Contactor Pressure Drop Curve

Testing activities then focused on measuring K_L at various operating conditions including temperature, fan speed and solution concentrations, to achieve the proposed success criteria. In May 2017, CE performed a number of air contactor tests which produced results of an average K_L value of 1.103 +/- 0.098 mm/s, exceeding one of the proposed success criteria.

The above tests relied on off-line solution concentration measurements to establish the mass of CO_2 absorbed by the capture solution, because preliminary tests showed that the online CO_2 measurement instruments were sensitive to sample location. Testing activities focused on identification of the reasons for the local sensitivity, and determination of methods to improve online measurement accuracy.

During the testing phase, CE observed and identified air contactor capture underperformance. This underperformance was suspected to be due to two variables: air bypassing the capture solution via gaps in and on the sides of the packing, and under-wetted packing. In Q4, CE investigated both variables to realize greater air capture performance.

Upon further investigation, many of the packing units within the air contactor were discovered to be installed incorrectly, thus not allowing air to flow optimally through the capture solution. Vendor SPX was contacted, resulting in the contract of a 3rd party company (Cooling Tower Maintenance) to re-install the misconfigured packing within the air contactor. In addition, the LI-

COR 840A sensor that CE uses to measure inlet and outlet CO_2 concentrations and absolute humidity within the air contactor, was successfully recalibrated to ensure accurate measurements were being conducted to calculate air contactor capture performance. These activities led to the improvement of measurement accuracy and overall air contactor performance.

In Q1 of BP2, CE and academic partner UBC Clean Energy Research Centre (CERC) conducted aerosol drift testing on the pilot air contactor, accomplishing the final success criteria from BP1. The objective of the drift test was to determine the maximum output concentration of aerosols both inside the plenum of the air contactor and in the area surrounding the air contactor fan during regular operations.

A series of baseline measurements were taken within the air contactor plenum, as well as at the outlet of the contactor to commission the testing equipment. Due to mixing of the air flow in the plenum and at the fan outlet, the air over either of these entire cross-sections can be assumed to be reasonably well-mixed at distances away from the packing and fan outlet where personnel may be working. Because of this, more representative results with regards to exposure limits can be obtained by comparing the average airborne KOH concentrations with the NIOSH limits rather than single point measurements. **Error! Reference source not found.** displays the results of this analysis, with standard deviations shown as error bars for each average. When examining the average airborne KOH concentration for both areas, the density of KOH in air is well below the NIOSH exposure limits of 2 mg/m^3. The respective average for the fan outlet and plenum was approximately 0.2 mg/m^3 and 0.5 mg/m^3.

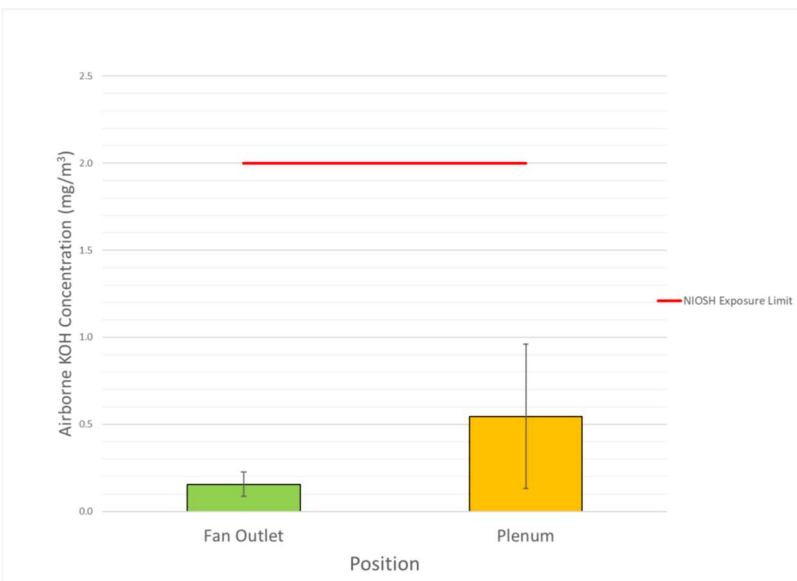

Figure 1-3 Average cross-sectional airborne KOH concentrations

Safe exposure limit shown as red line on graph

Benchtop Air Contactor

In Q4 of the project, CE commissioned and tested the benchtop air contactor, consequently completing the Success Criteria: Utilized benchtop air contactor to validate research pilot wetted surface area within an uncertainty range of +/- 0.2 (unitless).

Differential pressure has been previously correlated to air velocity through the benchtop air contactor packing. The fraction of wetted packing in the pilot air contactor is defined as the ratio between the mass transfer coefficient of the pilot air contactor to the mass transfer coefficient of the benchtop. Using the benchtop air contactor, the fraction of wetted packing surface area in the pilot air contactor was determined.

The benchtop air contactor provided CE with the ability to perform tests that are difficult to accomplish at pilot scale. Figure 1-4 is a picture of the benchtop air contactor adjacent to the pilot system.

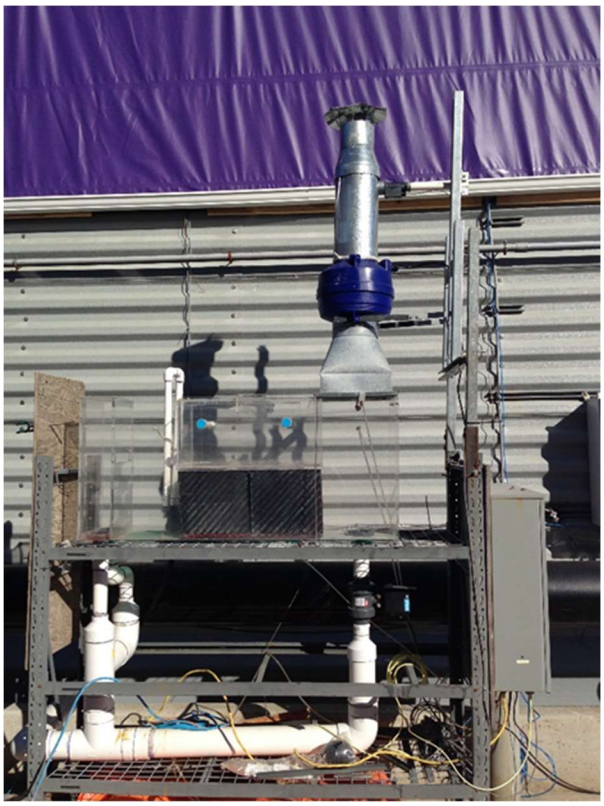

Figure 1-4 Benchtop Air Contactor

1.3.2.2 Pellet Reactor

Pilot Pellet Reactor

To-date many tests have been performed using system retention as an indicator for pellet reactor performance. Retention refers to the percentage of calcium carbonate extracted as mature pellets from the system rather than being caught in the outflow stream of capture solution as fines. It is desirable in a commercial system to target the maximum retention rate possible: higher retention means less capital and operating expenditure required for filtration equipment to deal with fines, and more captured carbon dioxide delivered to the end product. A baseline test was conducted to validate system retention without filtration of recirculation flow. These tests were conducted using both the pilot and lab-scale benchtop pellet reactor to establish a baseline and also validate that the two systems exhibit similar performance characteristics. Figure 1-5 is a side-by-side comparison of retention data collected for the pilot and benchtop units under these conditions. The two systems show comparable retention results of approximately 60% under the baseline conditions.

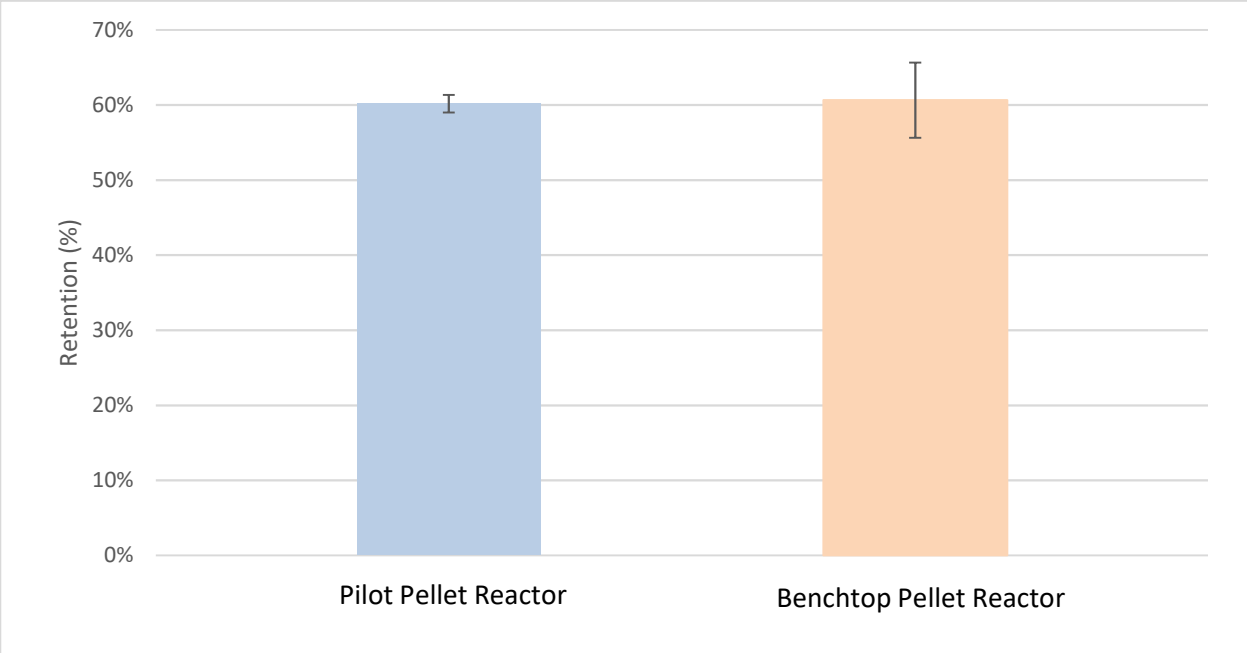

Figure 1-5 Pilot and Benchtop Pellet Reactor Baseline Retention

Additional discussion on how the benchtop pellet reactor has been used as a tool to predict pilot pellet reactor retention can be found later in this subsection. Following the baseline tests, CE conducted a series of analyses to investigate the effect of filtration on pellet reactor retention. These tests were guided by results produced in the benchtop pellet reactor. Figure 1-6 summarizes the results of these tests, and shows the impact of filtration on retention in the pilot pellet reactor. These data confirm that controlling the amount of fines entering the pellet reactor improves

retention.

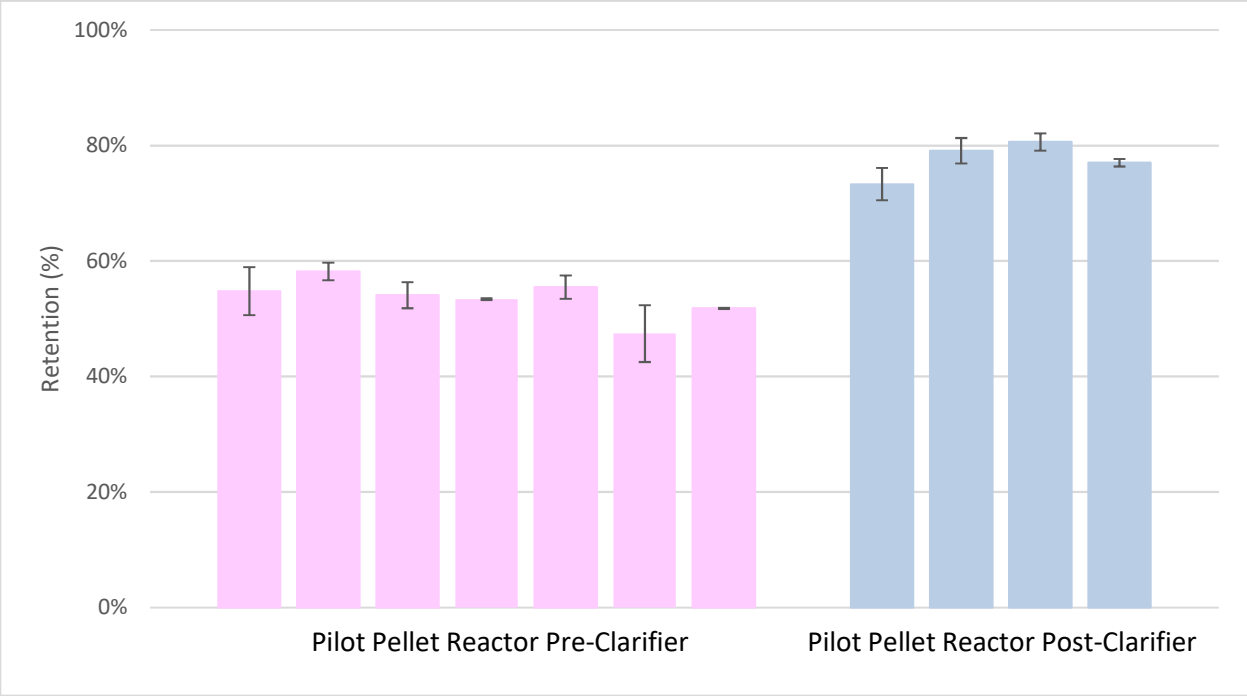

Figure 1-6 Pilot Pellet Reactor Sensitivity to Filtration

CE continued optimizing pellet reactor performance in Q4 by conducting tests that utilized specifically chosen operating parameters established from previous testing activities. These operating parameters were mainly determined by improving the balance of flow through the clarifier and centrifuge by altering flow rates and solids content; resulting in an increasingly efficient system and achieving a pellet reactor retention of 87%. These results demonstrate a potential to reach greater than 90% retention.

Lime Injection System

CE performed crucial maintenance/installation activities to the lime injection system. First, a magnetic flow meter was installed to create a much more efficient system that automates the injection flow rate, reducing operation people-hours. Additionally, this closed-loop control is more closely aligned with CE's commercial-scale engineering efforts, and important to de-risk at pilot scale. Second, CE's maintenance team disassembled the progressive cavity pump and replaced all mechanical parts excluding the motor; this included a new stator, rotor, and mechanical seals.

CE has identified two main operational issues with the current lime injection system and have allocated efforts to redesign a more efficient system that requires significantly less maintenance. As previously stated, the current progressive cavity pump requires frequent maintenance due to wear caused by grit within the lime slurry. To partially address this issue, CE tested a wet grit

removal system that was installed downstream of the slaker unit; discussed in section 1.3.2.7.

A critical feature of the current lime injection system is the low injection velocity to accommodate for the highly concentrated lime slurry. Low velocities can become problematic since it can lead to solids settling in the line, resulting in plugging; CE has encountered this phenomenon in the past.

CE's engineering team engaged with different vendors to procure a pump that is better suited for this lime system. CE selected and installed a peristaltic pump from vendor Flowrox.

Preliminary testing of the modified lime injection system showed that the system can operate continuously without plugging issues.

TK-310 – Lime Mixing Tank

CE's lime injection system consists of a mixing tank in which batch-made hydrated lime is accumulated and stored until it is injected into the pellet reactor. CE found that the lime slurry within the tank was not being adequately mixed, resulting in settling as well as an inconsistent lime concentration distribution within the tank. The tank was subsequently retrofitted with a larger motor and impellors to ensure thorough mixing. CE verified these modifications were effective by analyzing lime slurry samples before and after the modifications were implemented. The results of these analyses are illustrated in Table 1-1, which show significant improvement to the mixing within TK-310 following the mixing modifications.

Table 1-1 Available lime within slurry before modifications (orange) and after modifications (green)

Date	2018/03/21	2018/03/21	2018/03/22	2018/03/22	2018/03/28	2018/03/28
Location	TK-310 Bottom	TK-310 Top	TK-310 Bottom	TK-310 Top	TK-310 Bottom	TK-310 Top
Ca wt%	**27.1%**	**21.6%**	**31.2%**	**27.3%**	**26.3%**	**27.4%**
Δ	**5.5%**		**3.9%**		**1.1%**	

Benchtop Pellet Reactor

CE also focused heavily on lab scale activities to help predict pilot scale pellet reactor performance. As discussed above, Figure 1-5 demonstrates the similarities in retention results between benchtop and pilot pellet reactors at baseline conditions. Further studies looked at how varying filtration, upflow velocity, loading rate, and multiple injection locations, affects pellet reactor retention. Figure 1-7 illustrates the effect of filtration on benchtop pellet reactor retention, these data mimic similar results found in the pilot pellet reactor unit, shown in Figure 1-6 above.

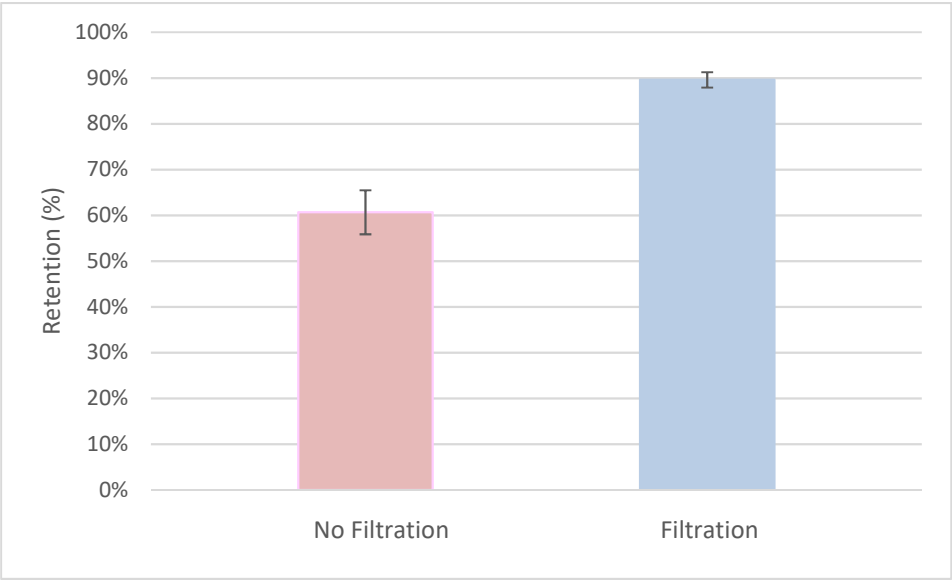

Figure 1-7 Benchtop Pellet Reactor Sensitivity to Filtration

Additional testing varied upflow velocity at constant calcium loading rates to determine what velocity provided the best bed conditions for proper fluid circulation and pellet growth. Testing confirmed that upflow velocities of ~55 - 65m/h supported higher retention results under current operating conditions. Post-DOE project investigations have focused on methods to maintain or improve retention at lower fluidization velocities. This may have additional economic benefits for the DAC process.

Tests were also conducted at various loading rates with a constant upflow velocity to determine the relationship between loading and retention, for a given injection method. The results showed a decline in retention as loading rate is increased, which suggests that further investigation into modifications to the current injection configuration and methods to improve retention at higher loading rates are areas of continued interest.

Multiple injection configurations were also tested in Q2 of the project performance period, as shown in Figure 1-8. A baseline test was conducted where the full 30 kg Ca/m^2h was injected upstream of the reactor bed. Following this test, two additional tests were conducted; the first with equally split injection between the upstream location and a location 2.6m from the entry at the bottom of the bed, and the second with equally split injection between the upstream location and a location 2.1m from the entry at the bottom of the bed. The results of these tests seem to suggest that splitting injection at higher loading had a small but negative effect on retention. CE is continuing testing to understand why this may be true or whether there are other underlying mechanisms at play.

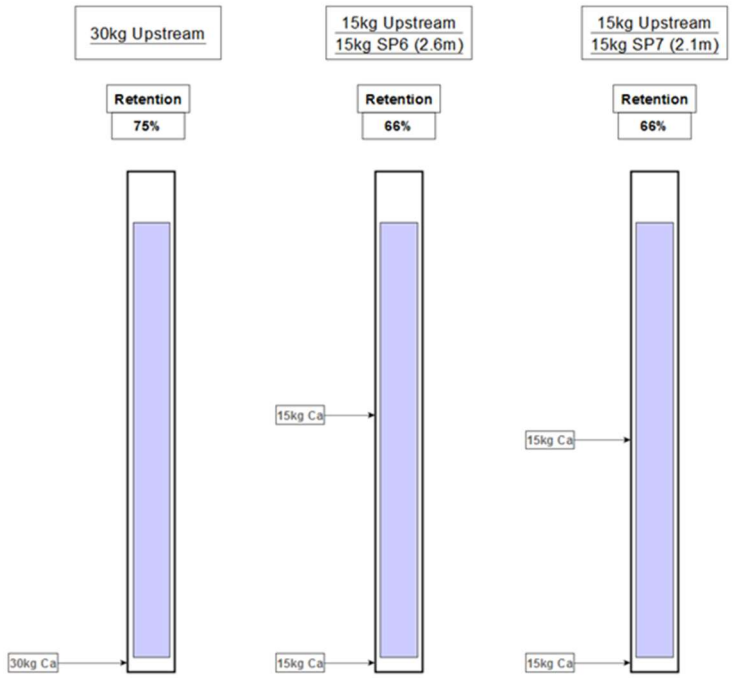

Figure 1-8 30 kg Ca/m^{2}h Loading Multiple Injection Tests

Pellet Wash Tests

During Q2 of the project performance period, CE experienced issues with the installed pellet dewatering system at pilot scale. The washer removed >80% of the residual alkali, but couldn't reduce pellet moisture content below 20 wt%, required for feeding into the pellet dryer, prior to being fed to the calciner. This additional water content has a detrimental impact, not only on the performance of the downstream dryer unit, but also on the heat requirements of the overall system, therefore CE was motivated to investigate methods for improving the pilot washer performance. CE initiated a lab study to investigate different types of industrial washers that would remove residual alkali, but also keep pellet moisture content at or below 20 wt%. As part of the study CE evaluated:

- Vacuum Belt Filtration; and,
- Shaker Screens.

Tests data was used by CE to:

a) Develop a preliminary commercial-scale vacuum belt filtration design with three washing and dewatering stages. Using this design, CE estimated that 2 m^2 of filter area was required to achieve 14% moisture content, using a 0.6 kW vacuum pump.
b) A preliminary design of a commercial-scale shaking screen dewatering system which would require between 1.5-2.5 m^2 of area to achieve <20 wt% moisture content of washed pellets.

Using the above filtration areas for each system, CE received budgetary quotes from vendors for the selected equipment at commercial-scale. The resulting prices were combined with operating cost estimates with respect to heat input into the dryer and compared. The resulting economic analysis showed that the shaking screens would be more cost effective given current pilot plant operating costs.

Following this analysis, CE sourced and purchased a shaker screen washer for the pilot plant, capable of removing residual alkali and keeping moisture content <20 wt%, which was installed in Q3 of the project performance period. Preliminary performance tests in Q3 showed the installed wash screen can reduce moisture content to approximately 12%, which is a significant improvement over the original washing performance of ~20%.

1.3.2.3 Calciner

The pilot calciner was operated to achieve various success criteria outlined in the PMP. Initial testing demonstrated that mechanical issues with the pellet feed system prevented steady-state operation. The original calciner system used a screw feeder which fed pellets through a rotary valve and pneumatic conveying system to input pellets to the calciner. CE was having issues getting a reliable, continuous feed so the system was modified to locate the screw feeder as close as possible to the calciner itself. The modified location of the screw feeder allows pellets to be fed directly, and continuously to the calciner system.

Following the improvements to the calciner feed system, the system was restarted and was operated for 40 hours continuously. Figure 1-9 illustrates the major temperature, flow, pellet feed and pressure trends throughout the extended run time.

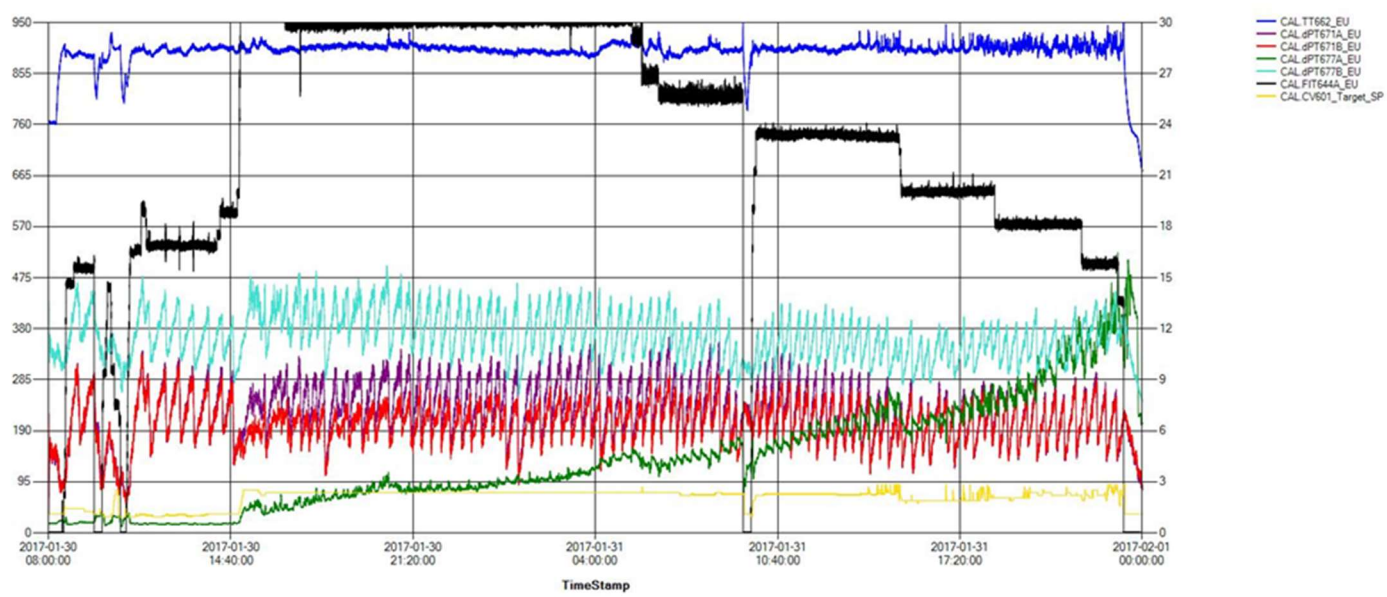

Figure 1-9 Calciner 40 Hour Continuous Test

The saw tooth pattern of the pressure readings is a result of batch discharging solids from the calciner. Every 15-20 minutes, solids were discharged from the calciner to reduce the differential pressure across the calciner bed. The operating temperature was kept as close to 900 °C as feasible as the blue line shows, except near the end of the run where temperature control became unstable and ultimately ended the run. The pellet feed rate (yellow) was kept mainly at 90 kg/h and was eventually lowered as the system started exhibiting instabilities.

High operating pressure in the main column resulted in the temperature instabilities which ultimately brought the run to an end. These tests demonstrated that the calciner can operate at an average feed rate 90 kg/h, and fluidization velocity above 1.3 m/s for extended periods of time (two of the proposed success criteria), and highlighted areas that CE can look to improve on while aiming to achieving longer calciner run times.

Q2 and Q3 of the project reporting period were dedicated to identifying the source of pressure instabilities due to fouling build up. Tests were performed at identical total pellet mass consumption, and a constant feed rate, fluidized with a mixture of O_2 and air to identify the optimal temperature window and establish fouling mechanisms. There were a number of mechanical issues, including two instances of air preheater failure which delayed test progress, however, CE was able to identify specific cold-spots contributing to recarbonation and fouling buildup, and retrofitted the calciner with heat tape to prevent cold-spot formation. Heat trace was previously installed on the cross-member to prevent fouling, however this proved to be ineffective. In Q4, CE's engineering team specified and procured a higher rated heat trace which was installed. The heat trace is covered in ceramic insulation to prevent heat loss and proved to be effective in eliminating cold spots.

Proof of concept testing

Much of Q4 was spent performing Proof of Concept (POC) testing activities. This consisted of shorter calciner tests that were run until a mechanical or electrical problem arises, unrelated to process conditions. The issues were then repaired which prompted the beginning of another test. These shorter calciner tests allowed CE to identify and troubleshoot electrical and mechanical problems, without allocating the full resources required to conduct a process validation experiment. The learnings from these POC tests are critical in understanding the mechanical nuances of a small-scale pilot system, however, will also inform commercial-scale design. Thus far, CE has identified mechanical issues with the pellet screw feeder and a programming error in the electric air heater, among other inefficiencies within the system.

In Q6, most of CE's resources were allocated to reliably operating the calciner. To achieve this, CE first conducted short-duration runs to identify various mechanical issues that would otherwise cause the system to fail during a long-duration test. These issues were resolved by making the modifications described below and resulted in the longest calciner run to date (described on next page).

Air Dilution Modification

There are two locations where ambient air is introduced to the calciner system. These air dilution points have the following effects on the calcination process:

- Diluting the hot gas stream with ambient air lowers overall CO_2 concentrations, ensuring the CaO is unable to re-carbonate downstream of the dilution point; and
- Diluting process gas with ambient air lowers the temperature of downstream gas and protects equipment from exposure to extreme temperatures.

In previous tests, CE encountered fouling at one of these points as the ambient air would cause the calciner walls to cool before the gas was adequately diluted, resulting in significant re-carbonation. To address this, CE connected the outlet exhaust of the jacket heater to the dilution point, introducing a >900°C diluent, minimizing heat loss, and therefore re-carbonation. This was proven effective as minimal fouling was observed during the long-duration test.

Calciner Run

In Q6 of the project period, CE conducted the longest test campaign to date; the pilot calciner was operated for a total of 90 consecutive hours with 72 hours of pellet feeding (~4,000 – 4,500 kg).

This long-duration test campaign had two main purposes:

1) To test the operational and mechanical changes that have been made during Q6; and
2) Achieve the success criteria for Subtask 3.2: Processed 15,000 kg of $CaCO_3$ in DAC pilot in a closed loop (calcination, slaking, causticization).

In addition to testing modifications, and processing significant $CaCO_3$ material, CE collected crucial data during this campaign which was sent to vendor Technip and will be necessary to design and engineer a commercial-scale calciner.

CE processed a total of 16,608 kg of pellets by the end of Q1 2018, fulfilling the operational requirements indicated by Subtask 3.2. Figure 1-10 shows the aggregate amount of material processed within the pilot calciner.

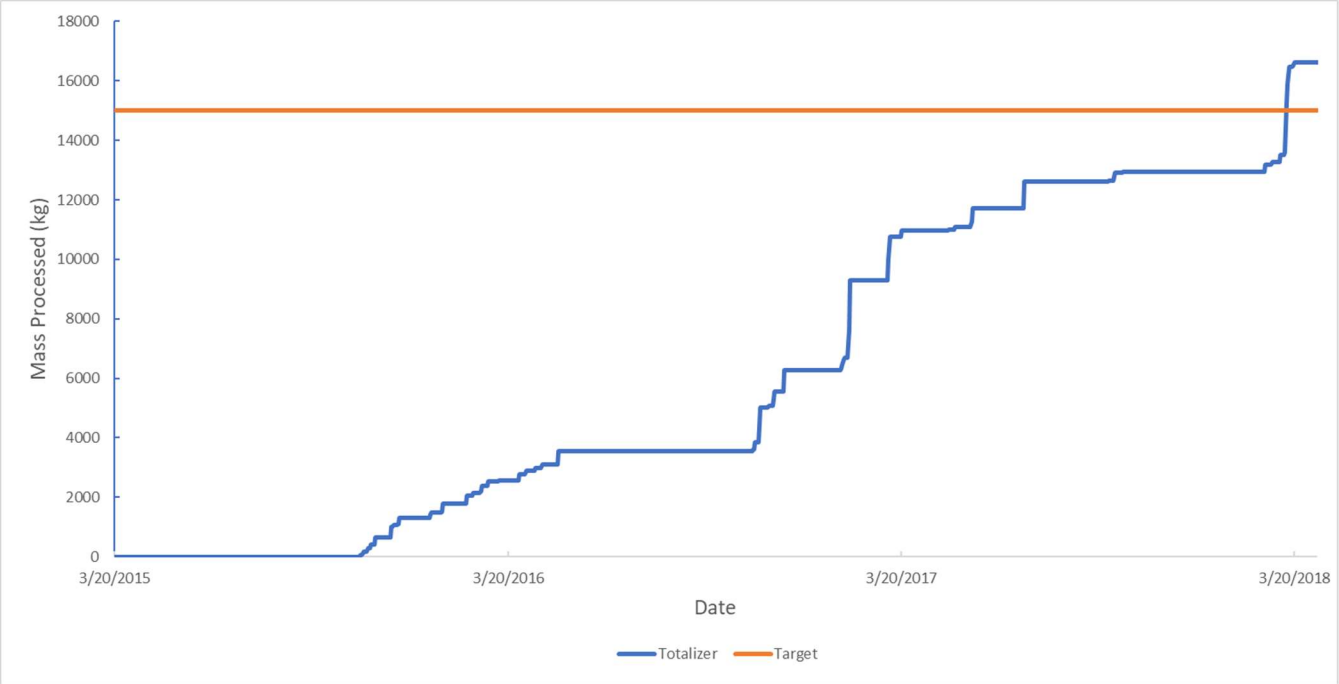

Figure 1-10 Total mass of pellets processed by pilot calciner

Blue trend indicates amount of processed material; orange trend indicates goal of 15,000 kg as indicated by Subtask 3.2.

In Q7, CE conducted solids sample analysis, summarized in Table 1-2.

Table 1-2 Material sampling results from long-duration calciner run

Date of Collection	3/12/2018	3/12/2018	3/12/2018	3/13/2018
Description	CaO Discharge	North End Inner Scale (scraped solids from surface facing away from pipe)	North End Outer Scale (scraped solids from surface facing pipe)	CaO
Analysis date	10-Apr-18	10-Apr-18	10-Apr-18	10-Apr-18
Mass % CaO in Sample*	**94.3%**	**95.4%**	**91.0%**	**94.9%**
Mass % $CaCO_3$ in Sample*	**5.7%**	**4.6%**	**9.0%**	**5.1%**
***Values have been normalized to exclude inert material used to preheat calciner.**				

During post-run maintenance, CE found significantly less fouling on calciner walls than previous runs. Of the observed fouling, the majority of material comprised of CaO, indicating that little re-carbonation occurred. CE will continue to optimize operating parameters to eliminate fouling of any kind.

1.3.2.4 Slaker

CE has performed slaker testing campaigns in two modes of operation to date: batch and continuous. These tests, as a whole, have focused on optimizing slaker performance. To obtain baseline data for general slaker performance testing, CE purchased commercially available CaO. In a comparative analysis, it was shown that CaO produced on site in CE's calciner was of the same quality as the commercially obtained product; site-made CaO produced a slurry with an average available lime content of 26.9 wt% while purchased CaO generated an average of 27.0 wt%.

In an attempt to reduce system downtime and increase efficiency of site resources, CE investigated, designed and commissioned a more efficient automated slaking system and process, which involved transitioning to a continuous slaking procedure. After numerous tests, baseline operating parameters for continuous slaking operation were generated, leading to successful continuous slaking runs.

During testing campaigns, operators encountered frequent problems with slaker performance due to the failing of pumps and the plugging of hoses during lime slurry injection. Upon further investigation, pieces of inert grit were found within the slurry, causing the obstruction of pump

lines and consequently causing the system to fail. To optimize slaker performance, many modifications were made to either remove the grit from the lime slurry, or ensure that the system could manage to run with the grit present. Modifications made include: lime holding tank impeller upgrade, parabolic screen installation, and the installation of a pressure fit injection line. With these modifications put in place, slaker performance shows notable improvement. Figure 1-11 illustrates data from the initial post-modification slaker test.

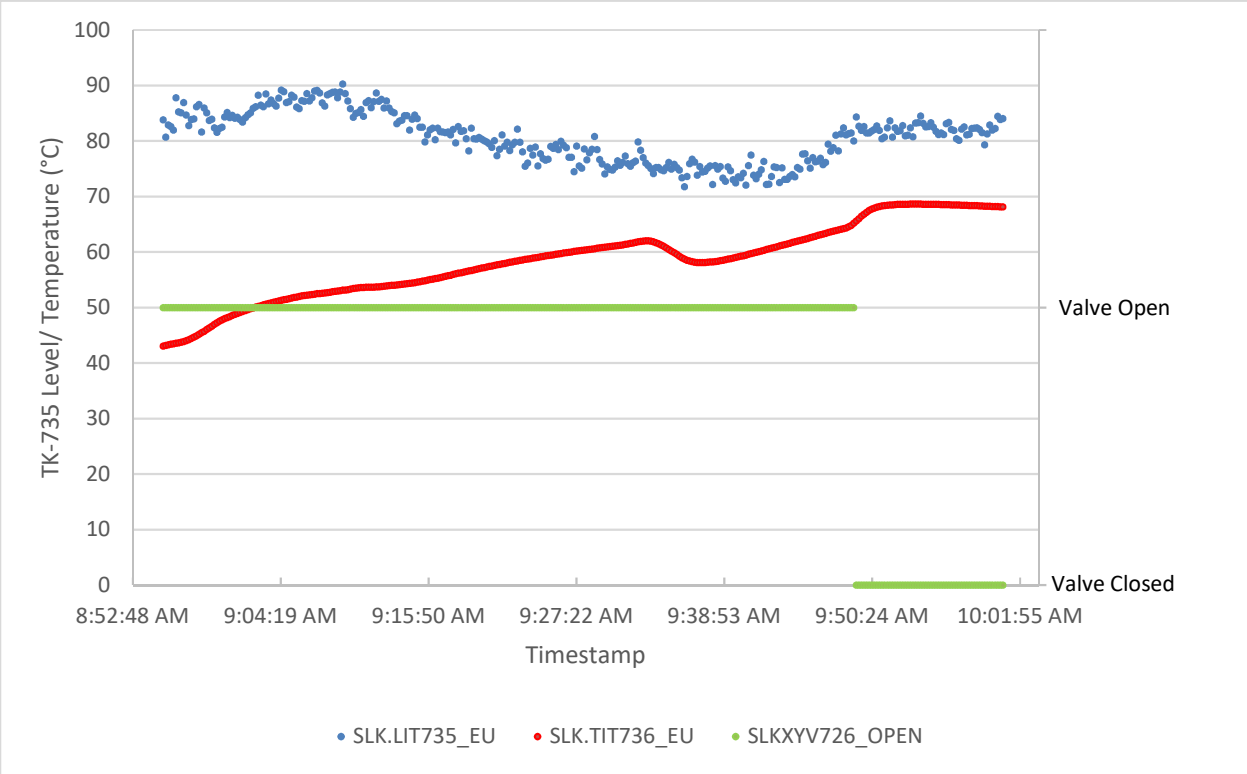

Figure 1-11 Slaker Performance Test

In Q4 of the project performance period, CE provided Hazen Research with a fully slaked lime slurry sample to perform a viscosity analysis. Hazen used a rheometer to create a viscosity profile as a function of sheering rate to perform this analysis. These results were essential in specifying a pump for the lime injection system, and were incorporated in the pump selection, as mentioned in section 1.1.1.1.

1.3.2.5 Available Lime Optimization Tests

CE worked to optimize slaker performance by producing a lime slurry with a high available weight percentage. Producing such a slurry is desirable for two main reasons: first, the amount of total water usage is reduced, and second, lime would be injected at a slower rate, decreasing the person-hours to operate the slaker. The available lime weight percentage affects two lime slurry system characteristics: 1) the “thickness” of the lime slurry and 2) the reaction temperature of slaking.

A lab test was conducted to investigate the optimization of operating parameters to produce a higher available lime weight percentage slurry. Lime slurries with different lime to water feed ratios were slaked in a lab setting while tracking changes in temperature over time (Figure 1-12).

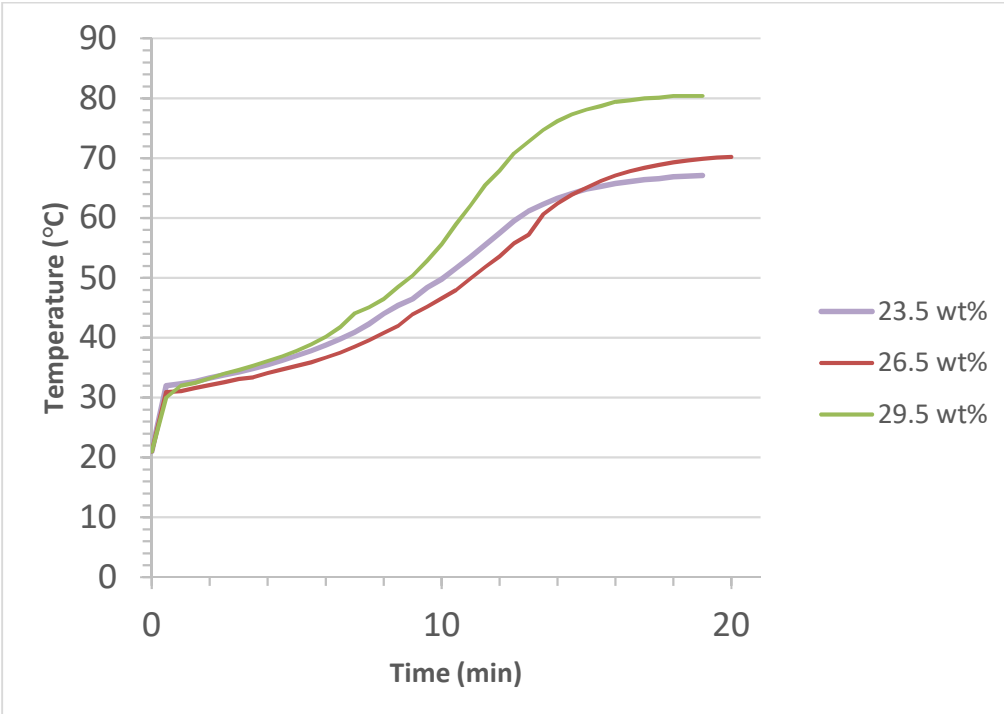

Figure 1-12 Slaking rate curves of 3 different available lime weight percentage slurries.

Once fully reacted, the transferability of the slaked lime slurry was qualitatively assessed by the feasibility of being pumped and injected into the pellet reactor.

1.3.2.6 X-Ray Diffraction Analysis

In Q4, CE conducted a conversion analysis on site-produced CaO, the results showing a complete yield of $Ca(OH)_2$ after slaking, thus successfully completing the following success criteria: Achieved 98% conversion of CaO produced by the calciner to $Ca(OH)_2$. To complete this analysis, CE used two different methods: an ASTM C-25 rapid sugar test and a powder x-ray diffraction (p-XRD) technique.

The carbonate determination of the calcined material suggests that the calcination conversion is ~ 90%, with a fraction of uncalcined material present ($CaCO_3$), and some inert materials. The carbonate determination of the slaked material indicated a higher $CaCO_3$ content, which can be attributed to the carbonation of the $Ca(OH)_2$ during sample work-up (this has been observed in previous laboratory testing). Due to the chemical similarity of CaO and $Ca(OH)_2$, there is no readily available quantitative analysis tool that can be used to differential in the bulk material. Based on this, CE has utilized powder x-ray diffraction, and the identification of present crystalline

phases to determine slaking conversion. The results from the p-XRD analyses are illustrated by Figure 1-13 and Figure 1-14.

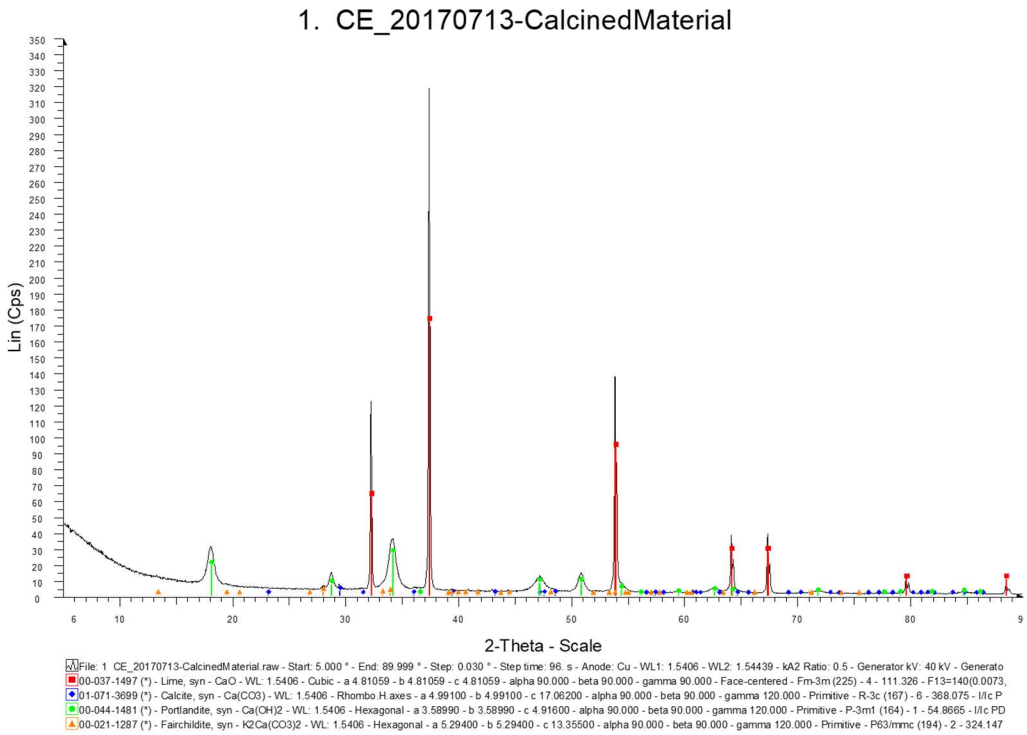

Figure 1-13 Calcined Material- Powder X-Ray Diffraction Pattern and Phase Identification

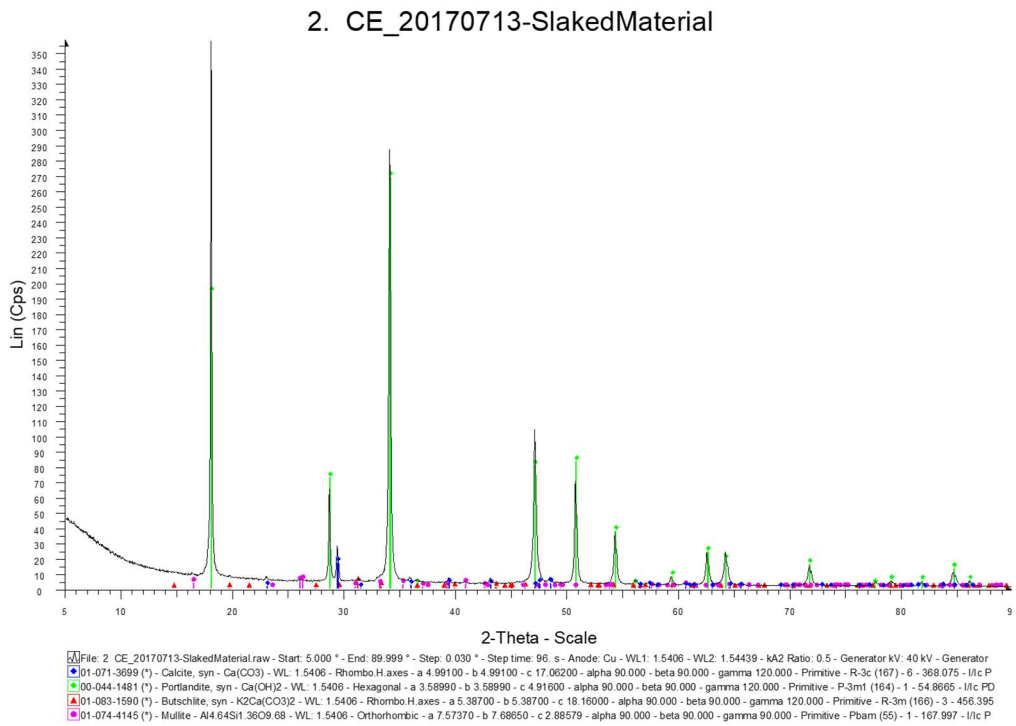

Figure 1-14 Slaked Material- Powder X-Ray Diffraction Pattern and Phase Identification

The p-XRD spectra of the calcined material identifies 4 phases present – Quicklime (CaO), Calcite ($CaCO_3$), Portlandite ($Ca(OH)_2$), and Fairchlidite ($K_2Ca(CO_3)_3$). It should be noted that during material preparation the quicklime is ground, using a mortar and pestle, and during this processing a portion of the quicklime is air-slaked to form $Ca(OH)_2$. CE has observed this previously in characterization of our CaO, and the conversion of CaO to $Ca(OH)_2$ under ambient conditions after grinding samples for characterization. In comparison, the p-XRD spectra of the slaked material does not contain any of the characteristic peaks associated with CaO, which is indicative of quantitative (complete) conversion of CaO to $Ca(OH)_2$.

1.3.2.7 Grit Removal

Over the course of the project, CE has experienced multiple issues with the lime injection system due to grit present in purchased CaO. The inert grit within the hydrated lime slurry had the tendency to plug equipment upstream of the injection point, causing system upsets and trips. A vibrating grit removal screen was installed in late-2017; however, was not commissioned until Q6. Upon commissioning, CE improved the grit removal system through operational trial and error, and has since been able to operate the system with minimal plugging upsets and trips.

1.3.3 Pellet Reactor + Air Contactor (Wet-end)

1.3.3.1 Fully-integrated Long-duration test

A 5-day integrated pellet reactor and air contactor test campaign was conducted on August 12th to 17th, 2018. The goal of this test was to prove long duration capabilities of operating the two units at a steady state, with little fluctuation in process solution composition. A secondary goal of the test campaign was to investigate the operability of the pellet reactor at a reduced fluidization velocity and its influence on system retention.

Individual pellet reactor and air contactor test campaigns have been previously performed, with most if not all providing some learnings on mechanical failures and system reliability. This long duration integrated run was executed with the intent to prove increased mechanical reliability of the system while gaining insight on the process solution balance between the individual units. The learnings acquired, and system modifications implemented over past tests, have proven useful as CE had no mechanical issues during the 5-day test.

Over the course of the run, the pellet reactor achieved an average retention of 86.4% (Standard Deviation of 6.8%) at a lower fluidization velocity. This achievement showed that the fluidization velocity can be decreased from 60 to 50 m/h with little impact on retention, thereby decreasing overall energy requirements. The air contactor achieved an average K_L (capture rate) of 0.86 mm/s over the course of the 5 days, slightly lower than previous tests which achieved 0.9-1mm/s.

1.3.4 Alternative Dilute CO_2 Capture Technologies Investigation: Solids Research

In the reporting period Q5 (end date 2017-12-31), CE conducted a SWOT comparison between CE's DAC and other dilute CO_2 capture technologies, completing BP2 Milestone 3a as described in the SOPO.

1.3.5 Success Criteria

To-date, as evidence of making substantial progress on the BP1 task objectives, CE has garnered valuable information about the performance characteristics of the direct air capture plant at both pilot and lab scale, and made significant equipment improvements. Table 1-3 summarizes BP2 success criteria as outlined in the PMP. As of the end of the project, CE has completed the following outstanding success criteria.

Table 1-3 BP2 Success Criteria

Decision Point	Success Criteria
Research Theme 1: Direct Air Capture Applied R&D	
Completion of Subtask 3.1, DAC Development and Enhancement: Application and Implications	Show that improved wetted fraction in pilot air contactor (by implementing lessons learned from air bypass discovery) resulted in improved K_L value in DAC pilot - **Completed** Modified the Pilot AC to reduce some of the bypass, but focus has shifted towards working with vendors for identification of design considerations to eliminate bypass issue in the Validation and Commercial plants
Completion of Subtask 3.2, Pilot Operations and Testing: Long-term Effects	Processed 15,000 kg of $CaCO_3$ in DAC pilot in a closed loop (calcination, slaking, causticization) - **Completed**
Completion of Subtask 3.3: Alternative Technologies Investigation: Solids Research	Compare 2 alternative technologies using SWOT comparison within context of dilute source capture - **Completed**
Completion of Subtask 3.4: Technology Optimization: Data Analysis and Ongoing Development	Improve commercial air contactor design, mitigating future air-bypass problems. Generate new commercial cost estimation value with vendor partner SPX – **Completed** Engaging with vendors in addition to SPX for validation and commercial designs– this has led to quotes for commercial scale AC post DOE project with improved costing
Completion of Subtask 3.5: Technology Optimization: Synthesis of Results and Recommendations	Submitted final report

1.4 Technology Cost Projections and Technical Assessment of Applicability to Coal Stream

1.4.1 Description

This exercise focused on the development of a techno-economic assessment (TEA) of the recipient's technology for: a) commercial scale direct capture of CO_2 from air (1 MT CO_2/year), and (b) application in a coal fired power plant (equipped with flue gas capture system) as a "polisher" to capture CO_2 emissions downstream of the capture system. Activities included data synthesis and process development and modeling utilizing data from current research pilot operations (pre-DOE project) to synthesize metrics that defined the performance characteristics of each unit operation in DAC. The developed metrics were used to develop major equipment specifications and create the basis of the initial technical and economic feasibility study and technology cost projections.

1.4.2 Progress

Following discussions with DOE staff, it was agreed to dedicate BP1 activities to development of a technology assessment plan (TAP), rather than a preliminary techno-economic analysis. The TAP guided the TEA activities in and provided a clear outline for the BP2 activities. Engineering activities focused on process modelling, and establishing system parameters for the TEA. The TAP established that the TEA would analyze an early commercial baseline 1 Mt-CO_2/y scale DAC plant, as there is no current available baseline plant in the DOE database.

The primary analysis was focused on generating a Baseline case for CE's early commercial DAC plant that captures ~ 1MT CO_2 annually from the ambient air. In addition, a secondary case (Case 1) was evaluated which investigates using a modified version of CE's DAC process to annually capture 1 MT CO_2 downstream of a subcritical PC post-CCS power plant. Case 1 was studied in order to examine the relevance of DAC technology to managing emissions from the coal-fired power generation industry. The value of the TEA lies not in the absolute accuracy of the cost estimates for each scenario, but in utilizing a consistent approach in comparing relative costs among the evaluated scenarios. The studies detailed by the TEA are not the first or only assessment of CE's DAC technology, but this is the most recent and most detailed techno-economic assessment to date, and work continues at CE to improve the process and reduce costs.

This TEA reported results based on measured pilot plant performance data for all major unit operations, and on an energy and material balance for the process at commercial scale computed using an Aspen process simulation. The cost estimation methodology follows AACE International (AACE) recommended practices; with an uncertainty range of -15%/+30%. The estimate meets AACE Class 4 requirements (i.e., feasibility study), based on the level of engineering design work performed. The cost estimates for this report were produced for CE by BBA, a Canadian EPC company with experience designing and building power and carbon capture projects. The main mechanical equipment prices were provided by vendor budgetary quotations that were completed and adjusted as needed.

Results from the Baseline case indicate that when CO_2 is delivered at 151 bara, the design requires either 9.85 GJ of natural gas, or a mix of 5.25 GJ of gas and 537 kWh of electricity, per ton of CO_2

captured. Depending on financial assumptions, energy costs, and the specific choice of inputs and outputs, the levelized cost per ton CO_2 captured from the atmosphere for an early commercial plant ranges from 227 to 304 $/t-CO2.The Total Plant Costs (TPC) reported here are in line with previous studies performed by CE. In addition to the TEA, design and experimental work was performed at CE's laboratory and pilot plant facility under this award.

The levelized cost to capture 98% of the flue gas CO_2 emissions in a subcritical PC power plant (Case 1 Option C) through a combination of Cansolv carbon capture system and a modified DAC system was estimated to range from 109 to 160 $/MWh of net power generated. Specifically, the Cansolv carbon capture system removes 90% of the CO_2 emissions from the flue gas stack, and the modified DAC system ("polisher") will remove 80% of the remaining CO_2. The cost impact on the total cost of electricity (COE) of removing 80% of the CO_2 remaining in the flue gas exiting the Cansolv carbon capture system, which is equal to an additional annual CO_2 capture of 1 MT, or an 8.9% increase in total CO_2 removal, is approximately 16%. Sensitivity analysis showed that the COE for the Case 1 was most sensitive to fluctuations in coal price, followed by uncertainty in capital cost estimation and financial assumptions.

A number of cost reduction opportunities were identified during the Value Engineering exercise associated with the Baseline case. These opportunities are recommended for further study and inclusion (where/if appropriate) in the commercial design, and involve opportunities for both the Baseline and Option 1 Cases, including:

- Improvement in the air contactor packing design;
- Relocation of the ASU close to the calciner area;
- Combination of steam turbines in power plant and DAC steam slaking loop into one single unique turbine;
- Performing detailed simulation of the power plant flue gas CO_2 absorber to confirm sizing.

In addition to the above project learnings and recommendations, after the initiation of the TEA phase of this project, CE realized additional key learnings associated with the DAC plant performance, utility and operational requirements, as well as cost reductions associated with strategic vendor collaborations – these were not represented within this TEA as they had developed after the TEA scope was frozen; however, CE is recommending these learnings be further investigated, and where appropriate implemented into the commercial design, and expects significant positive cost impacts on the first commercial plant as a result. Some of these additional learnings include:

- Supply savings through strategic vendor relationships: long term partnerships with key vendors will allow for negotiation of reduced prices for major equipment and services;
- Improved design and performance of key equipment (post DOE TEA project);
    - Testing underway to confirm the use of smaller pellet sizes in the pellet reactor, which would reduce capital (equipment) and operating costs;
    - Alternative filtration methods and configuration costs;
    - Improvements in AC packing design and footprint;
    - Reduced freshwater consumption
- Onsite power – CE's first U.S. commercial DAC plant utilizes renewable electricity, taking advantage of the associated cost reductions; the renewable energy cost is currently

estimated at ~$29/MWh without subsidies, and will eliminate the need for onsite power generation, while increasing the plant's capacity for atmospheric CO_2 capture.

- Operation labour: CE believes that the first commercial plant will have a tighter footprint and significantly fewer modules, for example in the pellet reactor subsystem, due to the above-mentioned improvements expected in performance. As a result, the operational staffing costs for the first early commercial DAC plant could be lower than what was originally estimated in this TEA.

To summarize, both studies involved two related implementations of CE's proprietary DAC process. The baseline technology is optimized for efficient removal of CO_2 from the atmosphere, and in conjunction with sequestration creates a "negative emission pathway". Case 1 technology uses a modified version of CE's DAC process to remove additional CO_2 from the stack gases of a conventional coal-fired power plant equipped with a carbon dioxide removal system. Both technologies, removing CO_2 from the atmosphere and mitigating anthropogenic emissions, are being recommended as desirable by the Intergovernmental Panel on Climate Change (IPCC), as well as other expert bodies in the climate change arena.

1.4.3 Success Criteria

A significant portion of the BP2 was dedicated to performing the TEA, the results of which have been previously submitted in the form of a stand-alone TEA report. During this period, CE successfully completed subtasks 5.1 and 5.2, 5.3 and 5.4 - Technology Cost Projections (Capital, Construction, and Operating) and Design Basis for Commercial Scale-up (Construction and Operation).

2 Conclusion and Recommendations

CE has garnered valuable information about the (a) performance characteristics of the DAC plant at both pilot and lab scale, and (b) economics of early commercial DAC plants, under the DOE award.

Significant equipment improvements and learnings were realized during the project, as outlined below:

- Improved air contactor air velocity and CO_2 instrumentation and measurements;
- Validated pressure drop across the air contactor at various air velocities – aligned with vendor specified pressure drop curve;
- Measured K_L at various operating conditions including temperature, fan speed and solution concentrations;
- Validated the benchtop pellet reactor for rapidly executing tests that are otherwise difficult to perform in the pilot system;
- Optimized filtration operation to improve pellet reactor performance;
- Optimized pellet reactor upflow velocities leading to cost improvements for the commercial system;
- Resolved washing system performance issues;
- Resolved re-carbonation fouling in the calciner by identifying and addressing specific cold-spots in the calciner
- Recognized and largely resolved performance and maintenance issues with current slaking system.

A TEA study was conducted based on measured pilot plant performance data for all major unit operations, and on energy and material balance for the process at commercial scale computed using an Aspen process simulation. The cost estimation was performed by BBA (a Canadian EPC company) and met the AACE Class 4 requirements (i.e., feasibility study), based on the level of engineering design work performed. The main mechanical equipment prices were provided by vendor budgetary quotations that were completed and adjusted as needed.

Based on the assumptions and framework of this TEA, it was found that the cost of capturing 1 MT CO_2 from ambient air in an early commercial DAC plant was 227-304 \$/t-CO_2 captured. In addition, the levelized cost to capture 98% of the flue gas CO_2 emissions in a subcritical PC power plant through a combination of Cansolv carbon capture system and a modified DAC system was estimated to range from 109 to 160 \$/MWh of net power generated.

The process learnings and equipment improvements realized during the project period would be transferred into design and operation of a fully integrated DAC validation plant capable of capturing 4.5 t CO_2/d from air. CE will continue to conduct core research and development activities at the validation plant. Process improvement opportunities identified during this work, in addition to cost reduction opportunities identified during the Value Engineering exercise associated with the Baseline case indicated that significant reductions in capital costs are available as CE scales up and proceeds through deployment of initial facilities. Furthermore, it is expected that there will be further learnings and technology improvements between the early and "Nth" generations of DAC plants, leading to additional cost reductions. While outside the scope of the study, CE and partners have identified initial target markets where revenues for captured

atmospheric CO_2 can exceed $250 USD /tonne-$CO_2$, thus giving CE an initial market in which to scale up and deploy the technology.

CE also wishes to acknowledge that the project was made possible by the forward-thinking strategy of the DOE's Fossil Energy (FE) carbon capture, utilization and storage (CCUS) R&D portfolio. The results of this effort provide DAC performance and costing data necessary for understanding and advancing commercial capture technologies, and it exemplifies U.S. leadership in this arena.

3 Revision History

This section shall provide the revision history of the Final Technical Report. Each revision shall be accompanied by a detailed explanation and the date of the change. Each revision shall be identified by a new revision number - the revision number on the title page shall be incremented accordingly. All revisions require the concurrence of the DOE Federal Project Manager.

2019-06-28: Revision 1 – Issued to DOE