Exhibit 7-A: Final Report for the Cryogenic Carbon Capture (CCC) Demonstration (Emerging CO_2 Capture) Program

Index of Reports Included

Report Name	Report
Q1 RMP Milestone Report - Self Cleaning HX and Dual Auger	SES report containing the basic designs for both a self-cleaning heat exchanger and the experimental dual solid-liquid separations system.
Q2 RMP Milestone Report	SES report containing the following: - The final designs, documentation of parts ordered, and initial tests of the experimental alternate refrigeration system. - The final designs and documentation of parts ordered of the experimental self-cleaning heat exchanger. - The design, documentation of parts ordered and installation of equipment for pre-treatment of real flue gases and dual solid-liquid separations.
Q3 RMP Report	SES report containing the following: - The purchase orders and initial test reports of improved instrumentation such as advanced cryogenic flow measurement and output measurement. - Results of testing for the experimental integrated system with simulated flue gas at minimum 1/4 tonne per day CO2 - Results of testing of the experimental integrated system tested with real flue gas.
Q4 RMP Report	SES report containing the following: - Designs and documentation of parts ordered for permanent skid-scale unit ops, including heat exchangers, dryers, separations.
Q5 RMP Report and Q5 RMP Supplement Report - Higher Flow Rate	SES reports containing the following: - Documentation of parts ordered for permanent skid-scale unit ops and skid integration. - Results of testing the permanent skid system with simulated flue gas at 1 tonne/day. - Shakedown testing completed.
Q6 RMP Report	SES report containing the following: - A description of the preparations and modifications at the Hunter PP site. - Documentation of insurance, transport, personnel trailer, and other on-site needs. - A description of the ongoing on-site setup and shakedown of the ECL testing skid.
Q7 RMP Report	SES report containing the following: - Finalized setup and operation of the ECL Skid at the Hunter PP. - A full report of the testing to-date under RMP funding, with continued testing occurring under the NETL contract.

Q8 RMP Report	The eighth quarter for this project fell between two phases of the project, and as such had no milestone associated with it.
Q9 RMP Quarterly Report	SES report containing the following: **Task A1** – Finalized integrated dryer design. Results of experiments used to validate design. Equipment sourced. **Task A2** – Final selection of the solid-liquid system, or other system designed to meet the same requirements, which will be tested. Initial long lead time parts ordered. Assessment of pollutant removal options and modeling of basic design of system.
Q10 RMP Report	SES report containing the following: **Task A1** – Record of dryer system equipment being ordered. **Task A2** – Finalized design and record of system ordered. Description of assembled solid-liquid or other separation system. Designs and parts ordered for the pollutant removal system.
Extended Testing Report	SES report containing the following: Analysis of the extended test runs of the small pilot focusing on the benefits gained from recent modifications made to the system.
Q11 RMP Report	SES report containing the following: **Task A1** – The receipt of the system and initial results of both assembly and dryer testing. **Task A2** – Results of initial testing and subsequent iteration on solid-liquid or other separations system. Description of assembled pollutant removal system.
Q12 RMP Report	SES report containing the following: **Task A1** – Results of further test results including using real flue gas and initial integration with skid system. Final Reporting. **Task A2** – Results of testing the finalized designs. Final Reporting. **Task A3** – Assessment of scale-up potential of innovative unit ops including dryer and solid-liquid separations.
Sargent and Lundy – CCC Scalability Report	Sargent & Lundy scalability study assessing the scalability of the technology for complete processing of flue gas at utility power plants.

QUARTERLY REPORT AND MILESTONE SUBMISSION

June 15, 2017

Submitted by

Sustainable Energy Solutions

Submitted to

Rocky Mountain Power

Sustainable Transport and Energy Plan (STEP)

Overview

This project uses an existing research and demonstration unit (the ECL skid) provided by Sustainable Energy Solutions (SES) and modifies it to improve process efficiency, reliability, or overall performance. This first development phase also includes skid preparations for later long-term, on-site testing at an RMP facility. This report details the work done towards the first milestone of this project.

Quarterly Milestones

As indicated in the Scope of Work for this project, the initial milestones involve basic design work, specifically on self-cleaning heat exchanger units and on the experimental dual solid–liquid separations system and equipment purchases.

Q1	CONTRACTOR will deliver a report containing the basic designs for both a self-cleaning heat exchanger and the experimental dual solid–liquid separations system. SES will also begin purchasing equipment for these systems.	6/15/2017	$ 35,656

Self-Cleaning Heat Exchangers

Previous field and in-house tests indicate that dissolved CO_2, solid CO_2, and flue gas impurities can accumulate in contact liquid in the CCC process. These materials potentially foul the heat exchangers over time. The heat exchanger at greatest risk is at the coldest point in the process and tends to precipitate CO_2 dissolved in the contact liquid.

The STEP project is supporting research into two mitigation strategies for this heat exchanger fouling. The first of these uses a fluid bed heat exchanger, being developed in partnership with Klaren, a company expert in this technology, and the second uses a more traditional cleaning system for a shell and tube heat exchanger.

Self-Cleaning Fluidized Bed Heat Exchanger

SES has designed, in cooperation with Klaren International, a Fixed Fluidized Bed Heat Exchanger. This heat exchanger continuously cleans itself using small particles that scour the heat exchange surface. The unit uses a single tube, and provides a proof of concept for the Cryogenic Carbon Capture process. This single-tube heat exchanger modularly scales to higher flowrates.

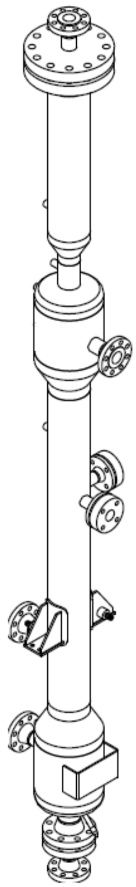


Figure 1. Fluidized bed self-cleaning heat exchanger

In addition to the design and sourcing of the primary heat exchanger provided by Klaren, SES will be implementing the following:

- Process fluid connections between the existing system and the new heat exchanger
- N_2 recirculation system as indicated in Figure 2
- Process instrumentation and electrical connections including power supply

- Integration with the main SES data logger
- The structure to support the heat exchanger
- The insulation surrounding the heat exchanger
- Unloading, erection, and installation

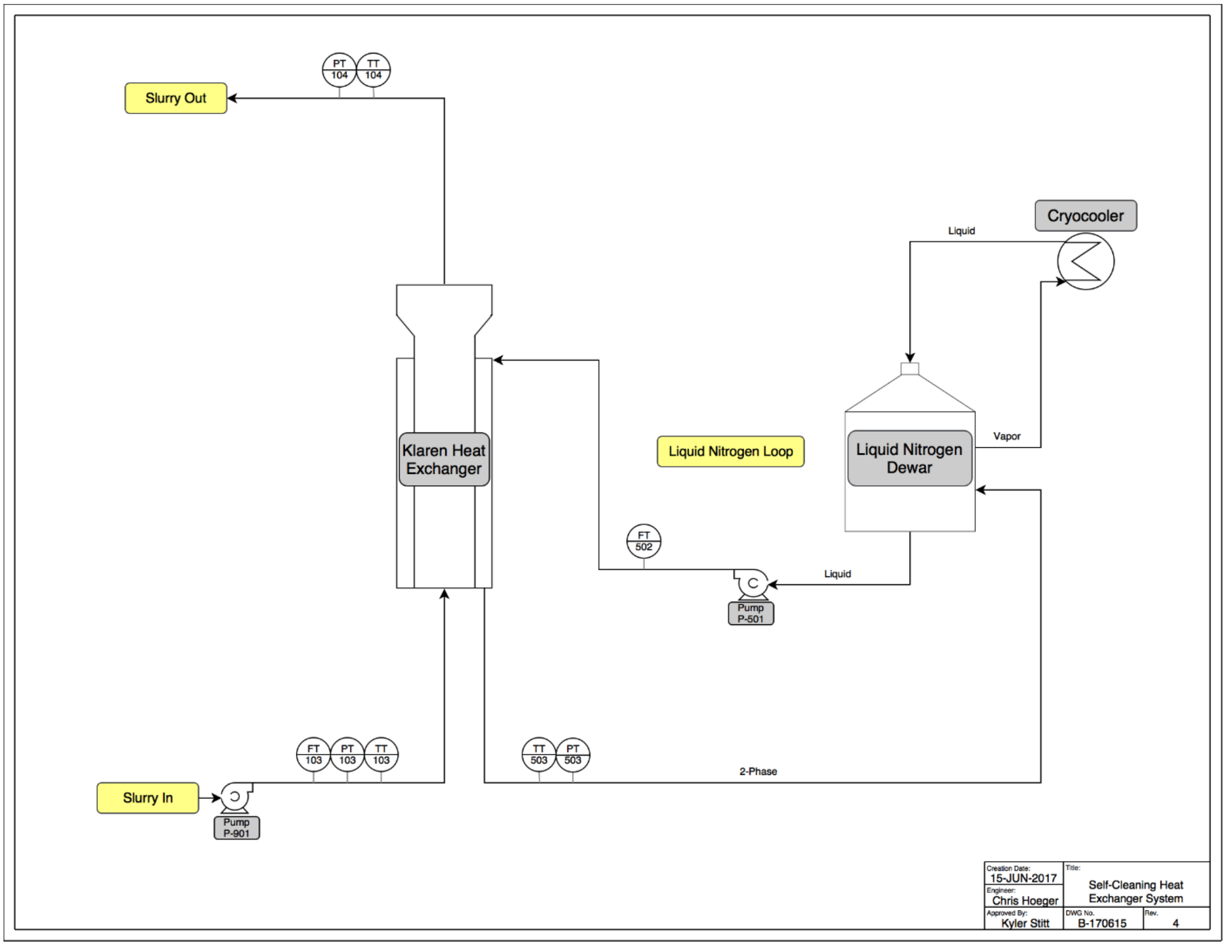


Figure 2. Basic PFD of the self-cleaning heat exchanger integrated with SES equipment

Self-Cleaning Shell-and-Tube Heat Exchanger

SES is also exploring a shell and tube heat exchanger with ball cleaning technology. This heat exchanger passes cleaning balls through the tubes periodically to remove deposits and appears primarily in water/water heat exchangers in power systems. The low-temperature, SES application requires some testing with tube sizes and at temperatures relevant to the SES process

Dual Screw Press Solid Separations System

SES runs the ECL skid system with a screw press, designed and built in house, to separate solid CO_2 from the direct-contacting. Field tests of this unit determined optimal flowrates and scaling issues. This has led to a system of two parallel systems that each run continuously. This increases the flow rate and turn-down ratio and more accurately reflects large-scale operation, which involves parallel independent screw presses.

In the screw press a slurry is pumped through a cylindrical filter. The filter captures the solids and the cleaned liquid recycles through the system. A screw (auger) continuously clears solids away from the filter to prevent it from plugging. The auger presses the solids through a restriction to remove as much contact liquid as possible and to raise the stream pressure. The resulting 80+% pure solid stream melts and passes through a distillation column for final purification. Modifying the current single-auger system to simultaneously operate a second auger requires control valve and pump modifications. Figure 4 shows the basic design of the dual screw press sled. This sled replaces the existing single-auger system in the ECL skid. Adding this second auger doubles the maximum flowrate of the previous system and leaves the minimum flowrate unchanged. These modifications include adding two additional cold boxes to the existing skid system, the upper and lower coldboxes.

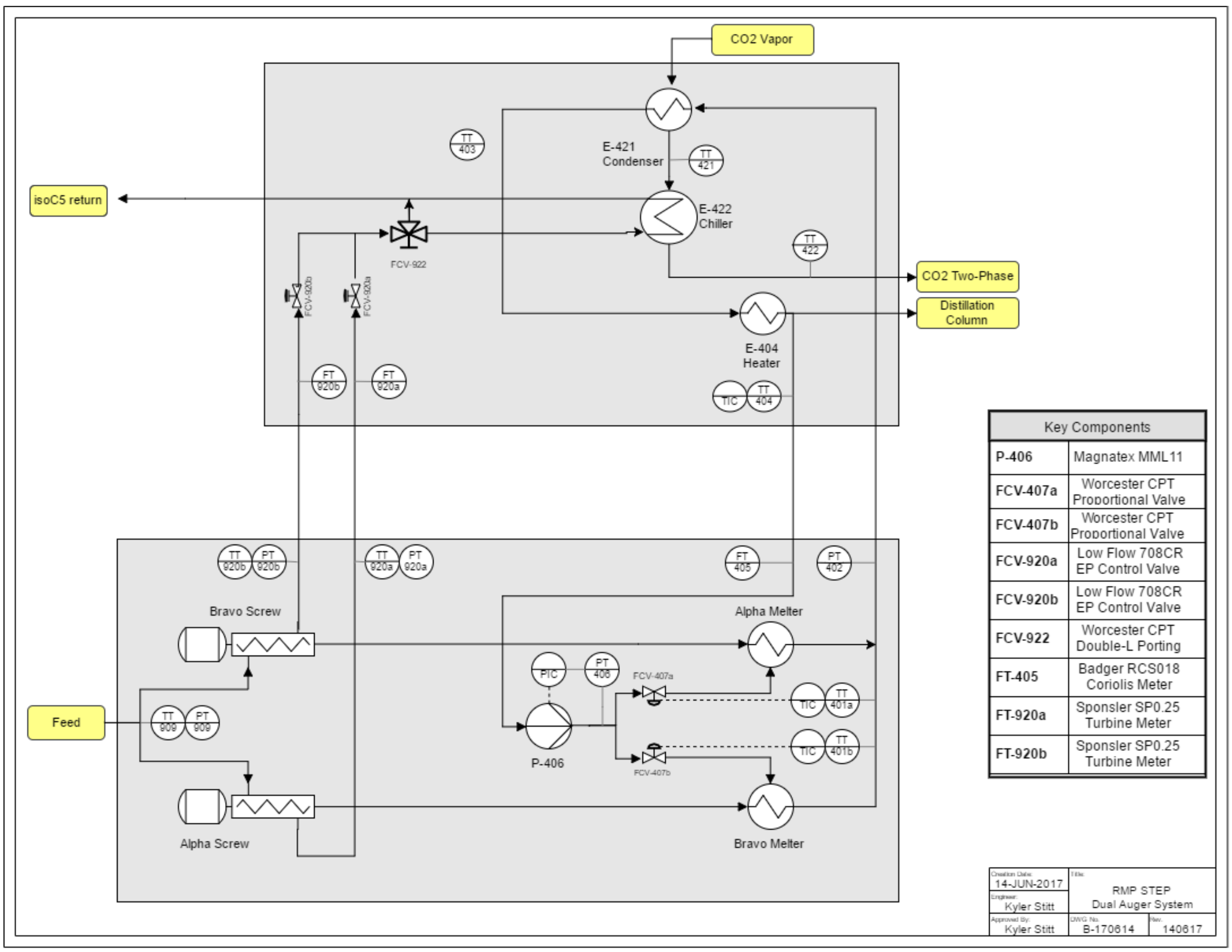


Figure 3. The two coldbox units for the solid–liquid separation system.

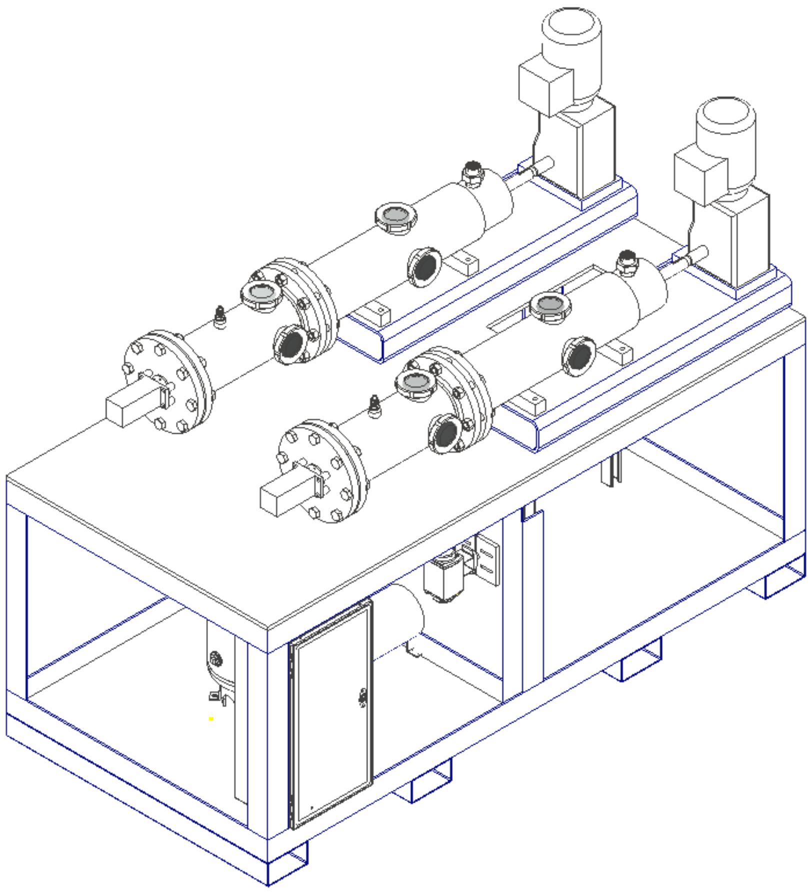


Figure 4. Isometric view of the Dual Screw Press and Lower Coldbox system

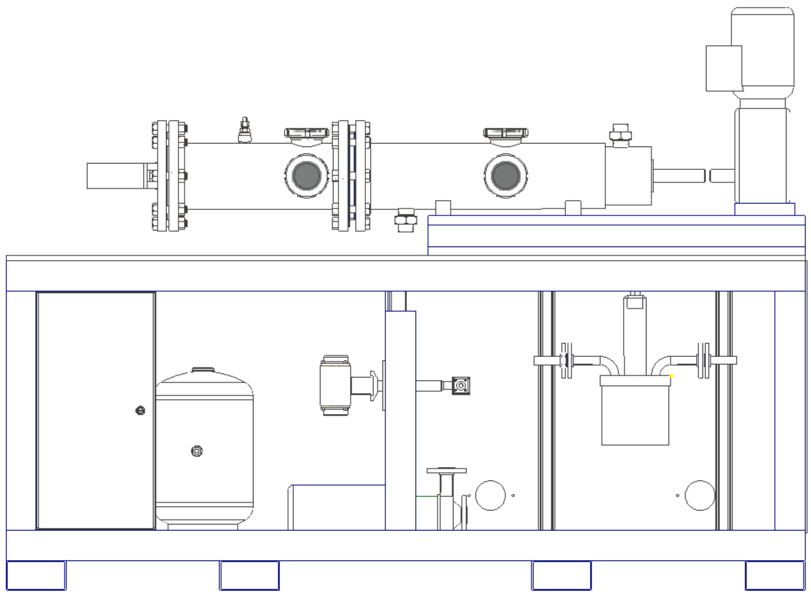


Figure 5. Side view of the Dual Screw Press and Lower Coldbox system

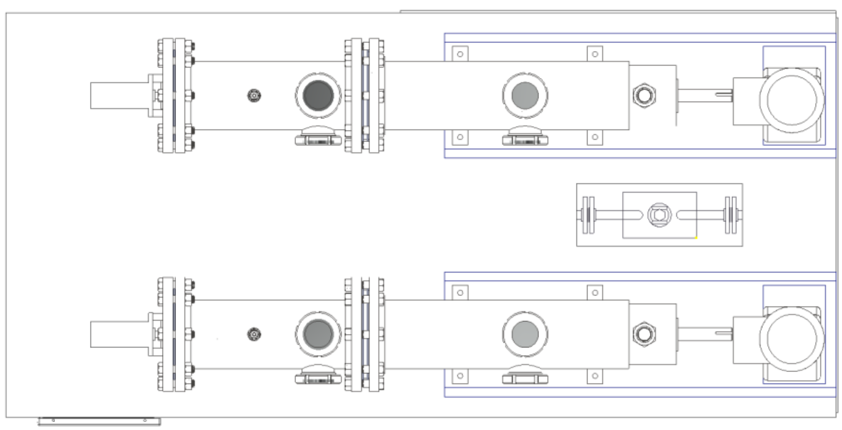


Figure 6. Top view of the Dual Screw Press and Lower Coldbox system

The Upper Coldbox contains additional control equipment and heat exchangers used in the overall dual auger system. This includes the valves needed to control the flow out of the filtered liquid portions of the augers, the heat exchangers and heaters required for the melting loop, and two of the turbine meters used for flow measurement.

Some of the key equipment for both coldboxes is detailed in Table 1 below. Some of this equipment has been sourced and ordered as part of this milestone. Additional equipment includes the structural components for the coldboxes, piping and tubing changes for the melter and screw press equipment, and an overhaul of the screw press plunger system used to provide back pressure for the solids filtering.

Table 1. Key Components of the Dual Screw Press and Melter system.

Description	Unit	Specific Part	Ordered
Melter Recirculating Pump	P-406	Magnatex MML11	Yes
Alpha Screw Liquid Release Valve	FCV-920a	Low Flow 708CR EP Control Valve	Yes
Alpha Screw Liquid Release Valve	FCV-920b	Low Flow 708CR EP Control Valve	Yes
Proportional Chiller Control Valve	FCV-922	Worcester CPT Double-L Porting	Yes

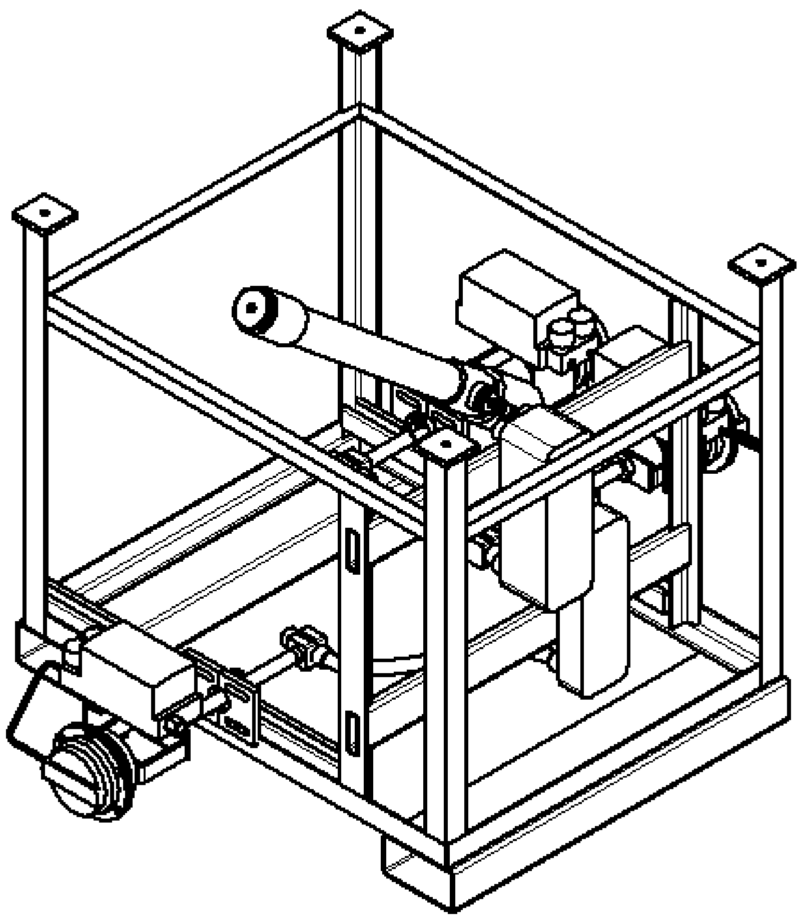


Figure 7. Isometric view of the Upper Coldbox system

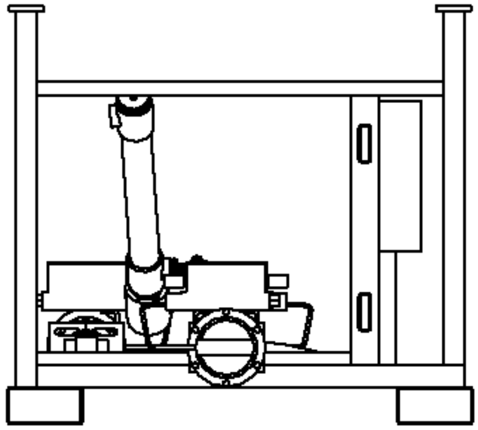


Figure 8. Front view of the Upper Coldbox system

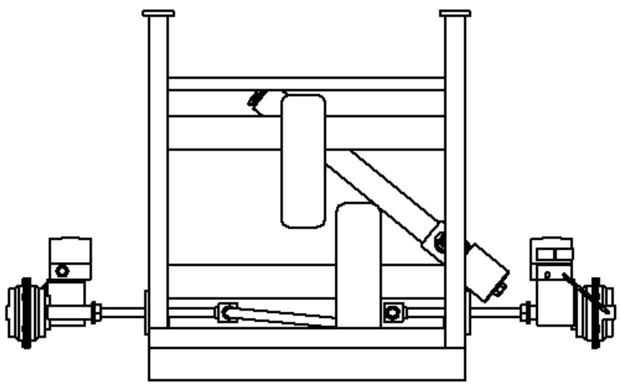


Figure 9. Side view of the Upper Coldbox system

QUARTERLY REPORT AND MILESTONE SUBMISSION

December 11, 2017

Submitted by

SUSTAINABLE ENERGY SOLUTIONS

Submitted to

ROCKY MOUNTAIN POWER

Sustainable Transport and Energy Plan (STEP)

Overview

This project modifies specific unit operations in an existing research and demonstration unit (the ECL skid) provided by Sustainable Energy Solutions (SES) to improve process efficiency, reliability, or overall performance. These modifications include experimental systems developed by SES. This first project development phase includes skid preparations for later long-term, on-site testing at an RMP facility. This report details the work done towards the third milestone of this project.

Quarterly Milestones

As indicated in the Scope of Work for this project, the third milestone involves the design and implementation of improved cryogenic flow and output measurement, followed by the testing of an integrated skid system with simulated flue gas at 1/4 tonne CO_2 captured per day, and testing with real flue gas using the in-house multi-fuel reactor. This reactor provided sufficient flow to meet the requirements of the milestone and was used to demonstrate significant progress towards a longer-term test. The exact milestones are described below.

Q3	SES will deliver a report containing the following: - The purchase orders and initial test reports of improved instrumentation such as advanced cryogenic flow measurement and output measurement. - Results of testing for the experimental integrated system with simulated flue gas at minimum 1/4 tonne per day CO_2 - Results of testing of the experimental integrated system tested with real flue gas.	11/15/2017	$ 110,533

In addition, this report contains updates on various unit operations that have previously been reported in quarterly reports, and that have continued to be developed during this quarter. These include the self-cleaning heat exchanger units being developed with our partners at Klaren International, a shell-and-tube self-cleaning heat exchanger, the experimental dual solid–liquid separations system, and the flue gas pre-treatment system.

Advanced Cryogenic Flow Measurement and Output Measurement

Process flow measurement and output stream monitoring represent critical development areas for the CCC process. The CCC system presents unique challenges for these measurements, as we have both cryogenic temperatures and slurries, which can cause fouling or failure of sensitive equipment. SES has overcome these challenges using several cryogenic flow measurements, specifically very low flow cryogenic turbine meters in the non-slurry sections of the system and Coriolis meters in the slurry sections of the system. The performance of these systems is described in turn below.

Cryogenic Turbine Meters

As part of the dual screw press cold box skid, SES installed cryogenic turbine meters that measure the outlet flow rate of each of the screw press systems. These measurements are vital as they enable full liquid control of the dual solid–liquid separations system. The turbine meters in the screw press outlets enable control of the flow and pressure drop across the filter. SES collaborated with Flow Technologies to use cryogenically rated turbine meters using specialized bearings and calibrations. As these were also in direct contact with our contact liquid, isopentane, they were rated for Class 1 Div 1 service. Figure 1 shows the specifications for these meters.

Description
FT4-8NEXBBLEAX5 - FT SERIES TURBINE FT4-8 = 1/2" Turbine Flowmeter, 3.0 GPM, 300°F max. NE = 1/2" NPT External Thread End Fittings XB = 10 Points, Extended Range Calibration in Oil Blend B = Non-Standard Calibration Range & Units L = Liquid Service E = 316 SS Housing / 430F SS Rotor A = 440C SS Ball Bearings X5 = RF PICKOFF, EXPLOSION PROOF CLASS I DIV 1 Calibration in Oil Blend: XBB = 10 Points, 0.2 to 0.6 LPM @ 0.8 cSt For liquid CO2 application
LA-5-C-MA-9 - LINEAR LINK LA = Linear Link Flowmeter Transmitter 5 = 19-32 VDC Power Required C = FTI RF (Carrier) Flow Output Signal MA = 0-5V Pulse Output Signal: Linear with Flow Rate 4-20mA Analog Output Signal: Linear with Flow Rate -9 = Explosion Proof Enclosure: Class 1, Div. 1, Groups A , B, C & D *Scaled one each to one each flow meter

Figure 1. Description and specifications for the FTI Cryogenic Turbine Meters.

During this quarter, we successfully integrated these meters into the CCC test skid system. Figure 2 shows these turbine meters as they are placed at the outlets of the screw presses.

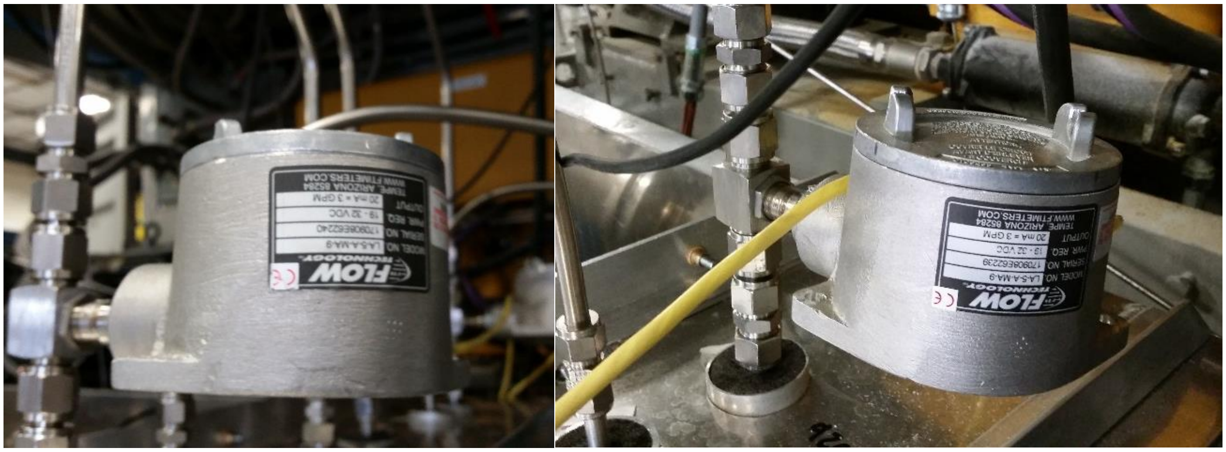


Figure 2. Flow Technology turbine meters installed to measure the outlet flow rate from each of the screw presses.

These meters were tested during the multi-pollutant tests at ¼ tonne CO_2 per day flow rates and using real flue gas. The results of these tests and the outputs of the turbine meters are explained in greater detail in the corresponding sections below.

Coriolis Meter

A Coriolis meter uses the principles of motion mechanics when the process fluid splits and enters the sensor. During operation, a drive coil stimulates the tubes to oscillate in opposition at the natural resonant frequency. As the tubes oscillate, the voltage generated from each pickoff creates a sine wave. This indicates the motion of one tube relative to the other. The time delay between the two sine waves (Delta-t) varies proportional to the mass flow rate. Figure 3 below shows the working principle of these flow meters.

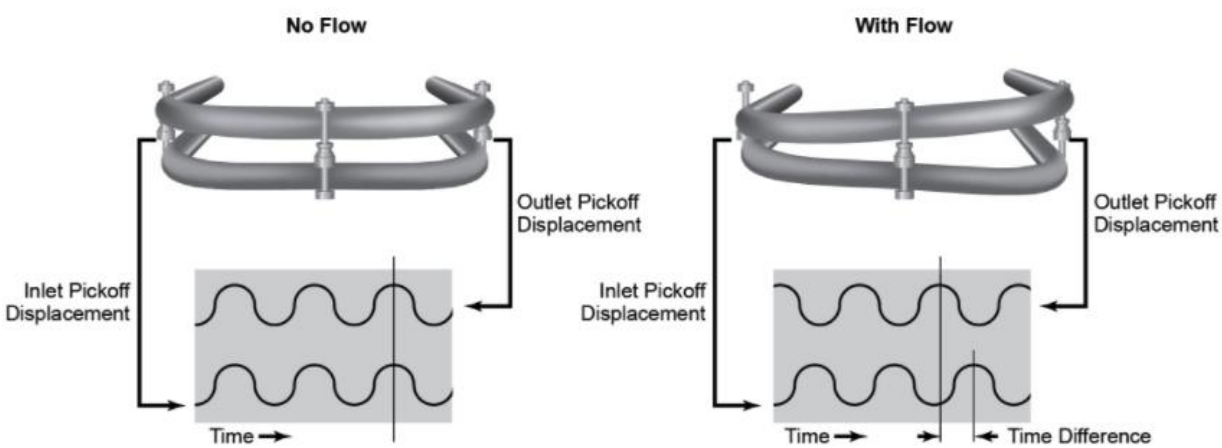


Figure 3. Principle of operation for a Coriolis meter (Courtesy of Emerson Automation Solutions).

One advantage of this type of measurement is that it gives both a direct mass flow measurement and a density measurement due to the fixed volume of the tubes. In many ways, it is more precise than displacement style flow meters such as the turbine meters above. Additionally, as the flow is not impeded by any sensors or equipment, it allows for more complex flows – like slurries – to be measured. One use of these types of meters is to measure the CO_2 slurry concentration in the stream by measuring the density and comparing to known densities of both our contact liquid and solid CO_2.

SES acquired an Emerson Micro Motion Coriolis Meter CMF025. The Micro Motion meters are some of the few that are rated for cryogenic temperatures. Figure 4 shows one of these Coriolis meters before installation, and Figure 5 shows the Coriolis meter in place covered in cryogenic insulation and a water vapor barrier.

Figure 4. Emerson Micro Motion CMF025 Coriolis Meter.

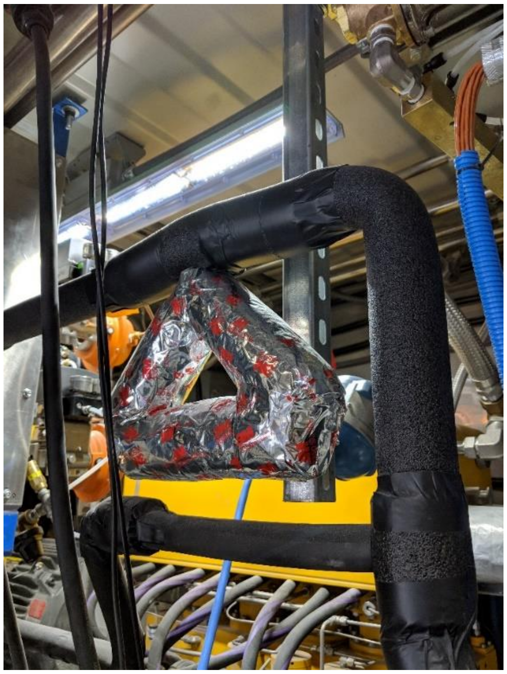


Figure 5. Emerson Coriolis meter installed leading from separations coldbox, covered in insulation.

This meter size generates a velocity that prevents CO_2 settling or sticking to the walls. Previous experiments indicated that a velocity of at least 1.5 meters/second prevents such fouling.

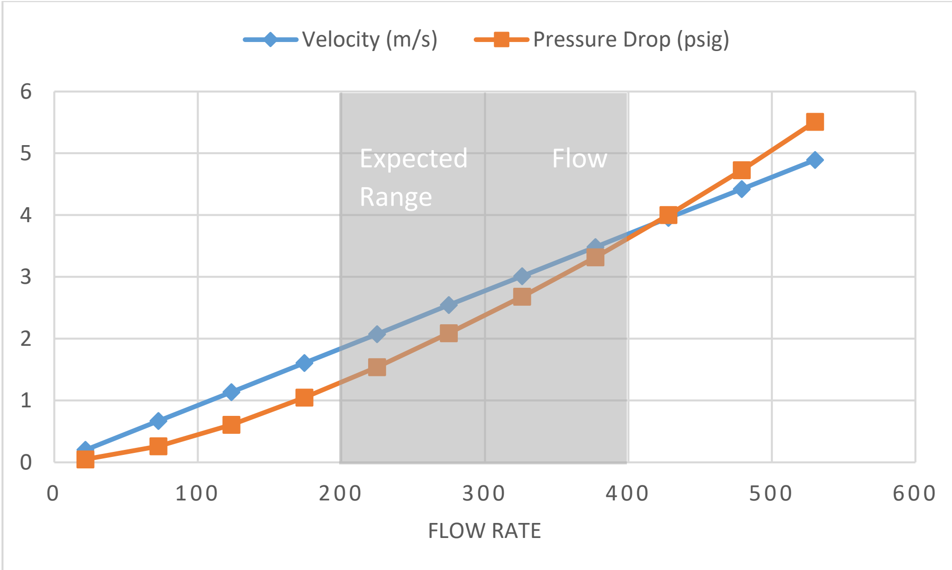


Figure 6. Slurry flow rate compared to the pressure drop and velocity of the slurry.

The Coriolis meter was tested during the multi-pollutant tests at ¼ tonne CO_2 per day flow rates and using real flue gas. This meter validated the outputs of the turbine meters and other Coriolis meters and further tested the required minimum velocities to prevent fouling. The results of these tests and the outputs of the Coriolis meter are explained in greater detail in the corresponding sections below.

Output Measurement and Control

Controlling the outputs of the CCC system and properly measuring them is another prerequisite to long-term testing. The primary output of concern is the flow of liquid CO_2. Isopentane, our primary contact liquid, can contaminate this stream, resulting in excess cost of operating the system due to its loss out the product CO_2 stream. In our current process, we purify this stream using a series of vapor–liquid separators and condensers. This separation occurs near the triple point of the of the CO_2, and so precise controls are required to achieve the appropriate temperatures and pressures. Figure 7 shows an updated P&ID of the separations system used by SES for the removal of solid CO_2 from the slurry streams and purifying it to a liquid CO_2 stream. The highlighted yellow box represents the new addition to this system, a vapor–liquid separations system.

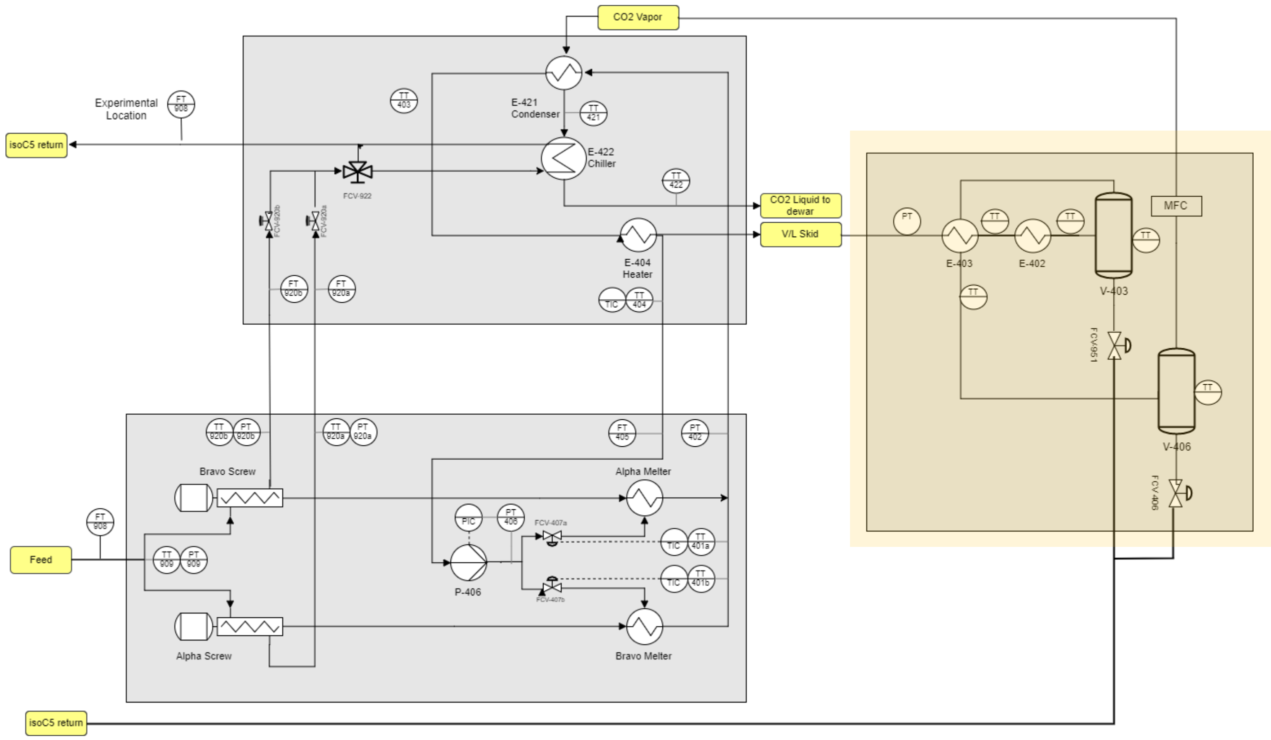


Figure 7. Separations system with added outlet measurement and controls (highlighted in yellow).

This new unit operation consists of two main vapor–liquid separators and two heat exchange units for controlling the temperatures into each system. Once the CO_2 has been separated from a majority of the isopentane in V-403, it is chilled in E-403 and further purified in V-406. The flow of vapor CO_2 is then measured in a Mass Flow Controller before being condensed into liquid CO_2 by being put through the E-421 Condenser and 4-422 Chiller, located in a separate coldbox. A key challenge is to ensure that the entire stream is condensed into liquid, and therefore precise temperature measurements are taken using TT-421 and TT-422, and pressure is measured and controlled throughout the vapor–liquid separations unit.

Simulated Flue Gas Testing at 1/4 Tonne per Day

SES demonstrated the skid-scale system at 0.25 tonne/day for 12 hours. We used a mixture of gases from CO_2 and LN2 Dewars to simulate a flue gas at an average composition of 10.4 mol% CO_2, added SO_2, CO, and NO pollutants using compressed air cylinders, with the balance N_2 (Figure 8) at an average flow rate of 42.1 SCFM (Figure 9). This test was performed using a closed-loop gas recycle that allows for continuous testing of the system without unnecessary expense when using gas Dewars to create the simulated flue gas. One key aspect of this particular test is that it included pollutants at levels that could reasonably be expected at the Hunter power plant. Table 1 gives a summary of overall run results.

Table 1. Results from the closed-loop test using simulated flue gas capturing ¼ tonne CO_2/day [1]

	Units	RMP 250 kg/Day Test
Start Date	–	25 Oct 2017
Start Time	–	4:28 pm
Stop Date	–	26 Oct 2017
Stop Time	–	4:42 am
Total Run Time	hr	12.2
Total CO_2 Captured	kg	170
Avg. CO_2 Capture Efficiency	%	96.1
Avg. CO_2 Capture Rate	kg/day	13.9
Avg. Flue Gas Flow Rate	SCFM	42.1
Avg. Flue Gas CO_2 Content	mol%	10.4
Avg. CO_2 Purity	%	99.4
Avg. Pressure Drop	psig	1.81
Avg. Coriolis Slurry Density	kg/L	0.791
Avg. Small Coriolis Slurry Density	kg/L	0.92
Avg. Melter Mass Fraction	%	77.0
Avg. Alpha Auger Flow Rate	kg/hr	79.1
Avg. Bravo Auger Flow Rate	kg/hr	79.0

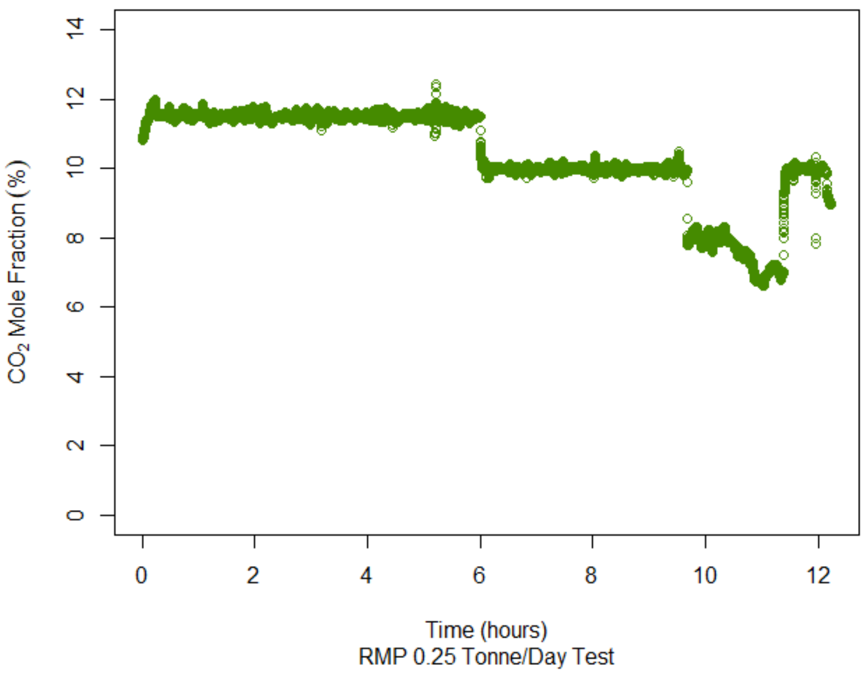


Figure 8. Inlet simulated flue gas CO_2 mole fraction for ¼ tonne CO_2/day closed-loop test [1].

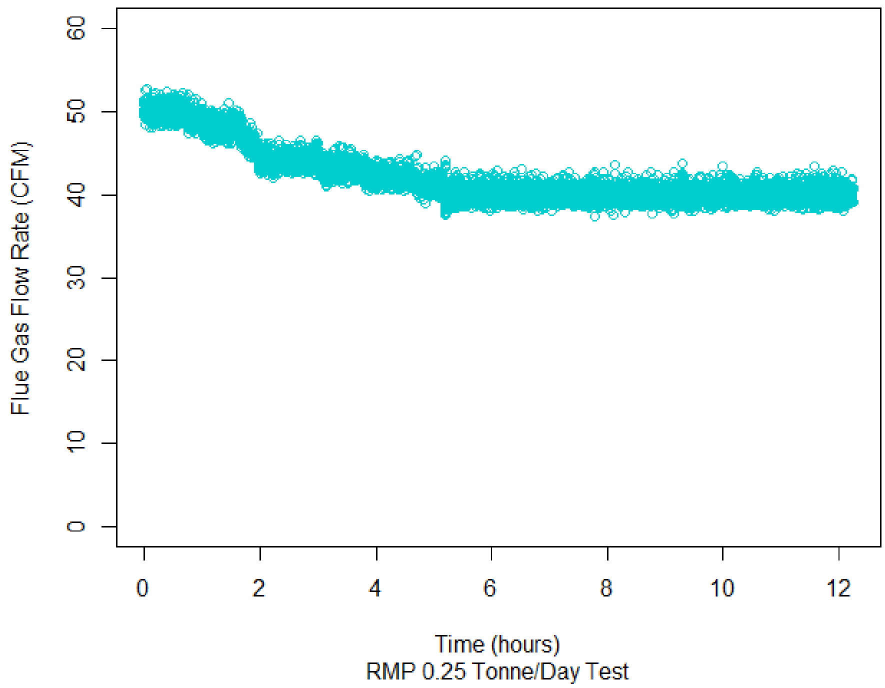


Figure 9. Flue gas flow rate [1].

The SO_2 inlet concentration, as seen in Figure 10, is higher than what is expected at the power plant, averaging 30.43 ppm. In fact, it is high enough to verify that CCC could reasonably come before the plant's flue gas desulfurization unit. Since we only have one FTIR unit, it was primarily used to measure the inlet gas composition. The outlet gas composition was measured at various times throughout the run, but was still run long enough to establish a good average outlet composition of 3.55 ppm, for a capture efficiency of 88.3% (see Figure 11). This test also established that the CCC system at these temperatures and pressures does not capture NO nor CO, as the inlet and outlet compositions were statistically similar (Figure 12).

This test verified that the CCC system, unlike many absorption systems, is very robust to the presence of SO_x, NO_x, and other pollutants, including CO. The system ran and captured CO_2 in the exact same way that it runs without any of these pollutants present. While this has been tested at smaller scales of the CCC system in the past, this is the first significant test at this scale, at these pollutant levels, and for this long of a testing period. This gives us additional confidence as we move toward our future testing milestones.

Over the course of the test, we captured 170 kg of CO_2 at a rate of 0.336 tonne CO_2/day (Figure 13), a CO_2 capture rate of 96.1%. The capture rate remained high over the course of the test (Figure 14).

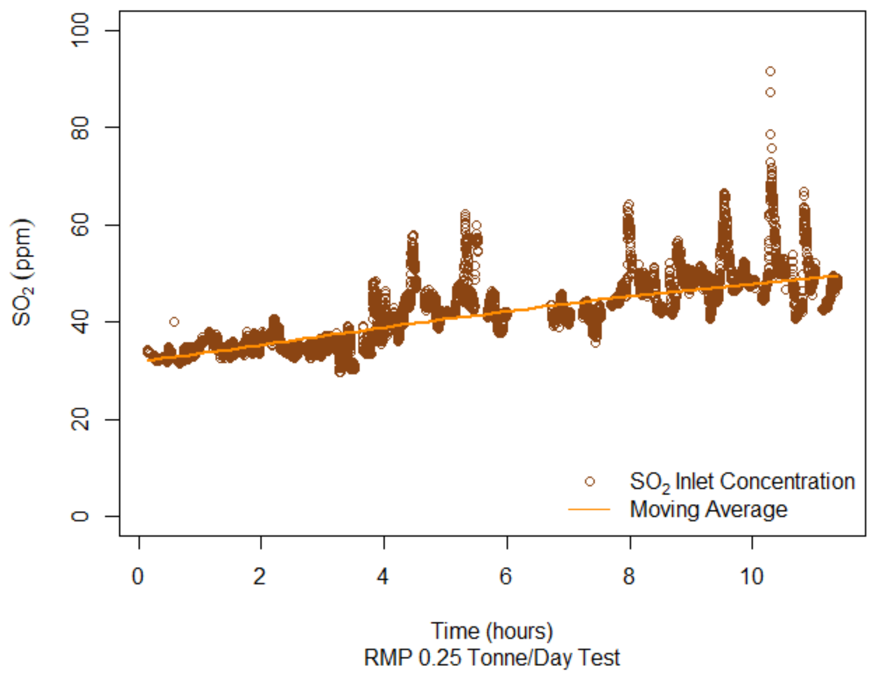


Figure 10. Inlet SO_2 concentration [1]

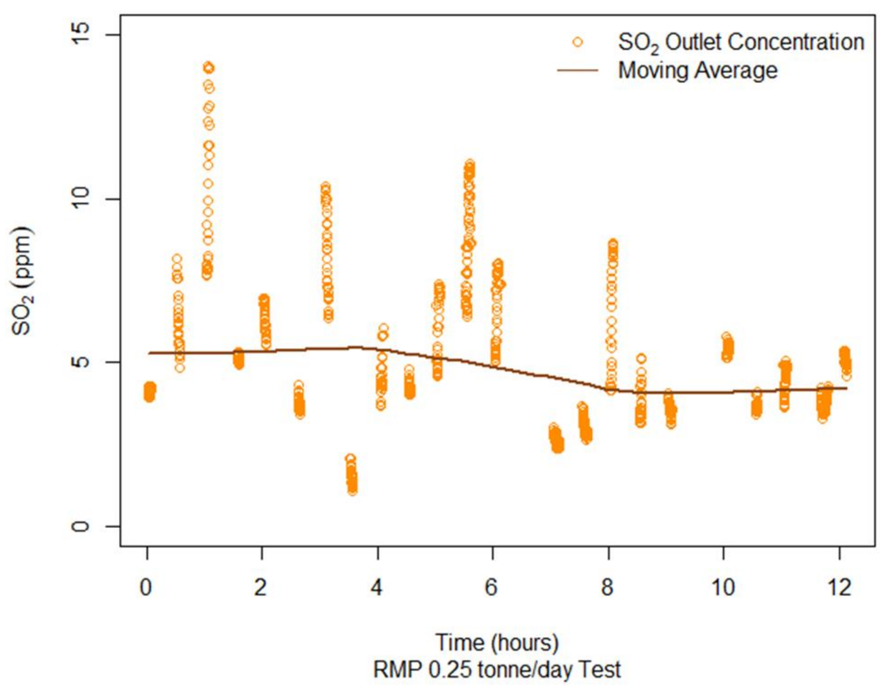


Figure 11. SO_2 outlet concentrations measured using FTIR [1].

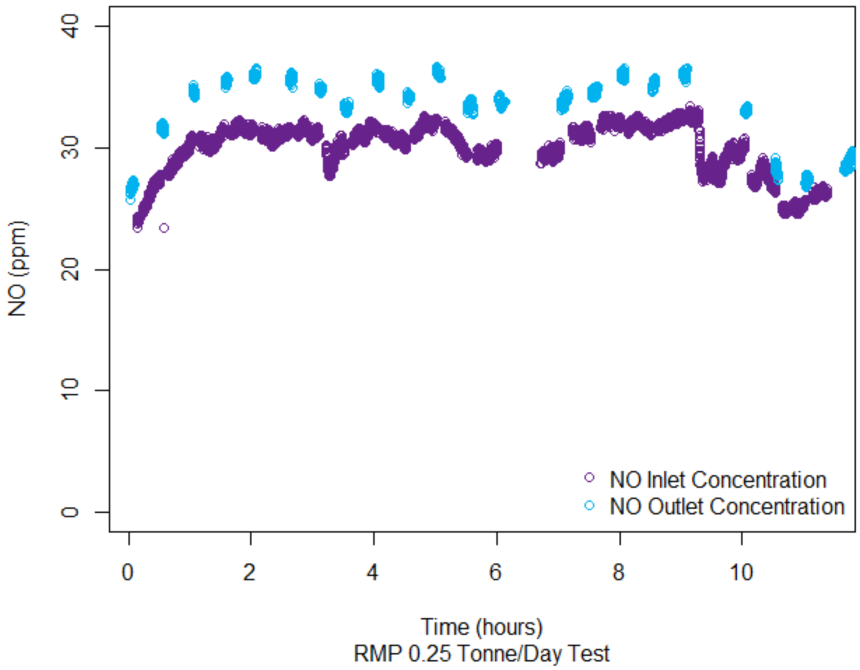


Figure 12. Inlet and outlet concentrations of NO. While it appears that the outlet concentration is higher than the inlet concentration, all of these measurements are within the measurement error of the FTIR [1].

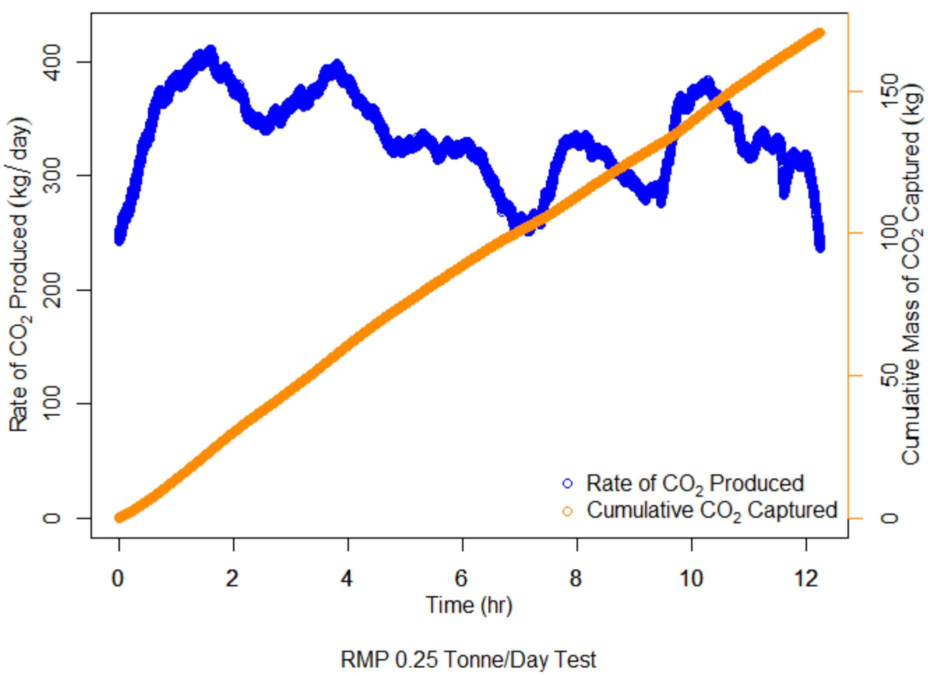


Figure 13. Cumulative CO_2 capture and CO_2 production rate over the course of the closed-loop ¼ tonne CO_2/day test [1].

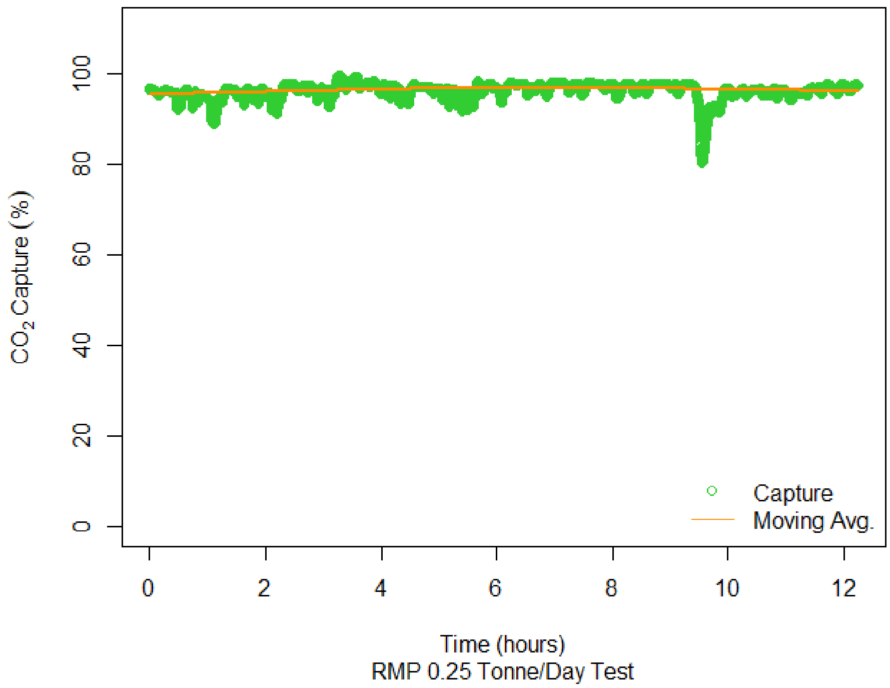


Figure 14. CO_2 capture over the course of the closed-loop ¼ tonne CO_2/day test [1].

Using an FTIR spectrometer, we measured the inlet, outlet, and CO_2 stream compositions. Of particular interest is the purity of the CO_2 stream exiting the process. We achieved an average CO_2 purity of 99.4% during this test. This greatly exceeds the CO_2 pipeline quality requirement (i.e., 95% purity), which CO_2 is used for enhanced oil recovery. This CO_2 stream only contained an average 166 ppm of SO_2. However, the concentration of SO_2 in the CO_2 outlet stream did not reach a steady-state value when the test was concluded. Additional testing will determine if the steady-state value matches predictions and to determine the best method moving forward for cleaning the SO_2 out of the outlet streams. This can also be seen in the apparent melter CO_2 mass fraction. The SO_2 accumulates in the CO_2 liquid and builds over time. As explained above, the CO_2 mass fraction in the melter is calculated via a density measurement that assumes the only components are CO_2 and isopentane. Adding a third component, such as SO_2, that has a higher liquid density than CO_2 causes an increase in the calculated CO_2 mass fraction. It appears that from hours 2 through 8 of the run that the fraction of CO_2 in the melter is increasing (Figure 15). However, this might also be due to accumulation of SO_2. Further testing will allow SES to better understand where the pollutants accumulate and how to remove them from the system.

This test also allowed us to use some of the new instrumentation that had been installed into the skid, such as the cryogenic turbine meters. The turbine meters allow us to measure the flow independently on each screw press so that they are easier to control and monitor. The outputs from the test can be seen in Figure 16. Both screw presses were kept at a very similar flow rate throughout the run, which represents an improvement in operations compared to the past.

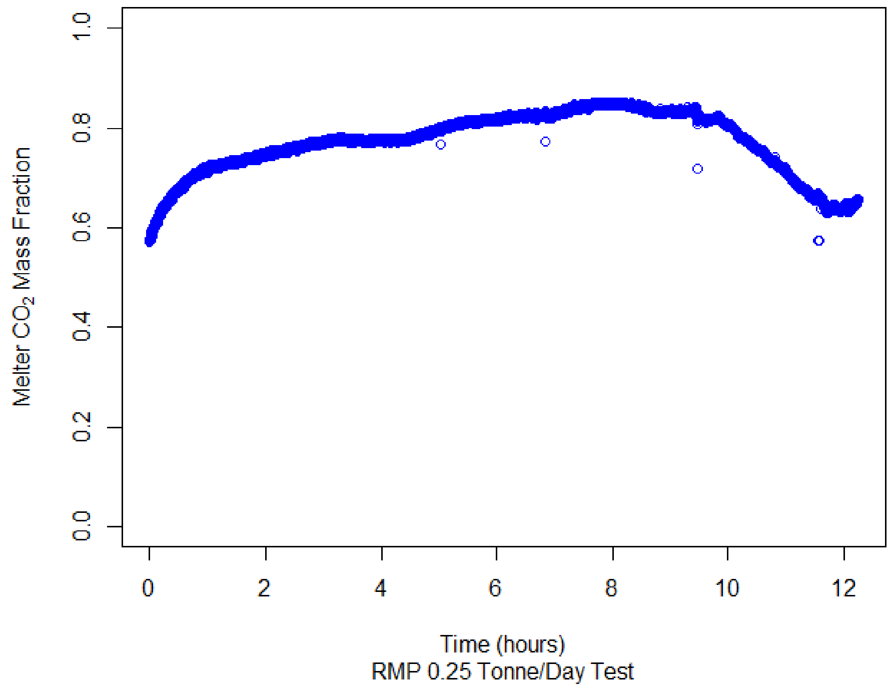


Figure 15. Calculated CO_2 mass fraction in the melter unit [1].

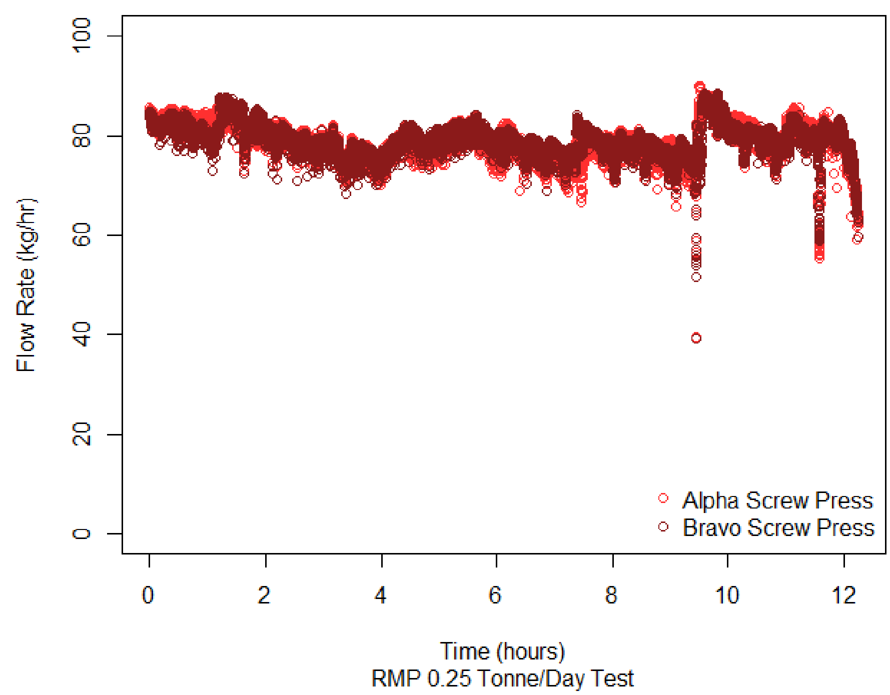


Figure 16. Flow measurement from the cryogenic turbine meters

Real Flue Gas Testing

SES has a multi-fuel reactor (MFR) onsite that allows us to combust a variety of fuels to produce our own flue gas. Most aspects of the new system design could be tested in a closed-loop flue gas circuit. However, some unit ops, including the dryer and other pretreatment equipment, require an open-loop test with real flue gas for us to be fully confident in their efficacy.

We ran the MFR at full capacity with natural gas as the fuel, which resulted in a CO_2 flow rate of approximately 200 kg/day. The entire flue gas stream was plumbed into the CCC skid and processed during the test. The average capture during the test was 95.9%, and the average composition of CO_2 in the inlet was approximately 8%. All unit ops performed as expected, and we had a successful controlled shutdown at the end of the run. This test included the dryer unit; the dew point of the gas was low enough that fouling in the gas recuperator was no different than in any runs that did not include water in the inlet gas. Additionally, all new instrumentation, including the cryogenic turbine meters and the new Coriolis flow meter, were installed and took data throughout the run. Table 2 gives a summary of the overall run results.

Table 2. Real flue gas test results summary

	Units	MFR Flue Gas
Start Date	–	7 Dec 2017
Start Time	–	8:28 am
Stop Date	–	7 Dec 2017
Stop Time	–	5:42 pm
Total Run Time	hr	9.26
Total CO_2 Captured	kg	37.3
Avg. Capture Efficiency	%	95.9
Avg. Capture Rate	kg/hr	4.03
Avg. Flue Gas Flow Rate	SCFM	29.7
Avg. Pressure Drop	psig	2.79
Avg. Coriolis Slurry Density	kg/L	0.768
Avg. Small Coriolis Slurry Density	kg/L	0.721
Avg. Melter Mass Fraction	%	52.8
Avg. Alpha Auger Flow Rate	kg/hr	83.6
Avg. Bravo Auger Flow Rate	kg/hr	79.8

During the test, there were two short periods of approximately 50 minutes total when the air compressor for the combustion air for the MFR overheated and shut down. During this time, the skid was kept in stasis and was unable to capture any CO_2 until the air supply problem had been fixed. Due to this MFR outage, there are two gaps in the data plots that correspond to these two outages. A plot of CO_2 capture over time is included in Figure 17.

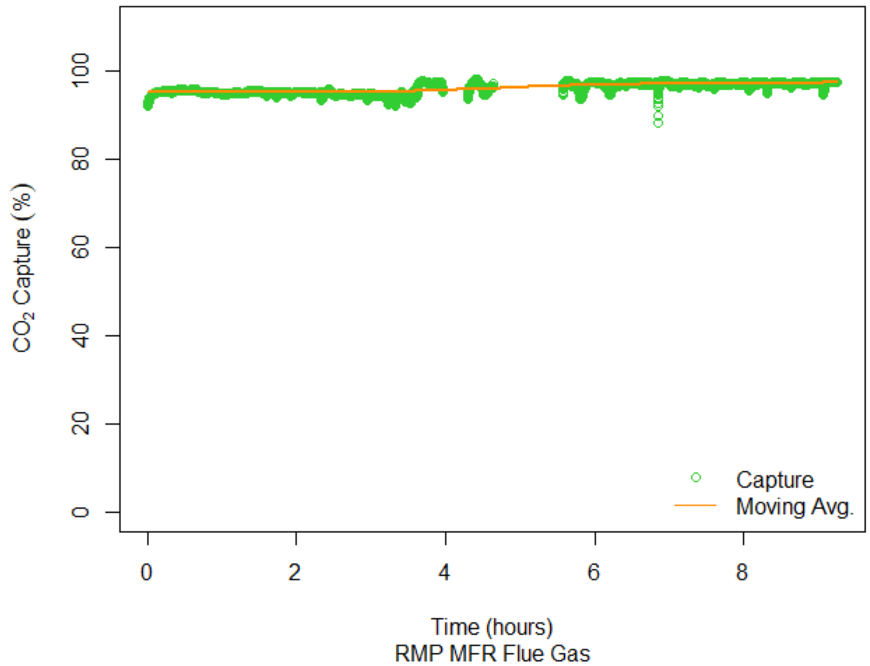


Figure 17. Capture data from the real flue gas test [1]

The test also allowed us to test our new integrated heat exchange system designed for CO_2 liquefaction. Although there were some controls issues that resulted in the formation of some solid CO_2, SES was able to successfully condense approximately 80% of the CO_2 on a mass basis throughout the majority of the run. Instantaneous and cumulative CO_2 rejection from the test are included in Figure 18.

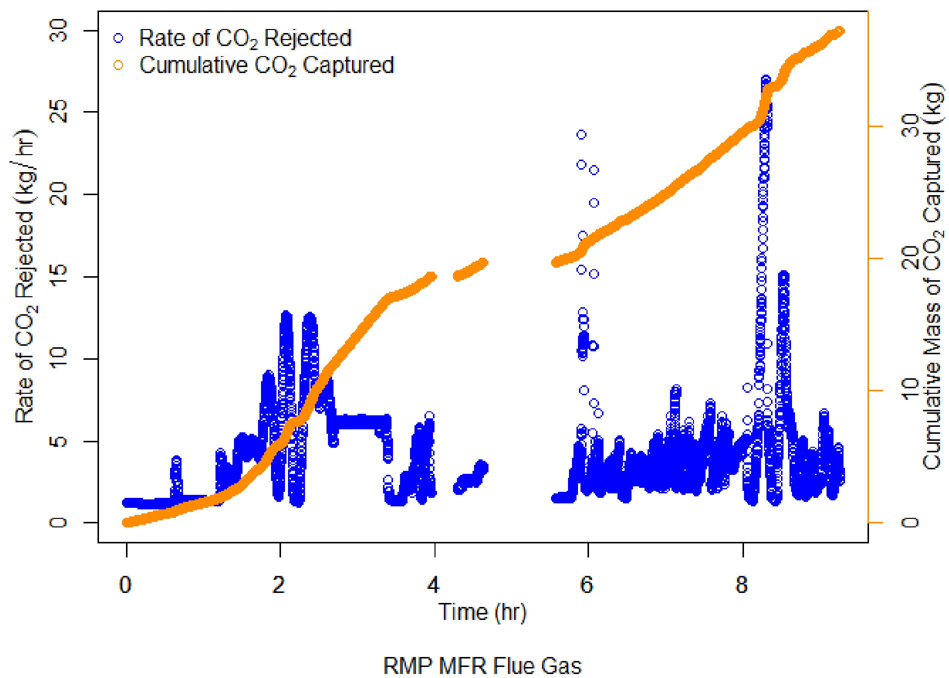


Figure 18. Instantaneous CO_2 rejection and cumulative CO_2 captured [1]

One other result of special import is the total system pressure drop of this test. The molecular sieve dryer unit previously resulted in significant enough pressure drop that it limited the total flow rate that the skid was capable of processing. At similar flow rates, a closed-loop run of the system that bypasses the dryer units results in a total system pressure drop of 2.11 psi. The pressure drop including the dryers was 2.79 psi, an increase of only 0.68 psi. This is a significant improvement compared with previous results. The system pressure drop throughout the course of the run can be seen in Figure 19.

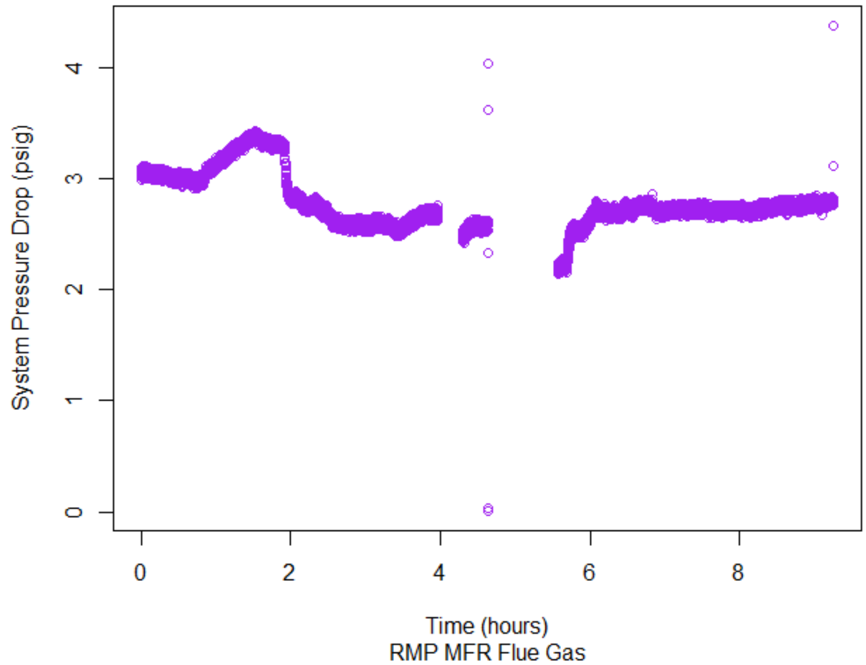


Figure 19. System pressure drop [1]

In terms of instrumentation, both cryogenic turbine meters used to measure the flow and the new small Coriolis meter were used during the run. SES completed all the instrument shakedowns during testing and received valuable data, as shown in Figure 20 and Figure 21. Figure 21 compares the density readings of our previously installed Coriolis meter with the new small Coriolis meter. The slight difference can be explained by the difference in process conditions at the two locations. The larger Coriolis meter is in a stream location that includes solid CO_2 and is at a colder temperature, leading to a higher density, whereas the small Coriolis meter is at warmer temperatures and the stream has been filtered to remove all solids, further decreasing the density reading.

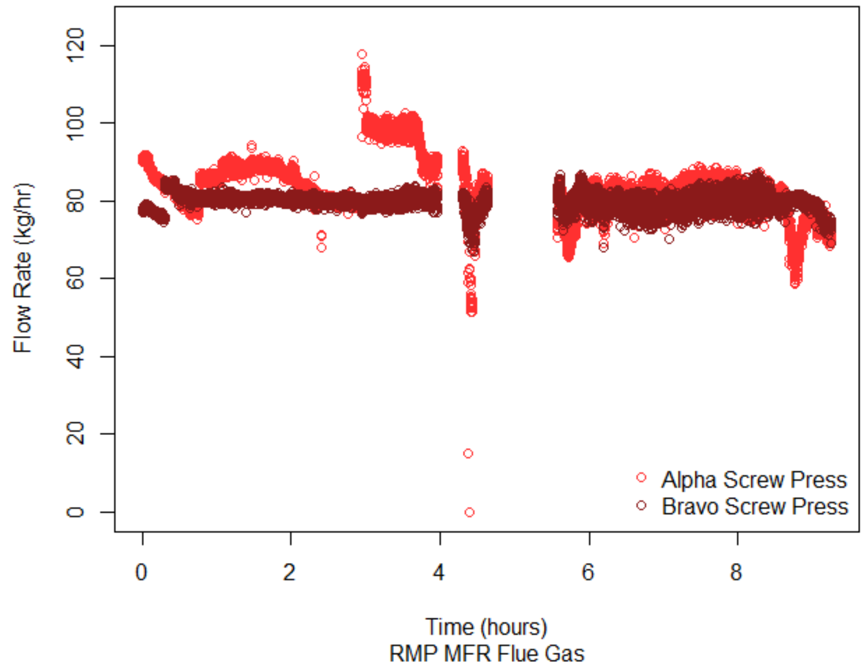


Figure 20. Cryogenic turbine meter flow data [1]

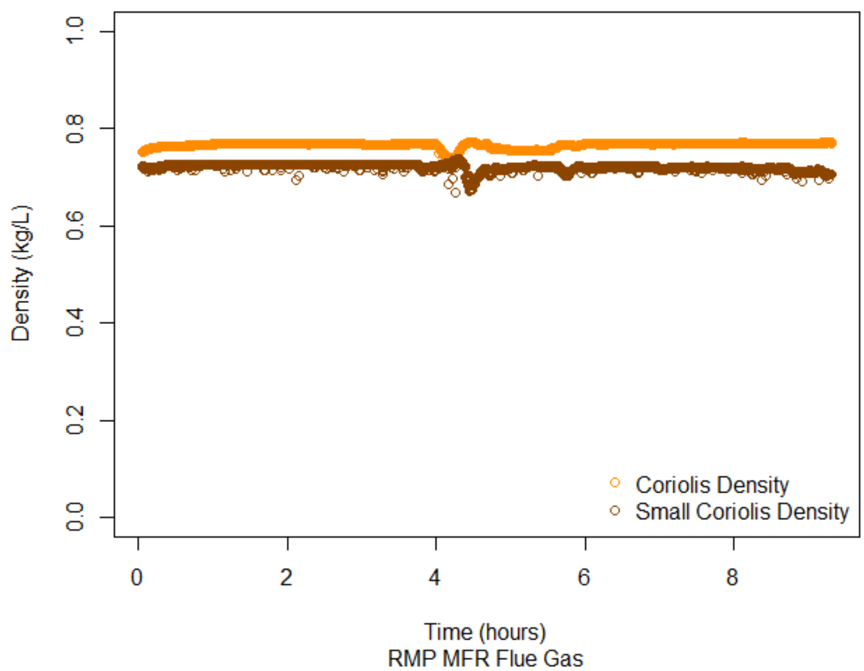


Figure 21. Comparison of Coriolis meter density data [1]

The test was a successful demonstration of every new piece of equipment and instrumentation integrated into the system. The dryer decreased the dew point low enough to allow the rest of the process to function and did so at a very low pressure drop. The new instrumentation allowed for much tighter control of the process, especially concerning the solid–liquid screw press separation units. The capture was effective and remained high the entire run, and the new CO_2 liquefaction equipment liquefied a significant portion of the outlet CO_2. There is still work to be done, including better control of the liquefaction system, but this test demonstrated good progress.

Self-Cleaning Heat Exchangers

SES has continued work towards self-cleaning heat exchangers, which will be used to prevent fouling in the various process heat exchangers over time. This section describes these continued efforts towards a traditional cleaning system for a shell-and-tube heat exchanger, and a self-cleaning fluidized bed heat exchanger being developed in partnership with Klaren International.

Self-Cleaning Shell-and-Tube Heat Exchanger

During the previous quarter, the in-house custom shell-and-tube heat exchanger was constructed here at SES, and communication has continued with the vendor who will provide the self-cleaning materials, WSA Engineered Systems. Figure 22 shows the current state of shell-and-tube heat exchanger mid-assembly. The structure and frame of this system have now been completed and SES is finalizing connections to the rest of the system.

Figure 22. The integrated shell-and-tube heat exchanger.

Self-Cleaning Fluidized Bed Heat Exchanger

During this quarter, SES worked with Klaren International to construct and ship the fluidized bed heat exchanger. This heat exchanger continuously cleans itself using small particles that scour the heat exchange surface. The unit uses a single tube, and provides a proof of concept for the CCC process. This single-tube heat exchanger also scales modularly to higher flow rates. A finalized P&ID of this heat exchanger and how it will be integrated with the equipment at SES is shown in Figure 23.

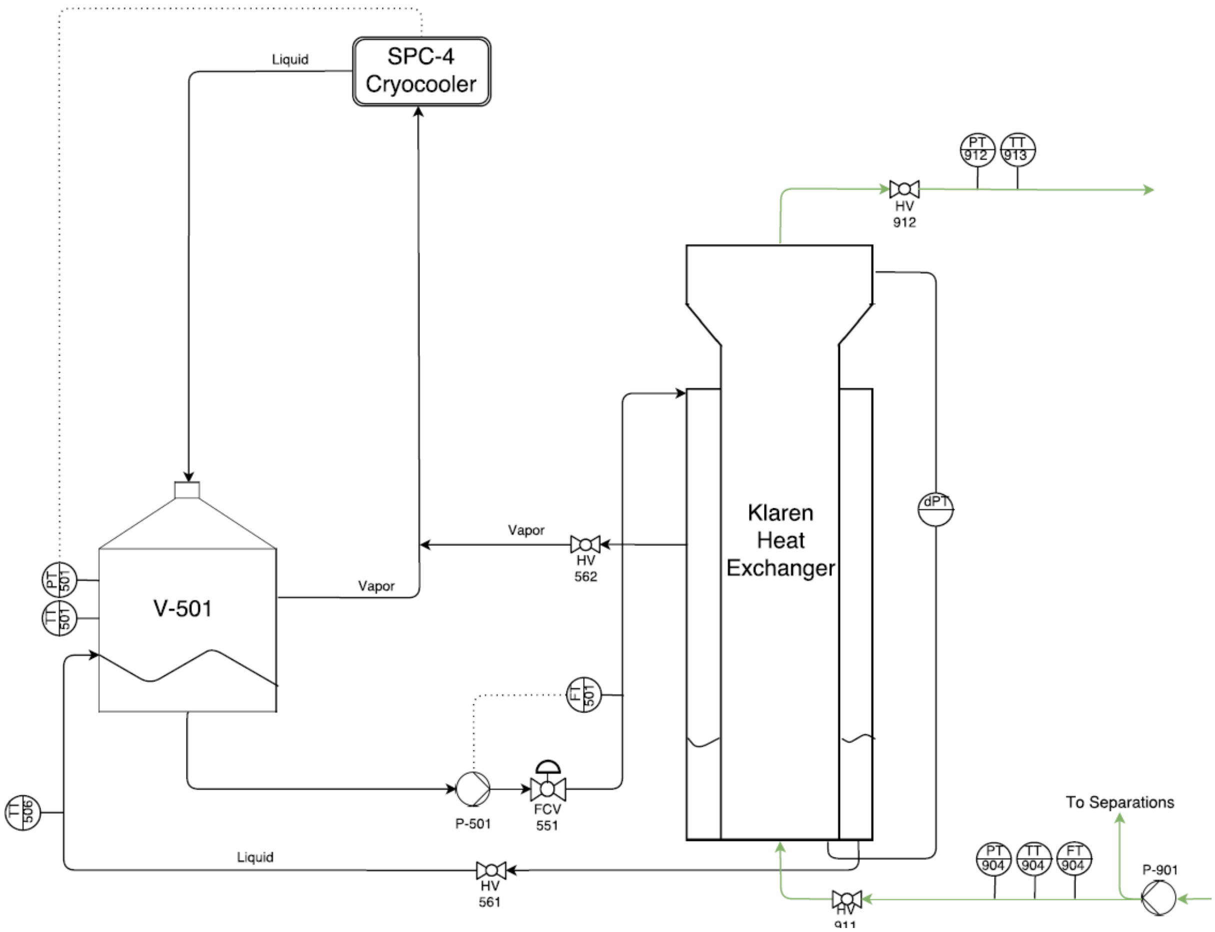


Figure 23. Finalized P&ID of the self-cleaning heat exchanger integrated with SES equipment

SES continued working with Klaren as they built the heat exchanger, and minor modifications were made, which are reflected in the finalized construction drawings in Figure 24. Of particular note is the moving of some of the ports for the sight glass and the instrumentation ports so that it will integrate better with our system, as well as a refinement of the how the internal tubing structure will be supported.

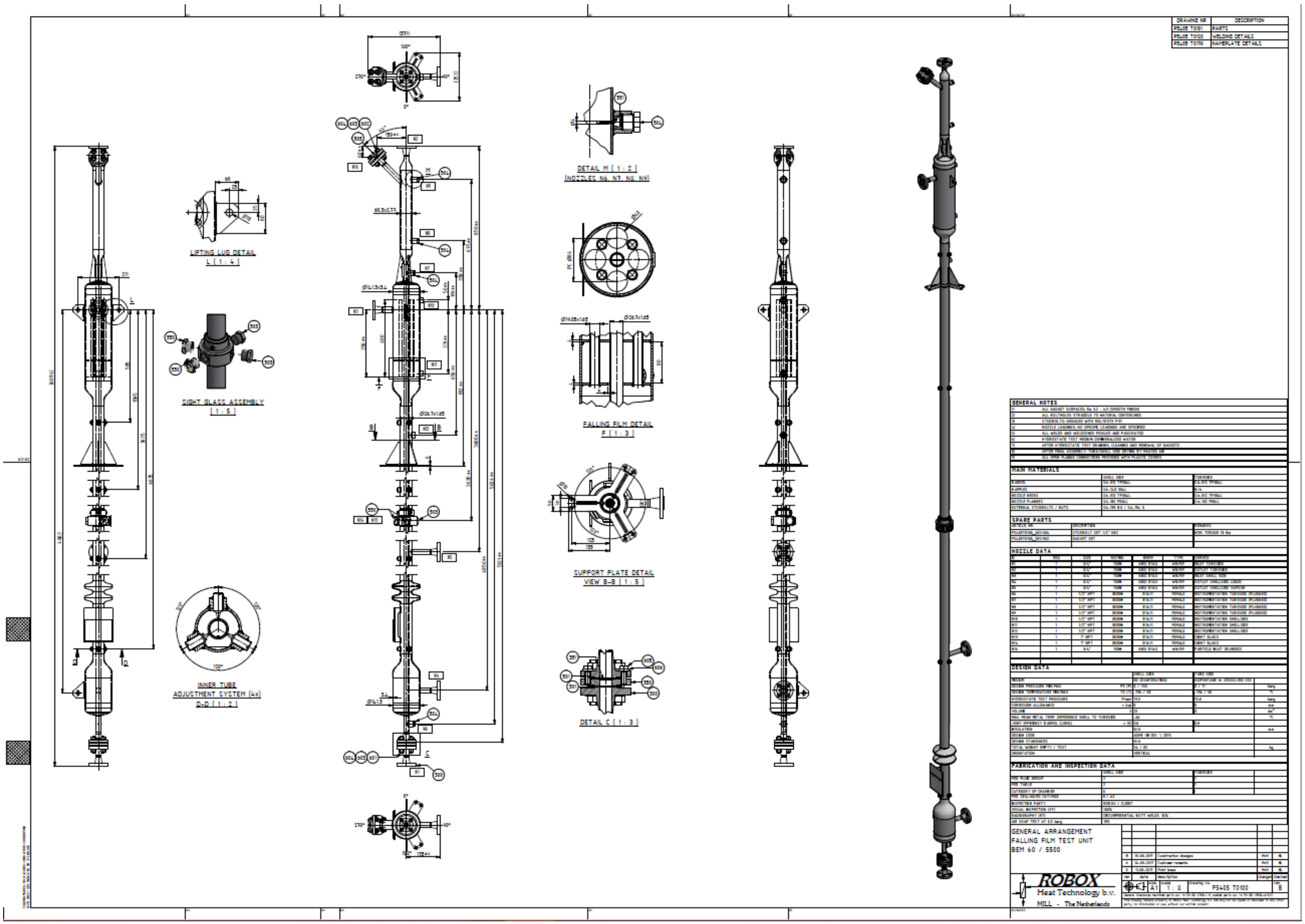


Figure 24. Finalized drawing of the self-cleaning heat exchanger made by Klaren International.

SES has now received the heat exchanger at our headquarters in Orem and work is continuing on the structure required to support and insulate the equipment. The heat exchanger and some of the supporting valves and tubing are shown in Figure 25.

Figure 25. The heat exchanger and additional equipment from Klaren International.

Flue Gas Pre-Treatment

SES has been working to improve some of our rudimentary dryer models including better models of pressure drop through the desiccant dryer and better dryer size estimates. This quarter, SES set up a series of experiments to validate those models and to quantify losses that would be difficult to incorporate. The primary goal of these tests is to improve our accuracy at estimating capitol and energy requirements on larger-scale systems.

One major obstacle in our current desiccant dryer is the regeneration time which in the past has been too long to be sustainable. Our first-generation desiccant dryer was significantly oversized to deal with upsets or changing conditions from source to source. However, there are negative impacts of the additional molecular sieve material. The heat capacity of the mol sieve desiccant is high enough that the sensible heating of the mol sieve is significant, though much smaller than the water heat of adsorption. To mitigate this problem, SES reduced the amount of desiccant in the system by about 20% and changed the flow direction of the flue gas to reduce adsorption/desorption during regeneration. Preliminary tests with this new configuration show promise for mitigating this problem. SES is also increasing the flow rate during regeneration to allow for increased heat input without overheating the desiccant.

In September and October of this year, SES finished incorporating the new gas distributors in the desiccant dryer tanks. SES completed a variety of tests and observed a pressure drop at or below 0.5 psi at 1 tonne/day CO_2 (~100 SCFM). This represents a significant reduction in pressure drop from previous measurements.

Figure 26. Updated dryers installed in the CCC skid.

SES also ran shakedown regeneration tests and tested the dryer on a flue gas stream from the MFR during the tests on real flue gas mentioned in a previous section. We precooled the gas to remove most of the water before it entered the desiccant dryer. The outlet dew point did not significantly change over the course of the test. Additional tests will be completed over the next few months to test the dryers at higher gas flow rates.

Dual Screw Press Solid Separations System

SES has finalized and integrated the dual screw press solid separations system. The simulated and real flue gas tests previously described in this report use this system as the primary solid-liquid separations unit. The exposed dual screw press system is shown in Figure 27.

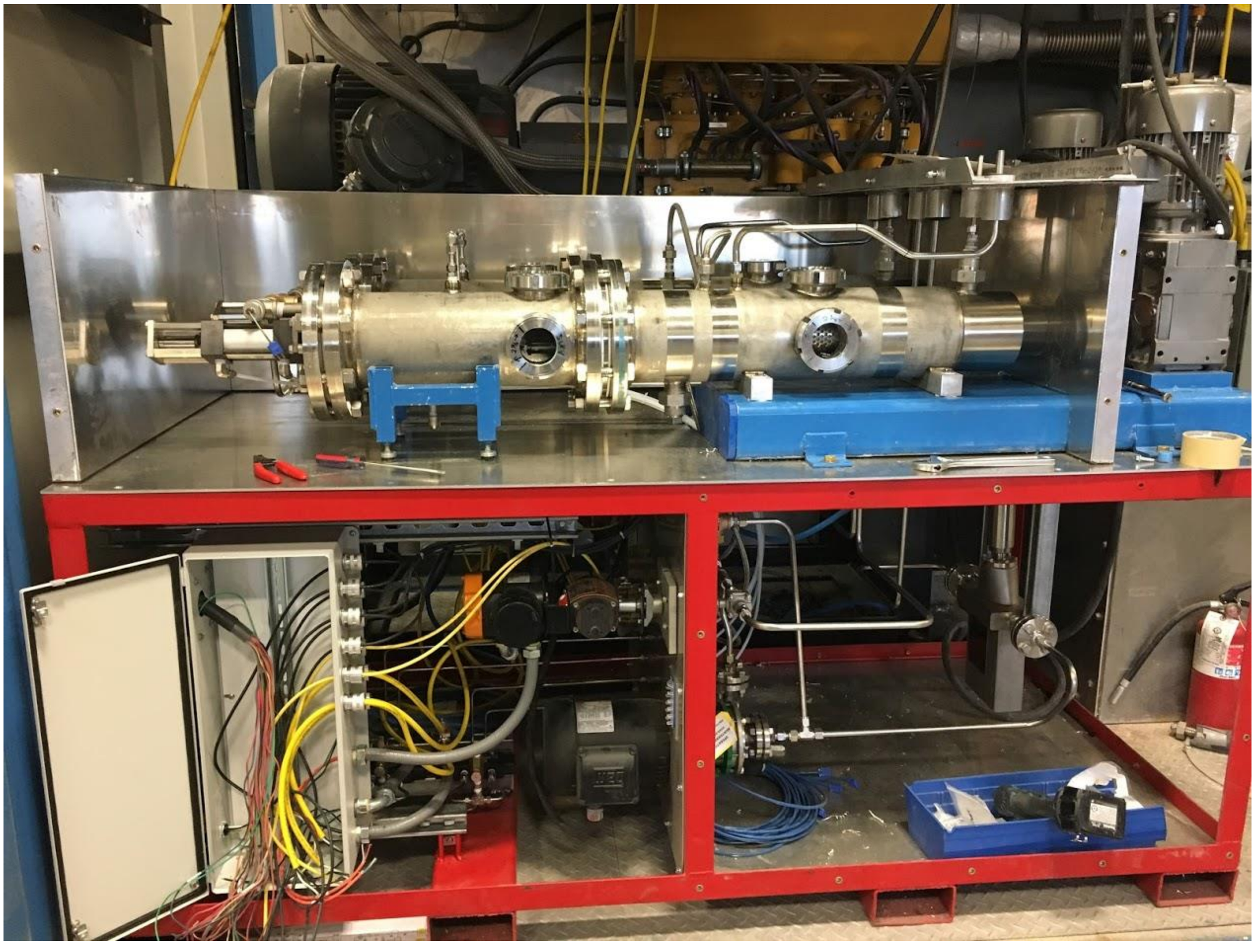


Figure 27. Lower cold box for the dual auger solid liquid separations system.

Testing indicates that the new modifications to the system produce more than double the flow rate of the previous single auger system. This is due in large part to refinements to the filter construction and our melting system. We also now have far better control over the flow rates into each of the screw presses, allowing for fully independent operation.

In total, SES built three separate cold boxes to house the screw presses and accompanying controls and instrumentation. This also allows independent work on each of these systems for more rapid turnaround on future modifications. The final integrated system compared to the original plans is shown in Figure 28.

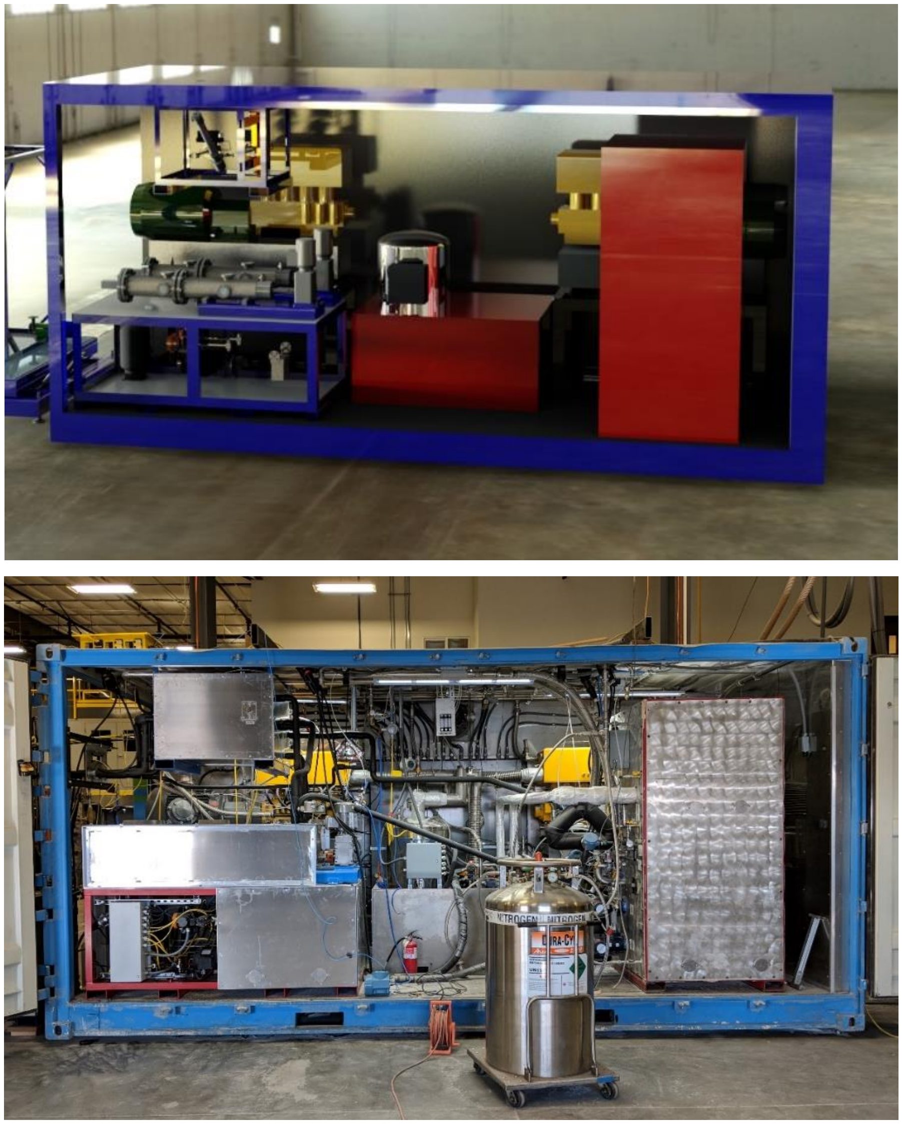


Figure 28. Comparison of the rendering of the cold box units to the final system integrated with the ECL Skid.

QUARTERLY REPORT AND MILESTONE SUBMISSION

December 11, 2017

Submitted by

SUSTAINABLE ENERGY SOLUTIONS

Submitted to

ROCKY MOUNTAIN POWER

Sustainable Transport and Energy Plan (STEP)

Overview

This project modifies specific unit operations in an existing research and demonstration unit (the ECL skid) provided by Sustainable Energy Solutions (SES) to improve process efficiency, reliability, or overall performance. These modifications include experimental systems developed by SES. This first project development phase includes skid preparations for later long-term, on-site testing at an RMP facility. This report details the work done towards the third milestone of this project.

Quarterly Milestones

As indicated in the Scope of Work for this project, the third milestone involves the design and implementation of improved cryogenic flow and output measurement, followed by the testing of an integrated skid system with simulated flue gas at 1/4 tonne CO_2 captured per day, and testing with real flue gas using the in-house multi-fuel reactor. This reactor provided sufficient flow to meet the requirements of the milestone and was used to demonstrate significant progress towards a longer-term test. The exact milestones are described below.

Q3	SES will deliver a report containing the following: - The purchase orders and initial test reports of improved instrumentation such as advanced cryogenic flow measurement and output measurement. - Results of testing for the experimental integrated system with simulated flue gas at minimum 1/4 tonne per day CO_2 - Results of testing of the experimental integrated system tested with real flue gas.	11/15/2017	$ 110,533

In addition, this report contains updates on various unit operations that have previously been reported in quarterly reports, and that have continued to be developed during this quarter. These include the self-cleaning heat exchanger units being developed with our partners at Klaren International, a shell-and-tube self-cleaning heat exchanger, the experimental dual solid–liquid separations system, and the flue gas pre-treatment system.

Advanced Cryogenic Flow Measurement and Output Measurement

Process flow measurement and output stream monitoring represent critical development areas for the CCC process. The CCC system presents unique challenges for these measurements, as we have both cryogenic temperatures and slurries, which can cause fouling or failure of sensitive equipment. SES has overcome these challenges using several cryogenic flow measurements, specifically very low flow cryogenic turbine meters in the non-slurry sections of the system and Coriolis meters in the slurry sections of the system. The performance of these systems is described in turn below.

Cryogenic Turbine Meters

As part of the dual screw press cold box skid, SES installed cryogenic turbine meters that measure the outlet flow rate of each of the screw press systems. These measurements are vital as they enable full liquid control of the dual solid–liquid separations system. The turbine meters in the screw press outlets enable control of the flow and pressure drop across the filter. SES collaborated with Flow Technologies to use cryogenically rated turbine meters using specialized bearings and calibrations. As these were also in direct contact with our contact liquid, isopentane, they were rated for Class 1 Div 1 service. Figure 1 shows the specifications for these meters.

Description
FT4-8NEXBBLEAX5 - FT SERIES TURBINE FT4-8 = 1/2" Turbine Flowmeter, 3.0 GPM, 300°F max. NE = 1/2" NPT External Thread End Fittings XB = 10 Points, Extended Range Calibration in Oil Blend B = Non-Standard Calibration Range & Units L = Liquid Service E = 316 SS Housing / 430F SS Rotor A = 440C SS Ball Bearings X5 = RF PICKOFF, EXPLOSION PROOF CLASS I DIV 1 Calibration in Oil Blend: XBB = 10 Points, 0.2 to 0.6 LPM @ 0.8 cSt For liquid CO2 application
LA-5-C-MA-9 - LINEAR LINK LA = Linear Link Flowmeter Transmitter 5 = 19-32 VDC Power Required C = FTI RF (Carrier) Flow Output Signal MA = 0-5V Pulse Output Signal: Linear with Flow Rate 4-20mA Analog Output Signal: Linear with Flow Rate -9 = Explosion Proof Enclosure: Class 1, Div. 1, Groups A , B, C & D *Scaled one each to one each flow meter

Figure 1. Description and specifications for the FTI Cryogenic Turbine Meters.

During this quarter, we successfully integrated these meters into the CCC test skid system. Figure 2 shows these turbine meters as they are placed at the outlets of the screw presses.

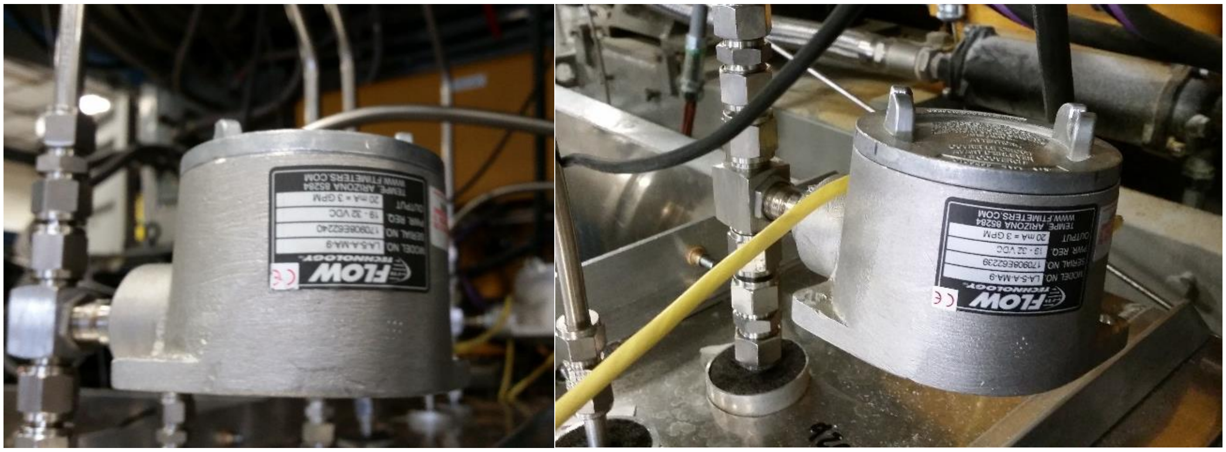


Figure 2. Flow Technology turbine meters installed to measure the outlet flow rate from each of the screw presses.

These meters were tested during the multi-pollutant tests at ¼ tonne CO_2 per day flow rates and using real flue gas. The results of these tests and the outputs of the turbine meters are explained in greater detail in the corresponding sections below.

Coriolis Meter

A Coriolis meter uses the principles of motion mechanics when the process fluid splits and enters the sensor. During operation, a drive coil stimulates the tubes to oscillate in opposition at the natural resonant frequency. As the tubes oscillate, the voltage generated from each pickoff creates a sine wave. This indicates the motion of one tube relative to the other. The time delay between the two sine waves (Delta-t) varies proportional to the mass flow rate. Figure 3 below shows the working principle of these flow meters.

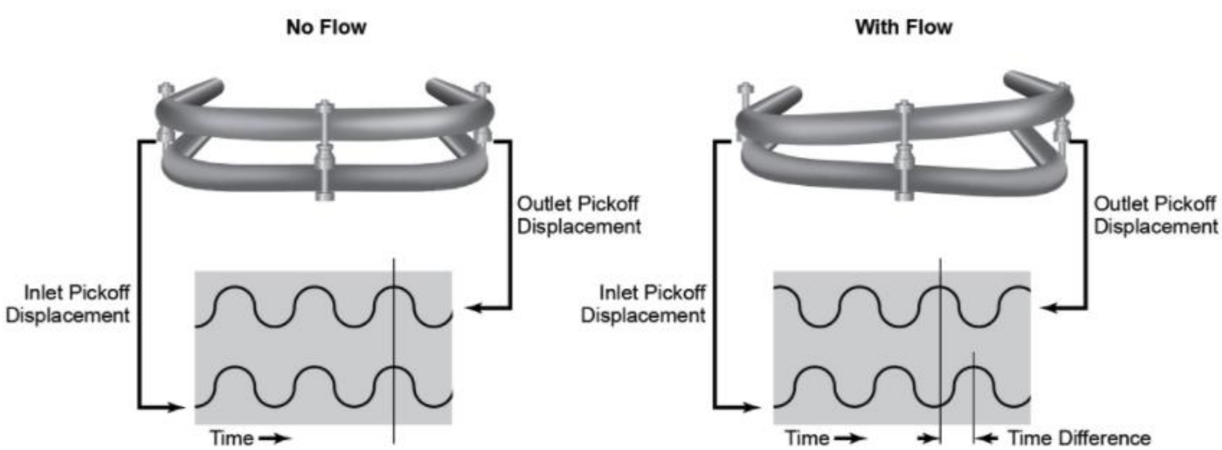


Figure 3. Principle of operation for a Coriolis meter (Courtesy of Emerson Automation Solutions).

One advantage of this type of measurement is that it gives both a direct mass flow measurement and a density measurement due to the fixed volume of the tubes. In many ways, it is more precise than displacement style flow meters such as the turbine meters above. Additionally, as the flow is not impeded by any sensors or equipment, it allows for more complex flows – like slurries – to be measured. One use of these types of meters is to measure the CO_2 slurry concentration in the stream by measuring the density and comparing to known densities of both our contact liquid and solid CO_2.

SES acquired an Emerson Micro Motion Coriolis Meter CMF025. The Micro Motion meters are some of the few that are rated for cryogenic temperatures. Figure 4 shows one of these Coriolis meters before installation, and Figure 5 shows the Coriolis meter in place covered in cryogenic insulation and a water vapor barrier.

Figure 4. Emerson Micro Motion CMF025 Coriolis Meter.

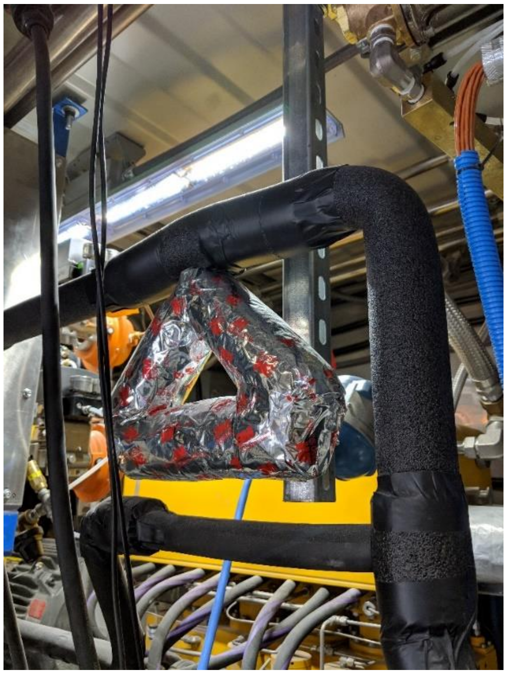


Figure 5. Emerson Coriolis meter installed leading from separations coldbox, covered in insulation.

This meter size generates a velocity that prevents CO_2 settling or sticking to the walls. Previous experiments indicated that a velocity of at least 1.5 meters/second prevents such fouling.

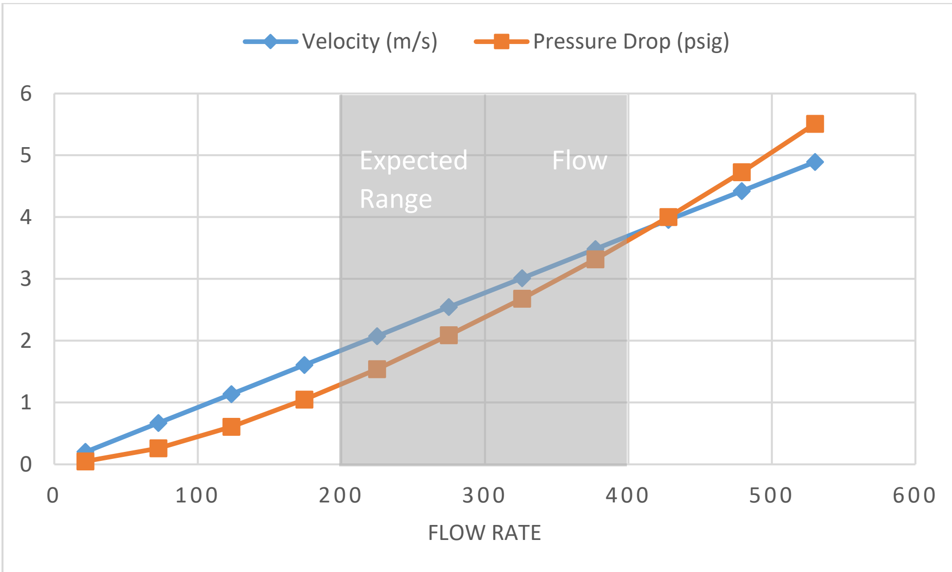


Figure 6. Slurry flow rate compared to the pressure drop and velocity of the slurry.

The Coriolis meter was tested during the multi-pollutant tests at ¼ tonne CO_2 per day flow rates and using real flue gas. This meter validated the outputs of the turbine meters and other Coriolis meters and further tested the required minimum velocities to prevent fouling. The results of these tests and the outputs of the Coriolis meter are explained in greater detail in the corresponding sections below.

Output Measurement and Control

Controlling the outputs of the CCC system and properly measuring them is another prerequisite to long-term testing. The primary output of concern is the flow of liquid CO_2. Isopentane, our primary contact liquid, can contaminate this stream, resulting in excess cost of operating the system due to its loss out the product CO_2 stream. In our current process, we purify this stream using a series of vapor–liquid separators and condensers. This separation occurs near the triple point of the of the CO_2, and so precise controls are required to achieve the appropriate temperatures and pressures. Figure 7 shows an updated P&ID of the separations system used by SES for the removal of solid CO_2 from the slurry streams and purifying it to a liquid CO_2 stream. The highlighted yellow box represents the new addition to this system, a vapor–liquid separations system.

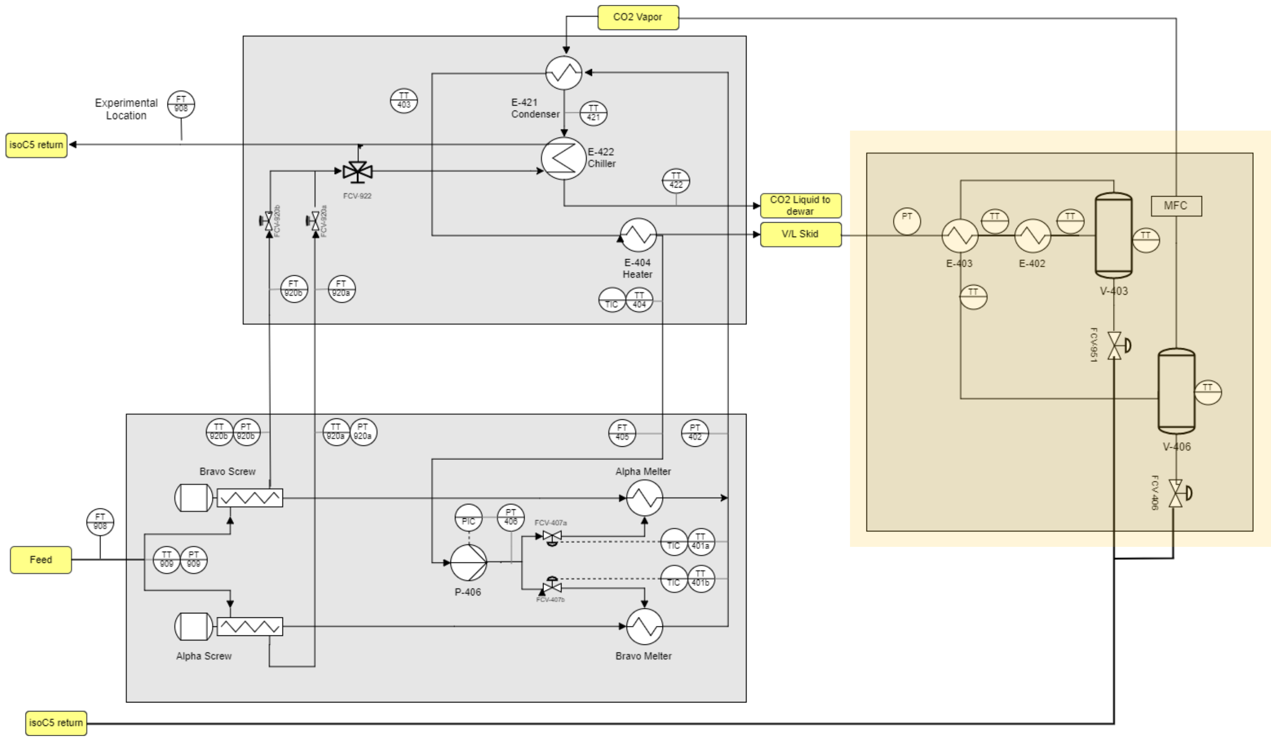


Figure 7. Separations system with added outlet measurement and controls (highlighted in yellow).

This new unit operation consists of two main vapor–liquid separators and two heat exchange units for controlling the temperatures into each system. Once the CO_2 has been separated from a majority of the isopentane in V-403, it is chilled in E-403 and further purified in V-406. The flow of vapor CO_2 is then measured in a Mass Flow Controller before being condensed into liquid CO_2 by being put through the E-421 Condenser and 4-422 Chiller, located in a separate coldbox. A key challenge is to ensure that the entire stream is condensed into liquid, and therefore precise temperature measurements are taken using TT-421 and TT-422, and pressure is measured and controlled throughout the vapor–liquid separations unit.

Simulated Flue Gas Testing at 1/4 Tonne per Day

SES demonstrated the skid-scale system at 0.25 tonne/day for 12 hours. We used a mixture of gases from CO_2 and LN2 Dewars to simulate a flue gas at an average composition of 10.4 mol% CO_2, added SO_2, CO, and NO pollutants using compressed air cylinders, with the balance N_2 (Figure 8) at an average flow rate of 42.1 SCFM (Figure 9). This test was performed using a closed-loop gas recycle that allows for continuous testing of the system without unnecessary expense when using gas Dewars to create the simulated flue gas. One key aspect of this particular test is that it included pollutants at levels that could reasonably be expected at the Hunter power plant. Table 1 gives a summary of overall run results.

Table 1. Results from the closed-loop test using simulated flue gas capturing ¼ tonne CO_2/day [1]

	Units	RMP 250 kg/Day Test
Start Date	–	25 Oct 2017
Start Time	–	4:28 pm
Stop Date	–	26 Oct 2017
Stop Time	–	4:42 am
Total Run Time	hr	12.2
Total CO_2 Captured	kg	170
Avg. CO_2 Capture Efficiency	%	96.1
Avg. CO_2 Capture Rate	kg/day	13.9
Avg. Flue Gas Flow Rate	SCFM	42.1
Avg. Flue Gas CO_2 Content	mol%	10.4
Avg. CO_2 Purity	%	99.4
Avg. Pressure Drop	psig	1.81
Avg. Coriolis Slurry Density	kg/L	0.791
Avg. Small Coriolis Slurry Density	kg/L	0.92
Avg. Melter Mass Fraction	%	77.0
Avg. Alpha Auger Flow Rate	kg/hr	79.1
Avg. Bravo Auger Flow Rate	kg/hr	79.0

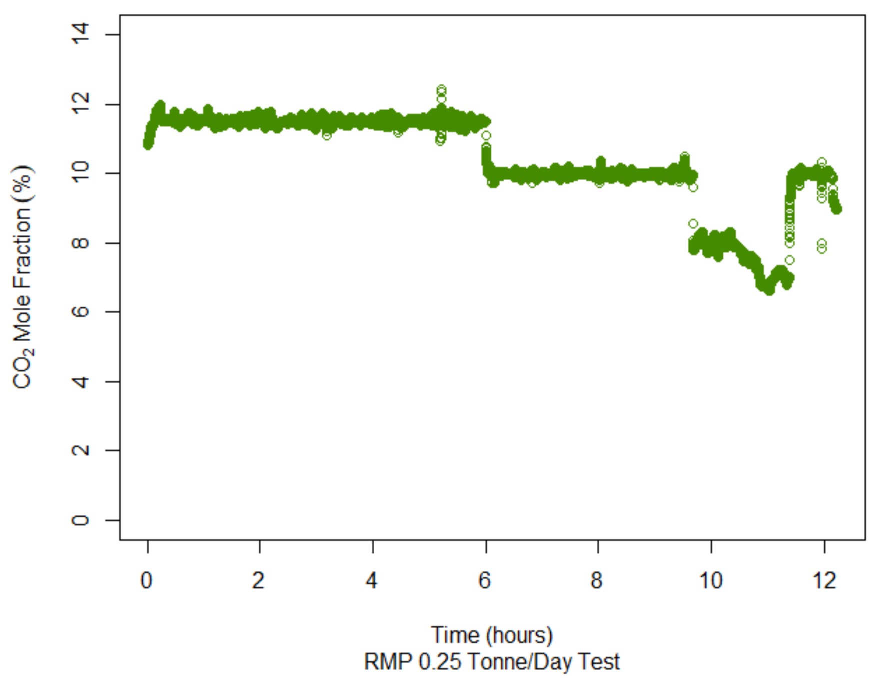


Figure 8. Inlet simulated flue gas CO_2 mole fraction for ¼ tonne CO_2/day closed-loop test [1].

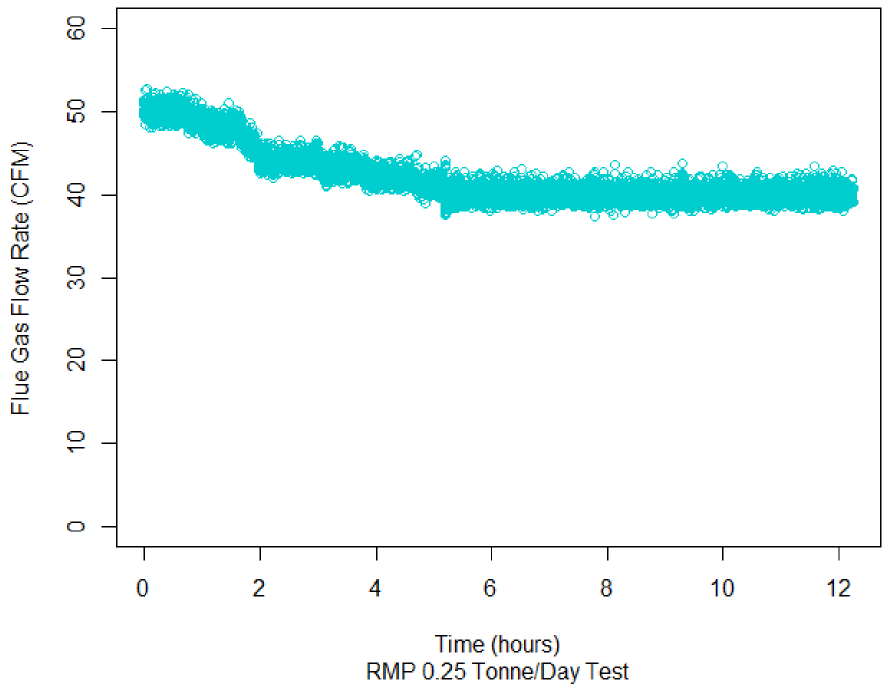


Figure 9. Flue gas flow rate [1].

The SO_2 inlet concentration, as seen in Figure 10, is higher than what is expected at the power plant, averaging 30.43 ppm. In fact, it is high enough to verify that CCC could reasonably come before the plant's flue gas desulfurization unit. Since we only have one FTIR unit, it was primarily used to measure the inlet gas composition. The outlet gas composition was measured at various times throughout the run, but was still run long enough to establish a good average outlet composition of 3.55 ppm, for a capture efficiency of 88.3% (see Figure 11). This test also established that the CCC system at these temperatures and pressures does not capture NO nor CO, as the inlet and outlet compositions were statistically similar (Figure 12).

This test verified that the CCC system, unlike many absorption systems, is very robust to the presence of SO_x, NO_x, and other pollutants, including CO. The system ran and captured CO_2 in the exact same way that it runs without any of these pollutants present. While this has been tested at smaller scales of the CCC system in the past, this is the first significant test at this scale, at these pollutant levels, and for this long of a testing period. This gives us additional confidence as we move toward our future testing milestones.

Over the course of the test, we captured 170 kg of CO_2 at a rate of 0.336 tonne CO_2/day (Figure 13), a CO_2 capture rate of 96.1%. The capture rate remained high over the course of the test (Figure 14).

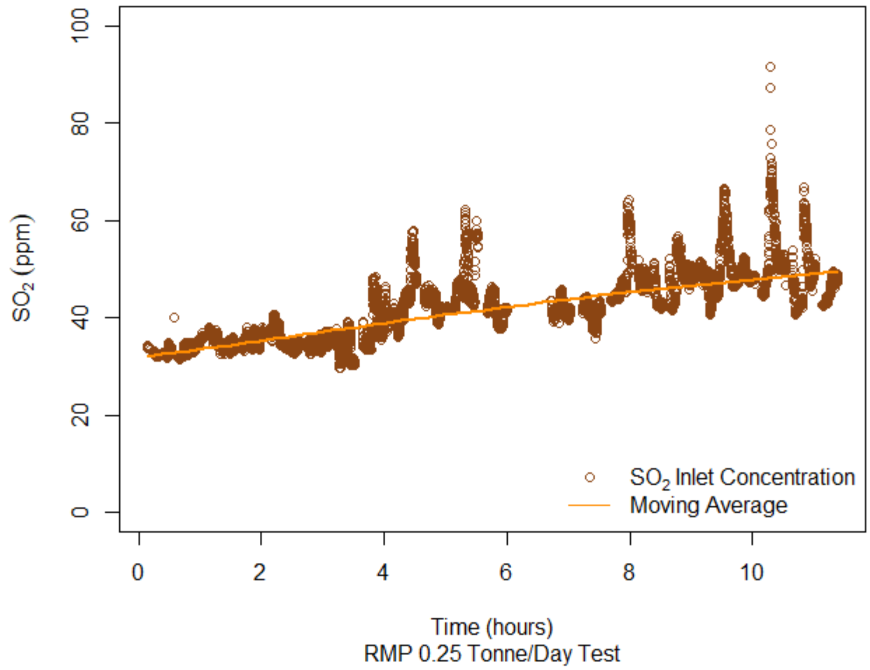


Figure 10. Inlet SO_2 concentration [1]

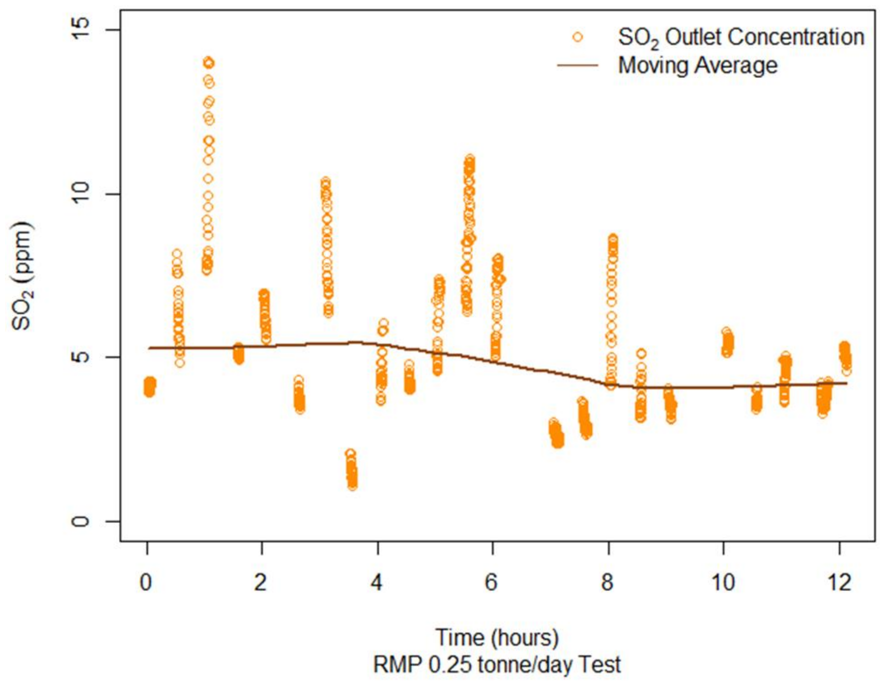


Figure 11. SO_2 outlet concentrations measured using FTIR [1].

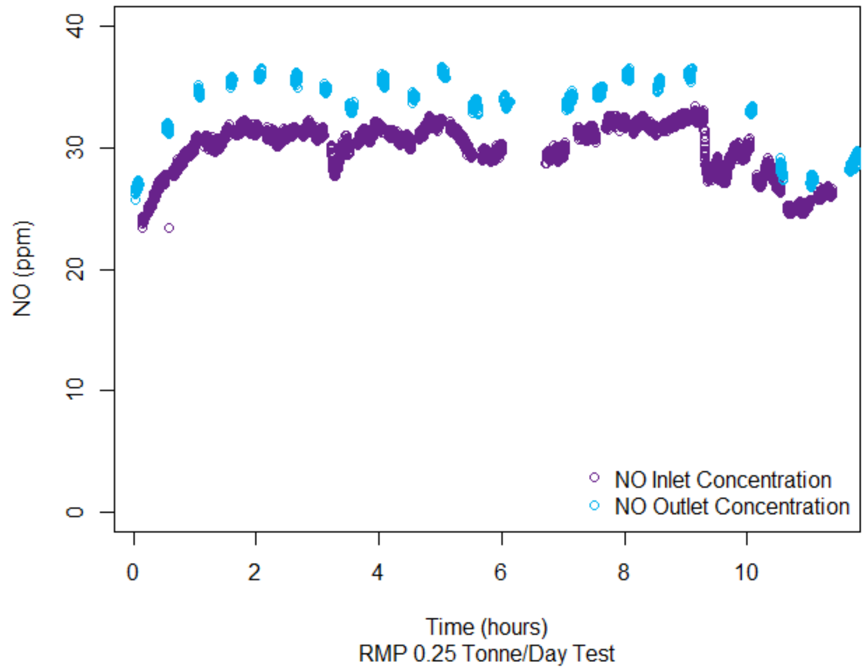


Figure 12. Inlet and outlet concentrations of NO. While it appears that the outlet concentration is higher than the inlet concentration, all of these measurements are within the measurement error of the FTIR [1].

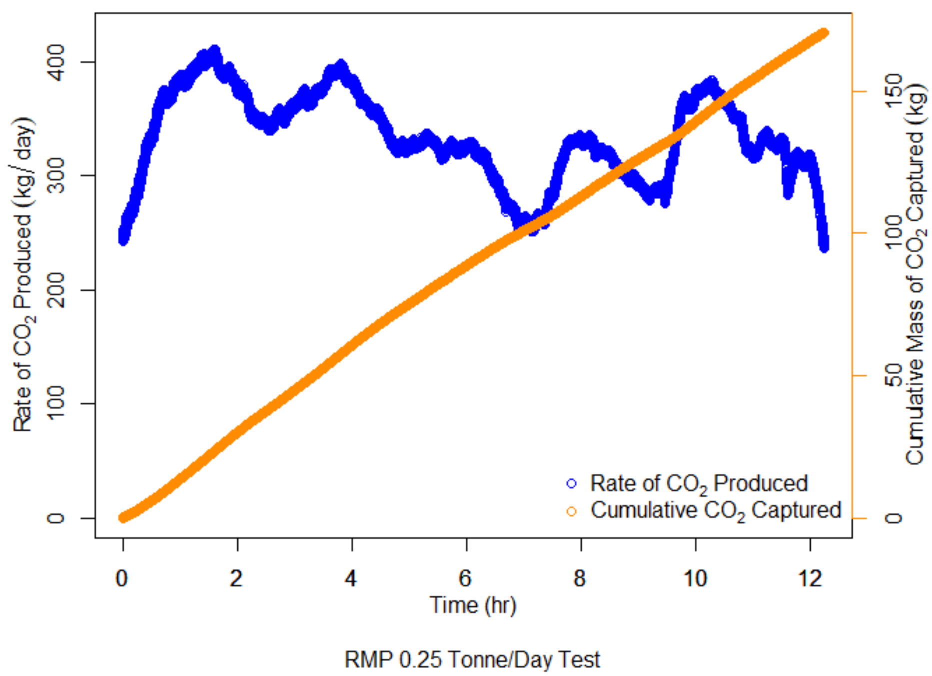


Figure 13. Cumulative CO_2 capture and CO_2 production rate over the course of the closed-loop ¼ tonne CO_2/day test [1].

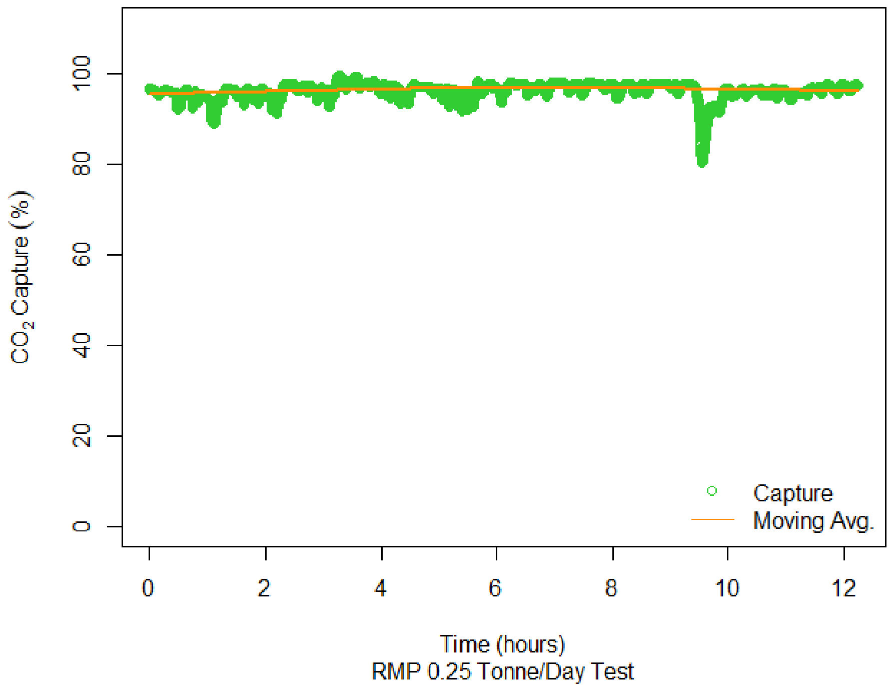


Figure 14. CO_2 capture over the course of the closed-loop ¼ tonne CO_2/day test [1].

Using an FTIR spectrometer, we measured the inlet, outlet, and CO_2 stream compositions. Of particular interest is the purity of the CO_2 stream exiting the process. We achieved an average CO_2 purity of 99.4% during this test. This greatly exceeds the CO_2 pipeline quality requirement (i.e., 95% purity), which CO_2 is used for enhanced oil recovery. This CO_2 stream only contained an average 166 ppm of SO_2. However, the concentration of SO_2 in the CO_2 outlet stream did not reach a steady-state value when the test was concluded. Additional testing will determine if the steady-state value matches predictions and to determine the best method moving forward for cleaning the SO_2 out of the outlet streams. This can also be seen in the apparent melter CO_2 mass fraction. The SO_2 accumulates in the CO_2 liquid and builds over time. As explained above, the CO_2 mass fraction in the melter is calculated via a density measurement that assumes the only components are CO_2 and isopentane. Adding a third component, such as SO_2, that has a higher liquid density than CO_2 causes an increase in the calculated CO_2 mass fraction. It appears that from hours 2 through 8 of the run that the fraction of CO_2 in the melter is increasing (Figure 15). However, this might also be due to accumulation of SO_2. Further testing will allow SES to better understand where the pollutants accumulate and how to remove them from the system.

This test also allowed us to use some of the new instrumentation that had been installed into the skid, such as the cryogenic turbine meters. The turbine meters allow us to measure the flow independently on each screw press so that they are easier to control and monitor. The outputs from the test can be seen in Figure 16. Both screw presses were kept at a very similar flow rate throughout the run, which represents an improvement in operations compared to the past.

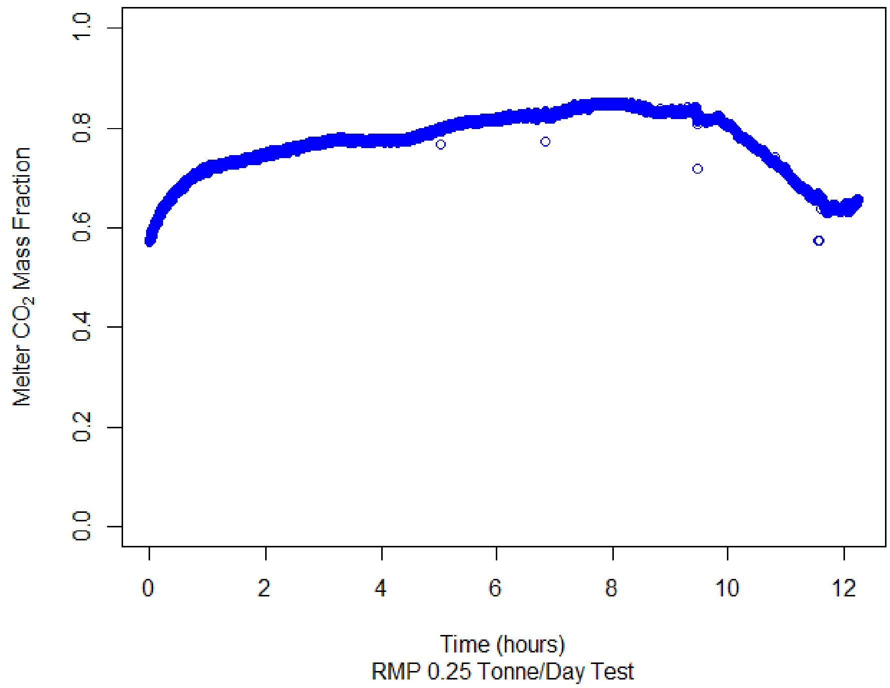


Figure 15. Calculated CO_2 mass fraction in the melter unit [1].

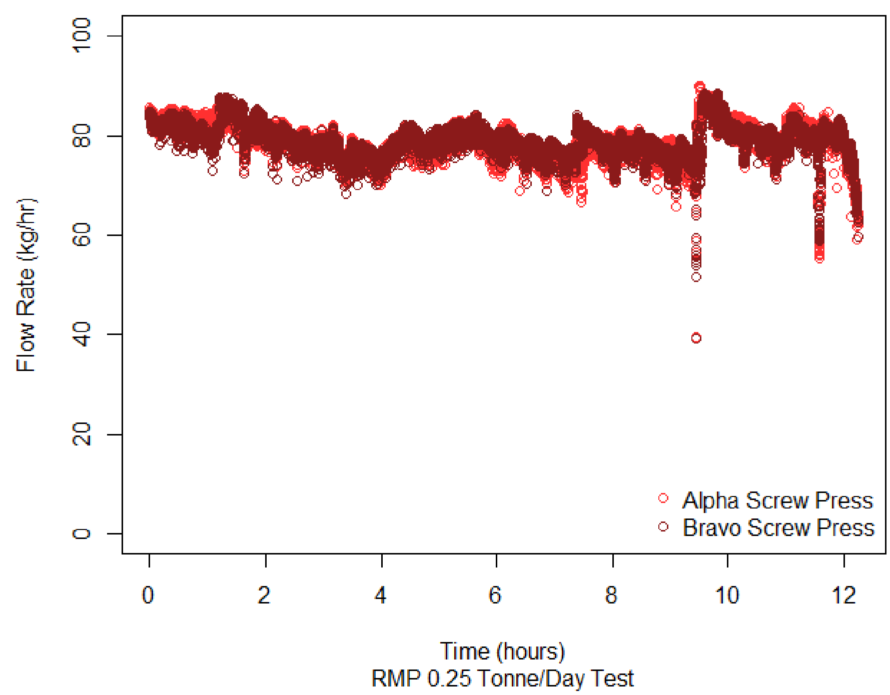


Figure 16. Flow measurement from the cryogenic turbine meters

Real Flue Gas Testing

SES has a multi-fuel reactor (MFR) onsite that allows us to combust a variety of fuels to produce our own flue gas. Most aspects of the new system design could be tested in a closed-loop flue gas circuit. However, some unit ops, including the dryer and other pretreatment equipment, require an open-loop test with real flue gas for us to be fully confident in their efficacy.

We ran the MFR at full capacity with natural gas as the fuel, which resulted in a CO_2 flow rate of approximately 200 kg/day. The entire flue gas stream was plumbed into the CCC skid and processed during the test. The average capture during the test was 95.9%, and the average composition of CO_2 in the inlet was approximately 8%. All unit ops performed as expected, and we had a successful controlled shutdown at the end of the run. This test included the dryer unit; the dew point of the gas was low enough that fouling in the gas recuperator was no different than in any runs that did not include water in the inlet gas. Additionally, all new instrumentation, including the cryogenic turbine meters and the new Coriolis flow meter, were installed and took data throughout the run. Table 2 gives a summary of the overall run results.

Table 2. Real flue gas test results summary

	Units	MFR Flue Gas
Start Date	–	7 Dec 2017
Start Time	–	8:28 am
Stop Date	–	7 Dec 2017
Stop Time	–	5:42 pm
Total Run Time	hr	9.26
Total CO_2 Captured	kg	37.3
Avg. Capture Efficiency	%	95.9
Avg. Capture Rate	kg/hr	4.03
Avg. Flue Gas Flow Rate	SCFM	29.7
Avg. Pressure Drop	psig	2.79
Avg. Coriolis Slurry Density	kg/L	0.768
Avg. Small Coriolis Slurry Density	kg/L	0.721
Avg. Melter Mass Fraction	%	52.8
Avg. Alpha Auger Flow Rate	kg/hr	83.6
Avg. Bravo Auger Flow Rate	kg/hr	79.8

During the test, there were two short periods of approximately 50 minutes total when the air compressor for the combustion air for the MFR overheated and shut down. During this time, the skid was kept in stasis and was unable to capture any CO_2 until the air supply problem had been fixed. Due to this MFR outage, there are two gaps in the data plots that correspond to these two outages. A plot of CO_2 capture over time is included in Figure 17.

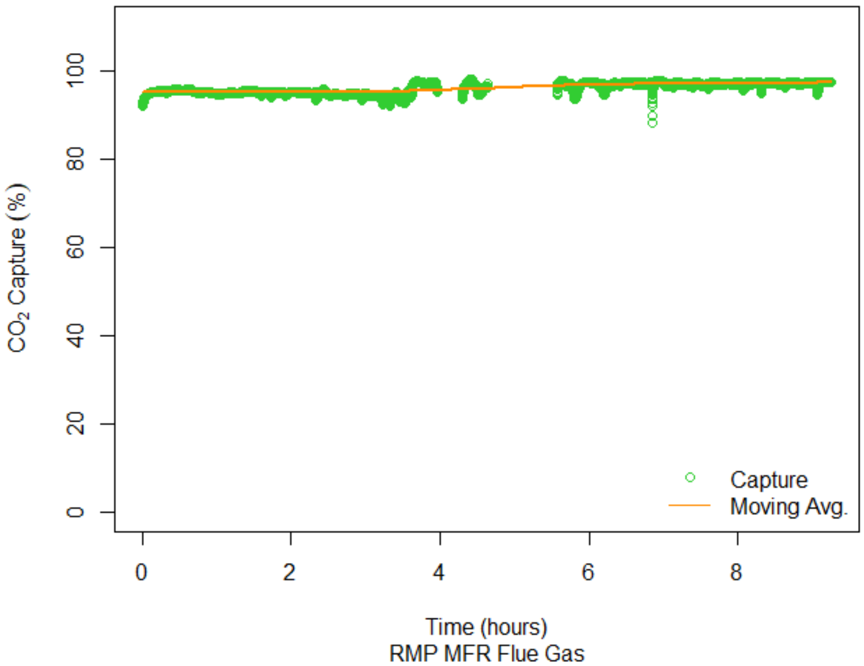


Figure 17. Capture data from the real flue gas test [1]

The test also allowed us to test our new integrated heat exchange system designed for CO_2 liquefaction. Although there were some controls issues that resulted in the formation of some solid CO_2, SES was able to successfully condense approximately 80% of the CO_2 on a mass basis throughout the majority of the run. Instantaneous and cumulative CO_2 rejection from the test are included in Figure 18.

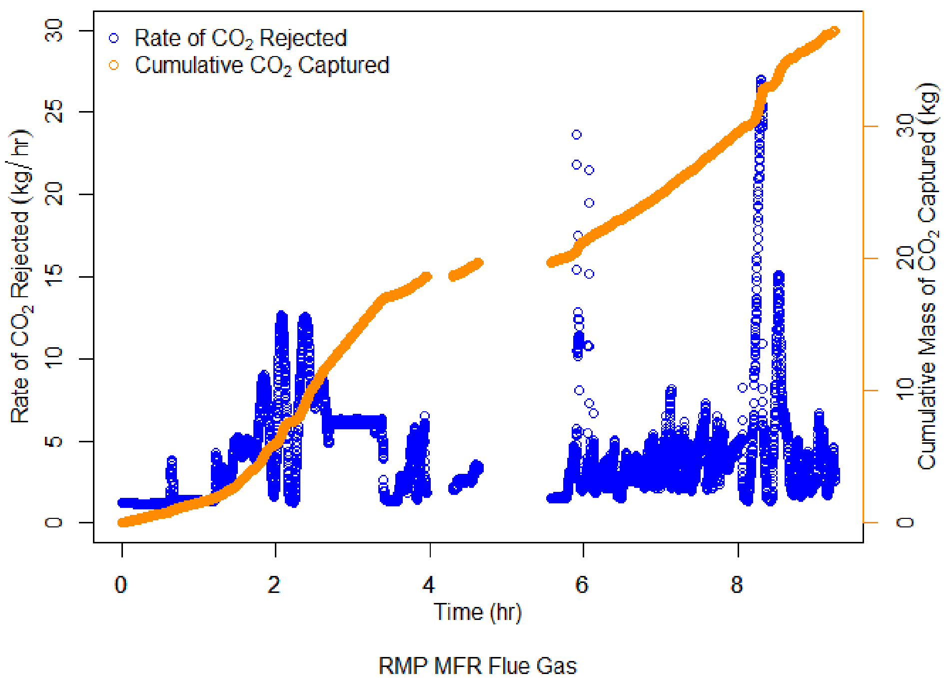


Figure 18. Instantaneous CO_2 rejection and cumulative CO_2 captured [1]

One other result of special import is the total system pressure drop of this test. The molecular sieve dryer unit previously resulted in significant enough pressure drop that it limited the total flow rate that the skid was capable of processing. At similar flow rates, a closed-loop run of the system that bypasses the dryer units results in a total system pressure drop of 2.11 psi. The pressure drop including the dryers was 2.79 psi, an increase of only 0.68 psi. This is a significant improvement compared with previous results. The system pressure drop throughout the course of the run can be seen in Figure 19.

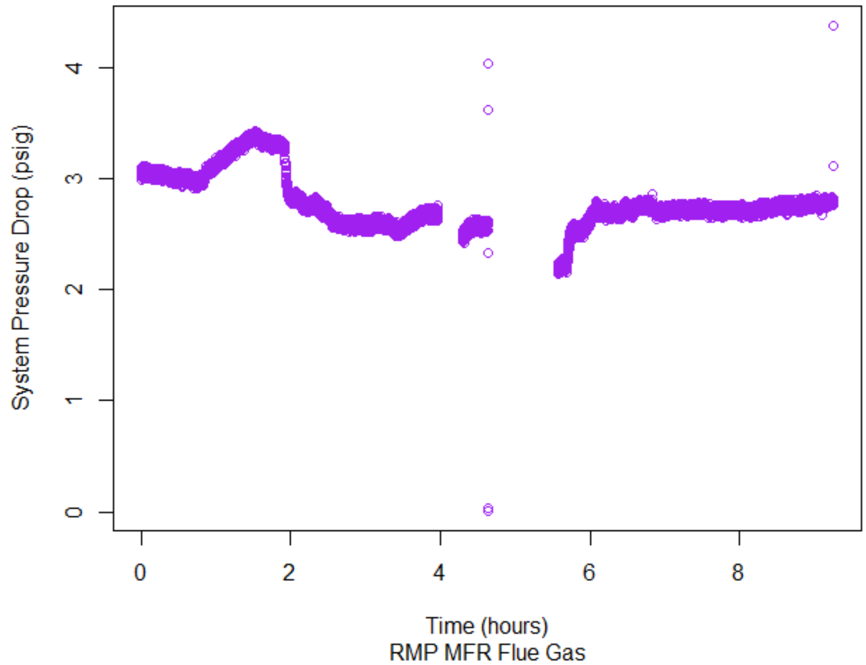


Figure 19. System pressure drop [1]

In terms of instrumentation, both cryogenic turbine meters used to measure the flow and the new small Coriolis meter were used during the run. SES completed all the instrument shakedowns during testing and received valuable data, as shown in Figure 20 and Figure 21. Figure 21 compares the density readings of our previously installed Coriolis meter with the new small Coriolis meter. The slight difference can be explained by the difference in process conditions at the two locations. The larger Coriolis meter is in a stream location that includes solid CO_2 and is at a colder temperature, leading to a higher density, whereas the small Coriolis meter is at warmer temperatures and the stream has been filtered to remove all solids, further decreasing the density reading.

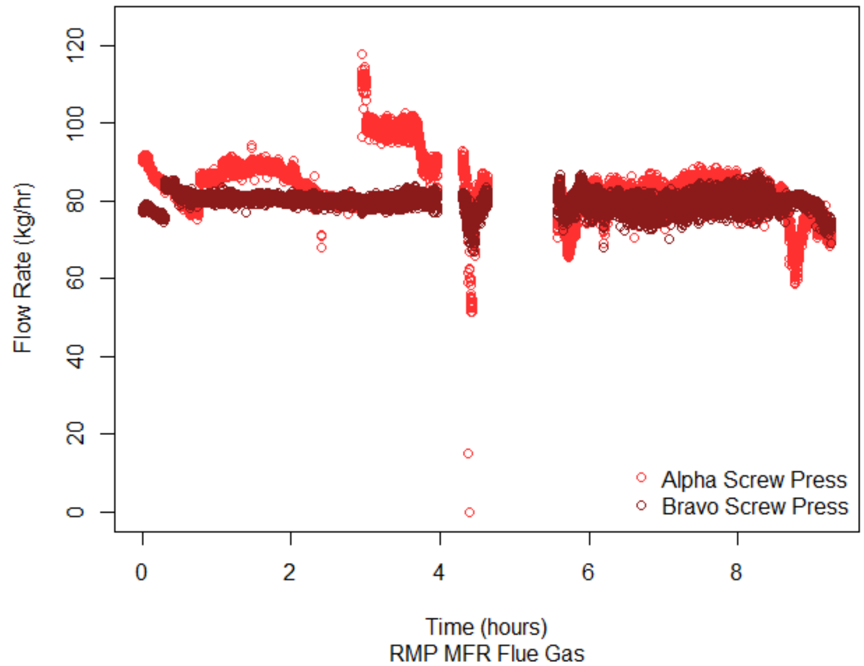


Figure 20. Cryogenic turbine meter flow data [1]

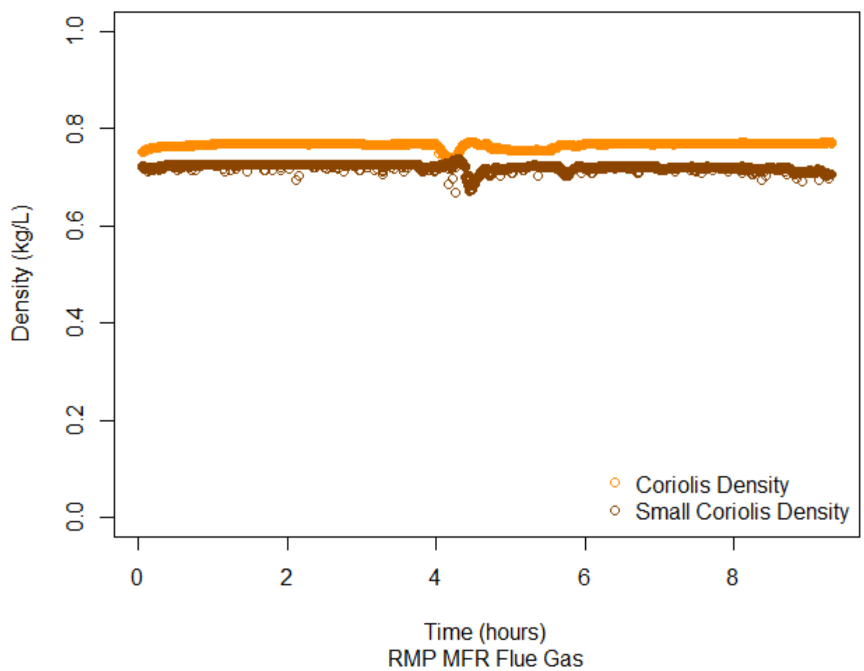


Figure 21. Comparison of Coriolis meter density data [1]

The test was a successful demonstration of every new piece of equipment and instrumentation integrated into the system. The dryer decreased the dew point low enough to allow the rest of the process to function and did so at a very low pressure drop. The new instrumentation allowed for much tighter control of the process, especially concerning the solid–liquid screw press separation units. The capture was effective and remained high the entire run, and the new CO_2 liquefaction equipment liquefied a significant portion of the outlet CO_2. There is still work to be done, including better control of the liquefaction system, but this test demonstrated good progress.

Self-Cleaning Heat Exchangers

SES has continued work towards self-cleaning heat exchangers, which will be used to prevent fouling in the various process heat exchangers over time. This section describes these continued efforts towards a traditional cleaning system for a shell-and-tube heat exchanger, and a self-cleaning fluidized bed heat exchanger being developed in partnership with Klaren International.

Self-Cleaning Shell-and-Tube Heat Exchanger

During the previous quarter, the in-house custom shell-and-tube heat exchanger was constructed here at SES, and communication has continued with the vendor who will provide the self-cleaning materials, WSA Engineered Systems. Figure 22 shows the current state of shell-and-tube heat exchanger mid-assembly. The structure and frame of this system have now been completed and SES is finalizing connections to the rest of the system.

Figure 22. The integrated shell-and-tube heat exchanger.

Self-Cleaning Fluidized Bed Heat Exchanger

During this quarter, SES worked with Klaren International to construct and ship the fluidized bed heat exchanger. This heat exchanger continuously cleans itself using small particles that scour the heat exchange surface. The unit uses a single tube, and provides a proof of concept for the CCC process. This single-tube heat exchanger also scales modularly to higher flow rates. A finalized P&ID of this heat exchanger and how it will be integrated with the equipment at SES is shown in Figure 23.

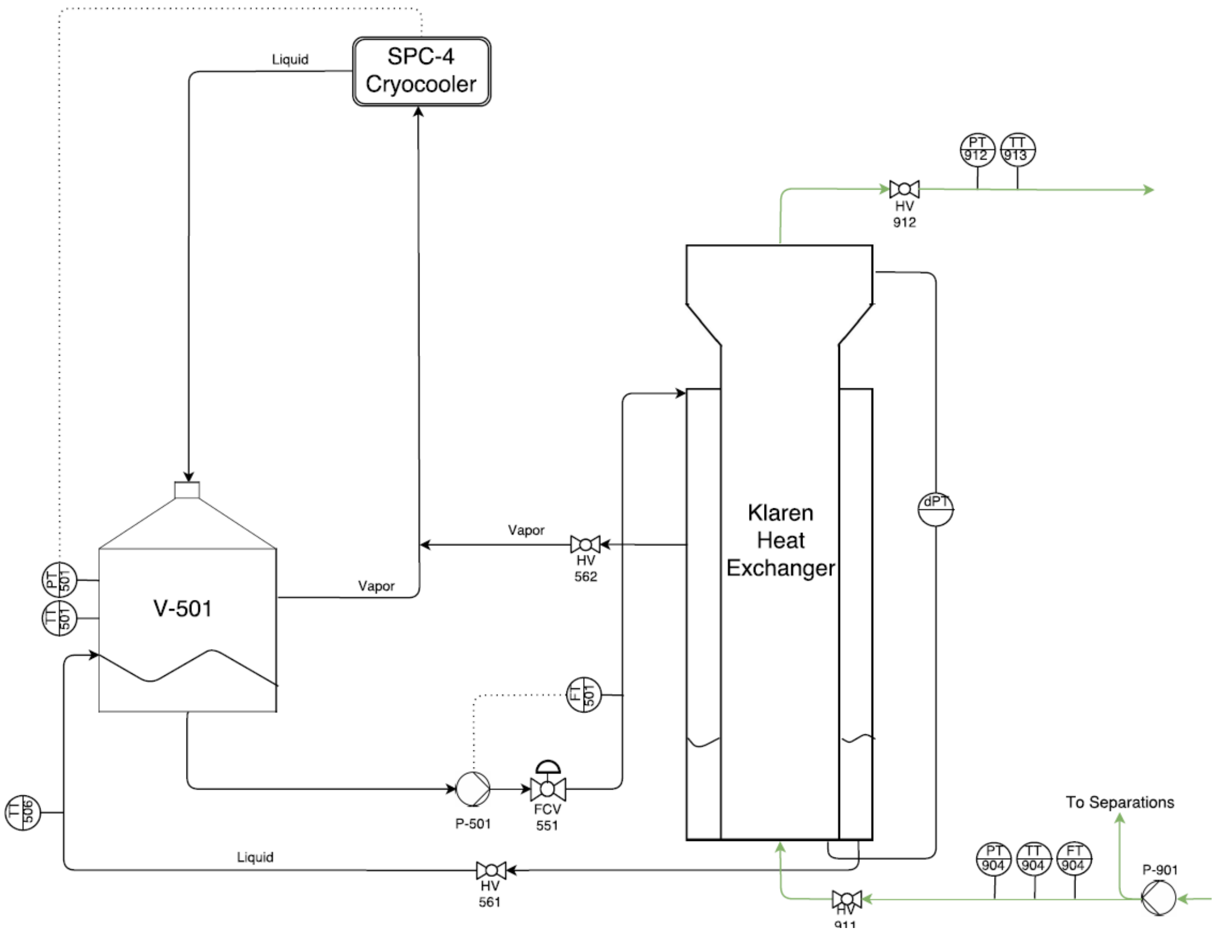


Figure 23. Finalized P&ID of the self-cleaning heat exchanger integrated with SES equipment

SES continued working with Klaren as they built the heat exchanger, and minor modifications were made, which are reflected in the finalized construction drawings in Figure 24. Of particular note is the moving of some of the ports for the sight glass and the instrumentation ports so that it will integrate better with our system, as well as a refinement of the how the internal tubing structure will be supported.

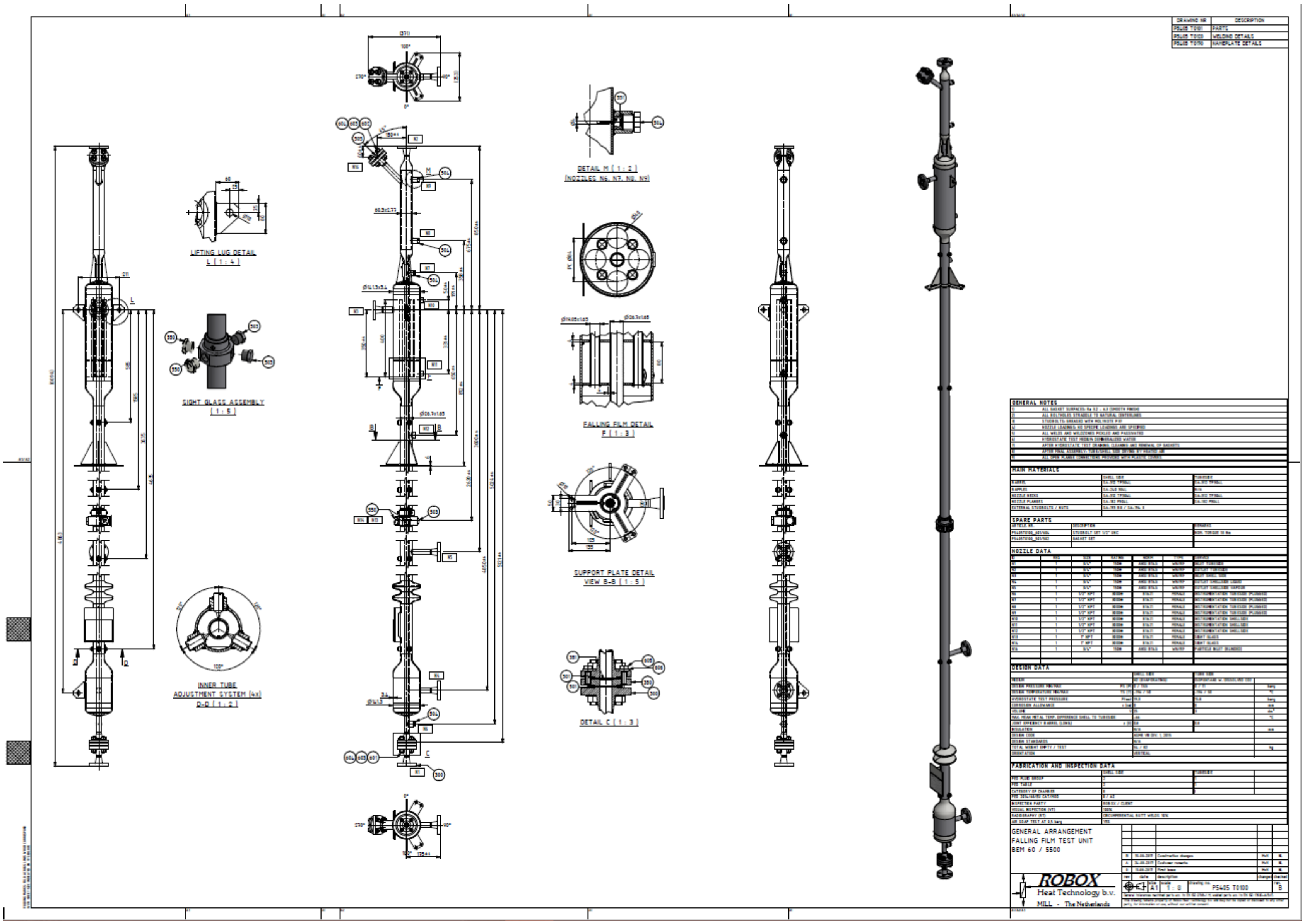


Figure 24. Finalized drawing of the self-cleaning heat exchanger made by Klaren International.

SES has now received the heat exchanger at our headquarters in Orem and work is continuing on the structure required to support and insulate the equipment. The heat exchanger and some of the supporting valves and tubing are shown in Figure 25.

Figure 25. The heat exchanger and additional equipment from Klaren International.

Flue Gas Pre-Treatment

SES has been working to improve some of our rudimentary dryer models including better models of pressure drop through the desiccant dryer and better dryer size estimates. This quarter, SES set up a series of experiments to validate those models and to quantify losses that would be difficult to incorporate. The primary goal of these tests is to improve our accuracy at estimating capitol and energy requirements on larger-scale systems.

One major obstacle in our current desiccant dryer is the regeneration time which in the past has been too long to be sustainable. Our first-generation desiccant dryer was significantly oversized to deal with upsets or changing conditions from source to source. However, there are negative impacts of the additional molecular sieve material. The heat capacity of the mol sieve desiccant is high enough that the sensible heating of the mol sieve is significant, though much smaller than the water heat of adsorption. To mitigate this problem, SES reduced the amount of desiccant in the system by about 20% and changed the flow direction of the flue gas to reduce adsorption/desorption during regeneration. Preliminary tests with this new configuration show promise for mitigating this problem. SES is also increasing the flow rate during regeneration to allow for increased heat input without overheating the desiccant.

In September and October of this year, SES finished incorporating the new gas distributors in the desiccant dryer tanks. SES completed a variety of tests and observed a pressure drop at or below 0.5 psi at 1 tonne/day CO_2 (~100 SCFM). This represents a significant reduction in pressure drop from previous measurements.

Figure 26. Updated dryers installed in the CCC skid.

SES also ran shakedown regeneration tests and tested the dryer on a flue gas stream from the MFR during the tests on real flue gas mentioned in a previous section. We precooled the gas to remove most of the water before it entered the desiccant dryer. The outlet dew point did not significantly change over the course of the test. Additional tests will be completed over the next few months to test the dryers at higher gas flow rates.

Dual Screw Press Solid Separations System

SES has finalized and integrated the dual screw press solid separations system. The simulated and real flue gas tests previously described in this report use this system as the primary solid-liquid separations unit. The exposed dual screw press system is shown in Figure 27.

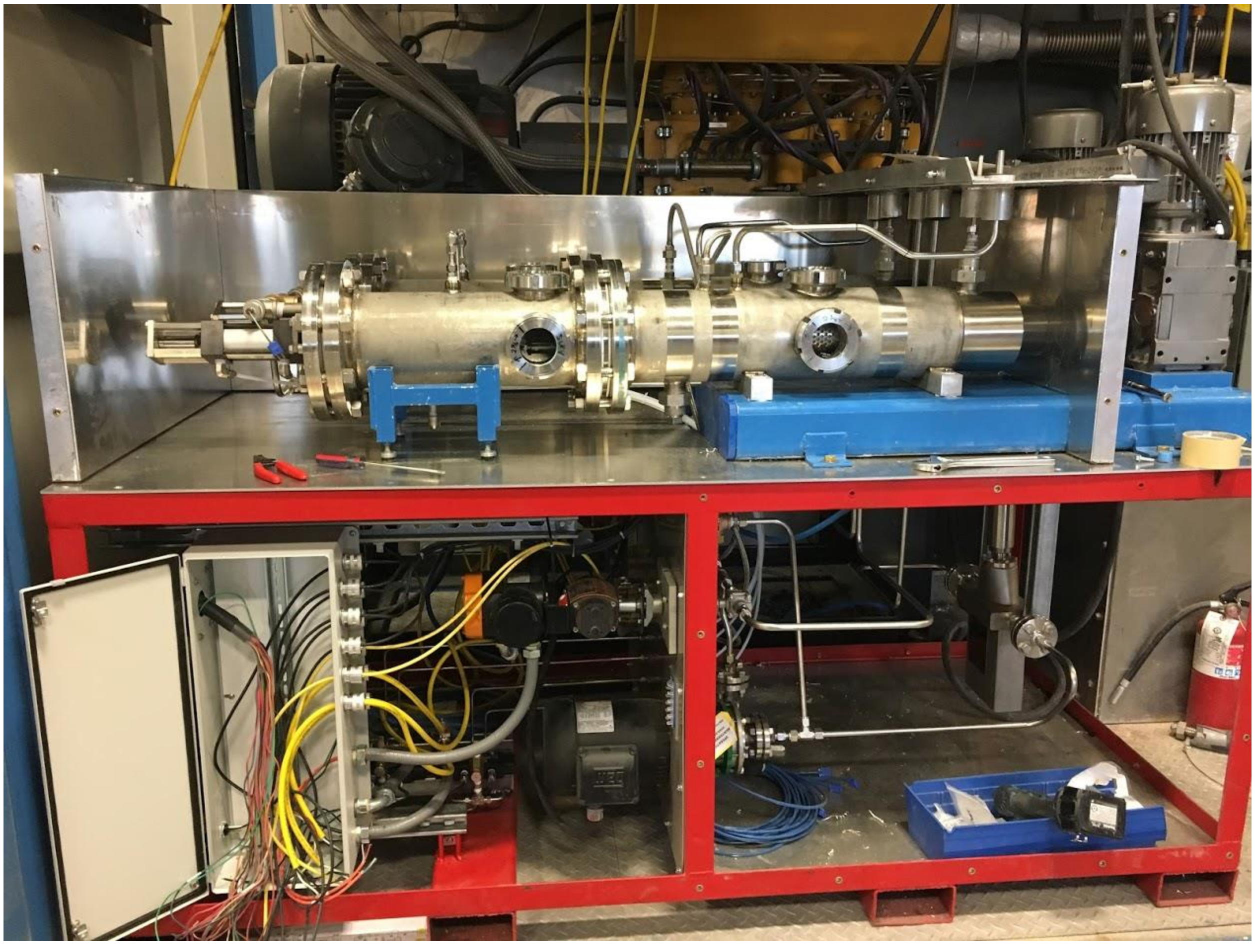


Figure 27. Lower cold box for the dual auger solid liquid separations system.

Testing indicates that the new modifications to the system produce more than double the flow rate of the previous single auger system. This is due in large part to refinements to the filter construction and our melting system. We also now have far better control over the flow rates into each of the screw presses, allowing for fully independent operation.

In total, SES built three separate cold boxes to house the screw presses and accompanying controls and instrumentation. This also allows independent work on each of these systems for more rapid turnaround on future modifications. The final integrated system compared to the original plans is shown in Figure 28.

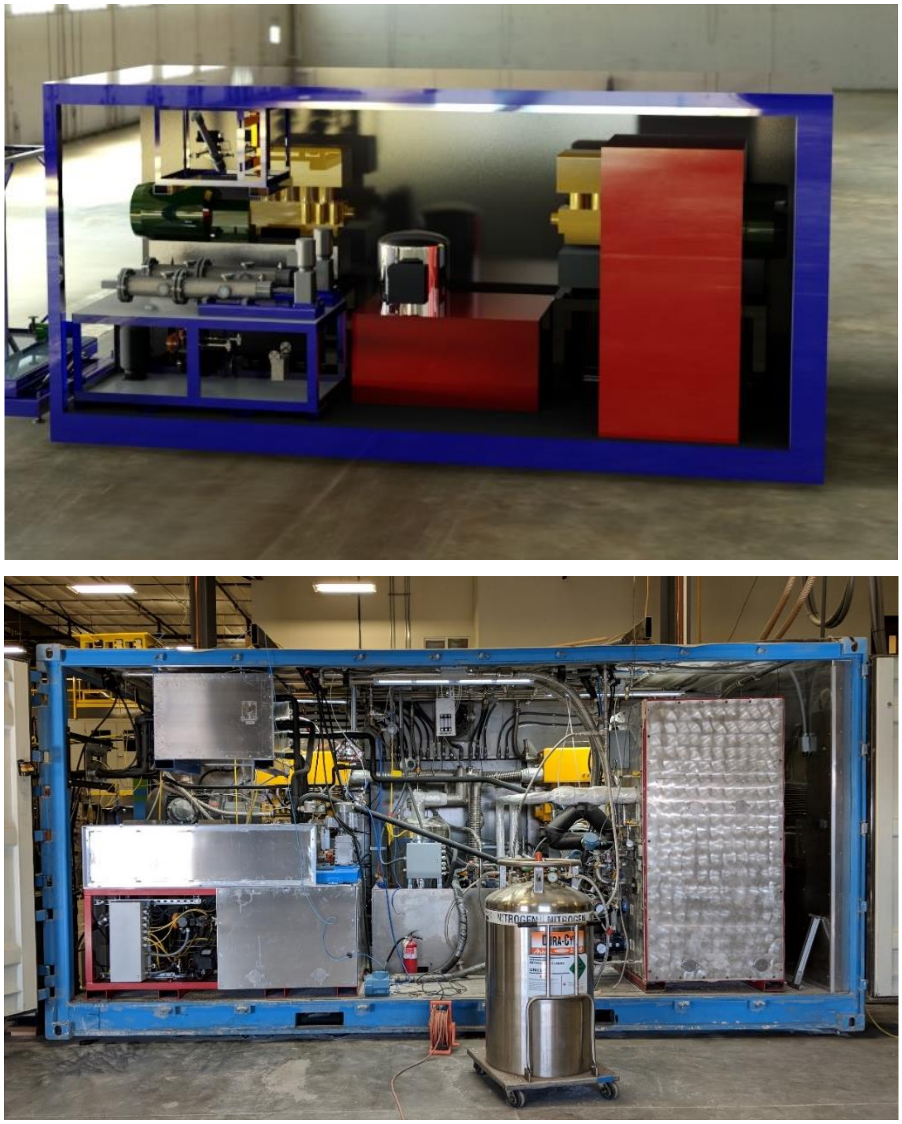


Figure 28. Comparison of the rendering of the cold box units to the final system integrated with the ECL Skid.

QUARTERLY REPORT AND MILESTONE SUBMISSION

February 15, 2018

Submitted by

SUSTAINABLE ENERGY SOLUTIONS

Submitted to

ROCKY MOUNTAIN POWER

Sustainable Transport and Energy Plan (STEP)

Overview

This project modifies specific unit operations in an existing research and demonstration unit (the ECL skid) provided by Sustainable Energy Solutions (SES) to improve process efficiency, reliability, or overall performance. These modifications include experimental systems developed by SES. This first project development phase includes skid preparations for later long-term, on-site testing at an RMP facility. This report details the work done towards the third milestone of this project.

Quarterly Milestones

As indicated in the Scope of Work for this project, the fourth milestone involves the design and documentation of more permanent skid scale unit operations. This includes the final designs and integration of the Klaren system, the shell-and-tube heat exchanger and its newly revised cleaning system, the refrigerant pumping system developed to feed these systems, the dryer and pretreatment system, and updates to the separations systems. The exact wording of the milestone is given below.

Q4	SES will deliver a report containing the following: - Designs and documentation of parts ordered for permanent skid-scale unit ops, including HX's, dryers, separations.	2/15/2018	$100,783

During this quarter, we also conducted higher flowrate testing with real flue gas at an external site. This testing was conducted over the course of two weeks at the Argos cement plant in Calera, Alabama. This represents a continued effort to increase the overall flow rate of the system in preparation for the upcoming testing, as well as to better understand the operation and improve the stability of individual unit operations.

Additional Testing with Real Flue Gas

SES completed tests using our in-house multi-fuel reactor (MFR), as described in previous reports. These experiments tested some aspects of the process that require open-loop operation, specifically the dryer and some pre-treatment equipment. The MFR produces a maximum CO_2 flowrate of approximately 200 kg/day when fired with natural gas.

This quarter involved additional tests and demonstrations with real flue gas with both the MFR and at the Argos Cement Plant in Calera, Alabama. The cement-plant tests increased the CO_2 flowrate to 12.5–15 kg CO_2/hour, which is equivalent to 300–360 kg CO_2/day. These tests lasted four days and resulted in the capture of 450 kg of liquid CO_2.

The coal-fired flue gas stream used in these tests resembled the planned flue gas conditions at the Hunter Power Plant more than our in-house natural gas fired flue gas stream in many ways. Figure 1 and Figure 2 show the ECL skid units at the cement plant. The average capture during the test was 96.3%, and the average CO_2 fraction in the inlet gas was approximately 12.7%.

Figure 1. ECL Chiller skid being unloaded at Argos cement plant.

Figure 2. Test site in Calera, Alabama for extended system testing with real flue gas.

Table 2 gives a summary of the overall run results, as well as a comparison to the previous run using the MFR flue gas. Plots of CO_2 capture over time while at the Argos Cement Plant appear in Figure 3.

Table 2. Real flue gas test results summary from test using flue gas from the MFR and tests at Argos Cement Plant.

	Units	MFR Flue Gas	Alabama1	Alabama2	Alabama3	Alabama4
Start Date	–	7 Dec 2017	20 Jan 2018	22 Jan 2018	23 Jan 2018	24 Jan 2018
Total Run Time	hr	9.26	12.8	9.37	15.8	9.28
Total CO_2 Captured	kg	37.3	227	156	224	154
Avg. CO_2 Capture Efficiency	%	95.9	97.2	97.4	96.3	93.8
Avg. CO_2 Capture Rate	kg/hr	4.03	15.7	15.8	14.2	15.6
Avg. Flue Gas Flow Rate	SCFM	29.7	43.7	38.4	34.4	40.6
Avg. Flue Gas CO_2 Content	mol%	7.88	12.3	13.1	13.1	12.2
Avg. Pressure Drop	psig	2.79	3.26	2.28	3.37	6.93
Avg. Coriolis Slurry Density	kg/L	0.768	0.788	0.791	0.79	0.783
Avg. Melter Mass Fraction	%	52.8	0.538	0.669	0.517	0.585
Avg. Alpha Auger Flow Rate	kg/hr	83.6	95.3	80.4	77.9	84.3
Avg. Bravo Auger Flow Rate	kg/hr	79.8	81.5	78	74.6	79.5

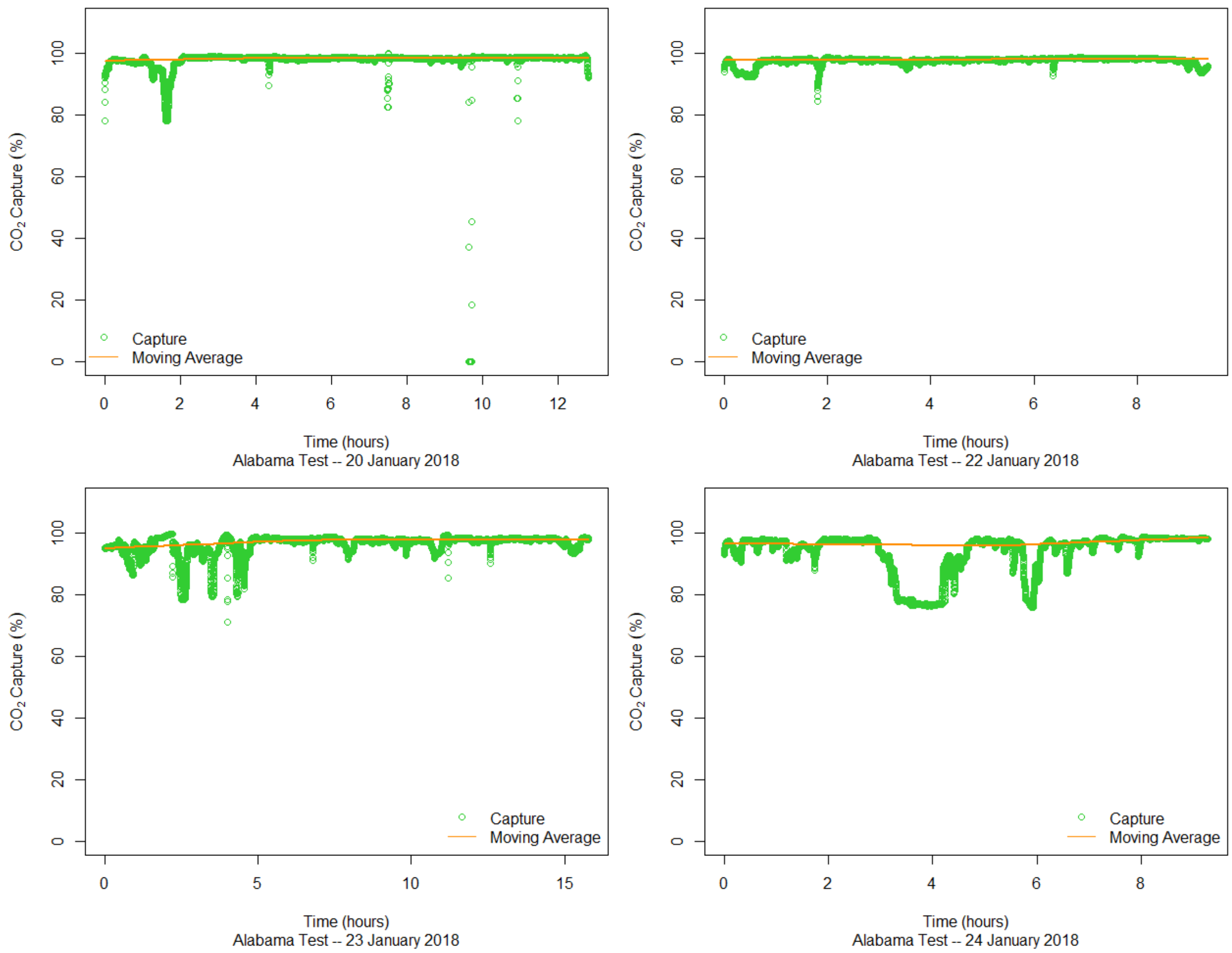


Figure 3. Capture data from real flue gas testing at the Argos Cement Plant [1].

These tests used the improved integrated heat exchange system designed for CO_2 liquefaction. This system successfully condensed over 80% of the CO_2 on a mass basis through most of the run (Figure 4~~Figure 4~~).

These tests built on the previous in-house tests using the MFR and were successful demonstrations of running the system at a higher flow rate and with liquid CO_2 output. Overall system operation also improved, including the ability to recover from minor upsets. The data collected during these tests illustrate improvements in the design and operation of the dryer, the pre-treatment equipment, and solid–liquid separations, which will be described in greater detail below.

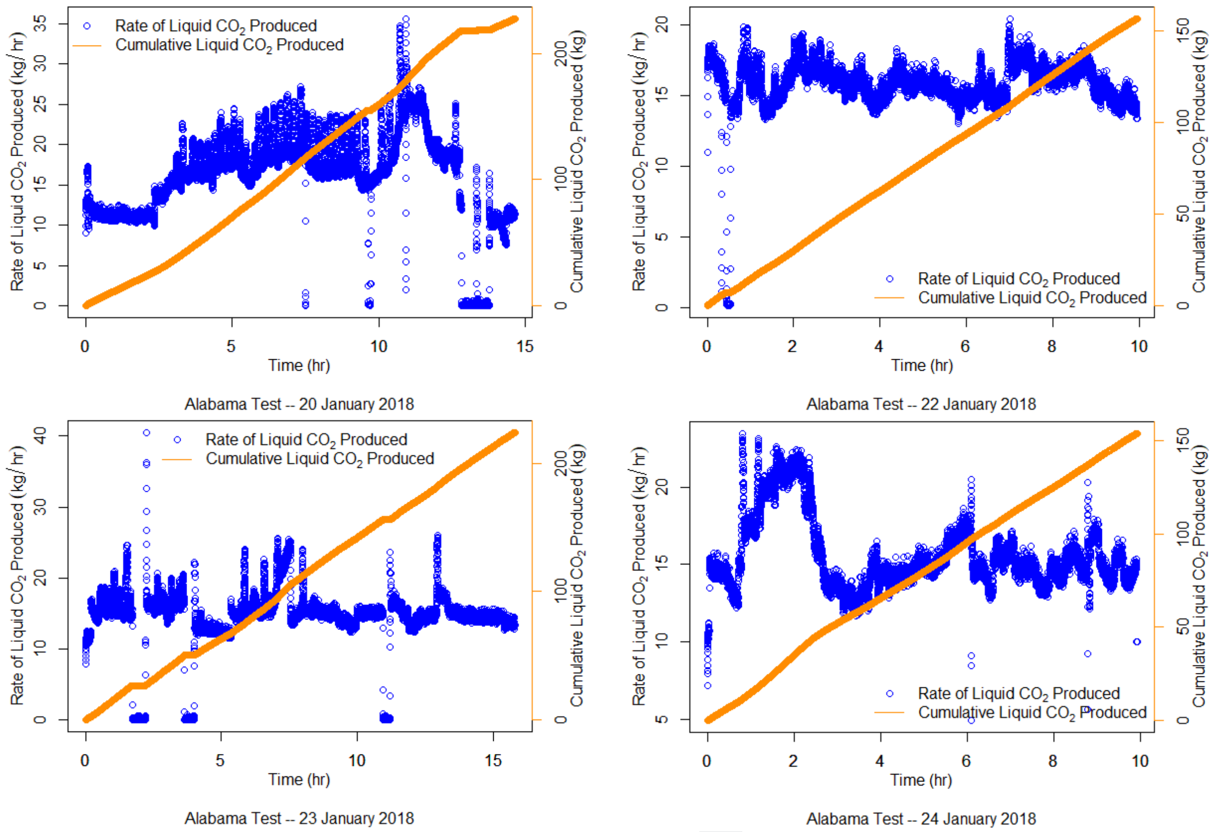


Figure 4. Instantaneous CO_2 rejection and cumulative CO_2 captured [1].

Dryers

Funding from this project has helped SES to modify and improve the drying system on the skid in preparation for long-term testing at the Hunter Power Station. These modifications successfully operated with simulated flue gas, real flue gas in the lab, and flue gas from a commercial source during this quarter. This testing validated the process models, tested the dryer under different conditions (including a process upset), and informed changes to the dryer system moving forward.

The dryer includes several parts:

- *Optional booster blower*. Suction pressure on the main system blower affects system performance. At higher elevations, the low atmospheric pressure can lead to an unwanted increase in temperature in the main blower. The booster blower helps mitigate this by creating an intermediate step between the atmosphere and the main blower.
- *Flue gas pre-cooler*. The pre-cooler removes bulk water before the system main blower.
- *Aftercooler with chilled water.* The aftercooler removes additional water at the blower discharge. It also cools the gas before it enters the desiccant dryer.
- *Desiccant beds*. The conditioned flue gas enters one of two desiccant beds with mol sieve 3A that brings the flue gas to a dew point near –100 °C.

Earlier in this project, we modified the desiccant bed configuration in two big ways: The first was to change the flow configuration so the flue gas flows from the top down and the regen gas flows from the bottom up. This results in a drying gradient of wet to dry from top to bottom during all points in the desiccant adsorption–regeneration process. This allows desiccant use after partial regeneration. The second change was a significant modification to the gas distributor that reduced the pressure drop by a factor of four.

Our initial experiments used flue gas from the MFR system burning natural gas. These tests were especially important because testing and regenerating the dryer is not currently possible in the closed-loop simulated flue gas runs.

Figure 5 shows the sample port on the MFR during setup. The sample line is the vertical leg of the T connection in the top of the photograph. The circle in the bottom of the photograph is a mirror that reflects the image of the inside of the MFR. The glow in the mirror is the flow straightener near the top of the MFR, just below the natural gas combustion region. This image records live natural gas combustion. However, the flue gas it is well mixed and almost invisible.

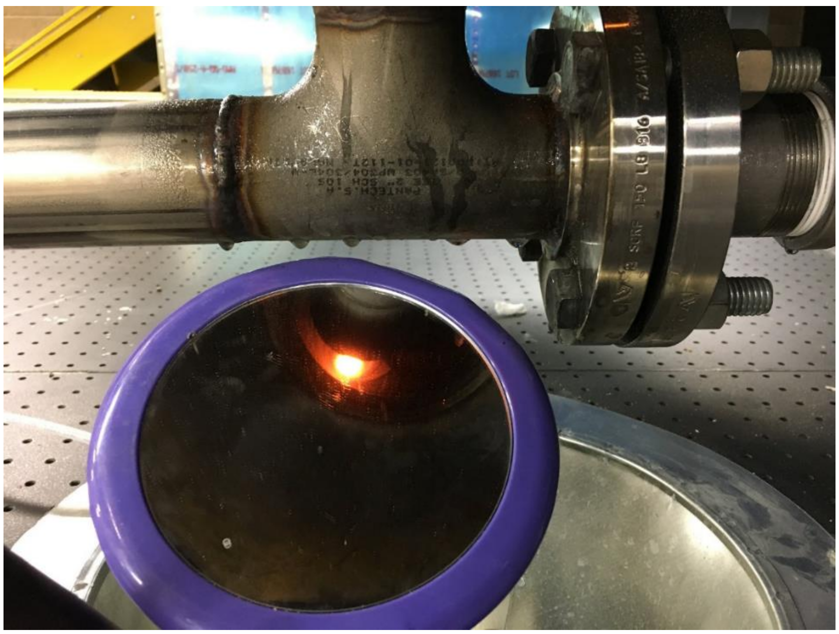


Figure 5. Sample port on the MFR during setup before being sealed.

In January 2018, we continued to test the system using flue gas from the MFR (burning natural gas) supplemented with nitrogen and carbon dioxide gas to achieve a flowrate and composition similar the flue gas at the Argos cement plant. These preparatory tests demonstrated that the system dries the flue gas and regenerates the mol sieve desiccant beds.

These longer tests included multiple regeneration cycles in succession and verified that the new system could sustainably and continuously remove water from the flue gas. During the first test run at the Argos plant, the drain line and pump that remove water from aftercooler plugged and condensed water flooded the desiccant bed. This upset condition went undetected until after the beds were switched, flooding the second desiccant bed. This unintentional operation error did provide an opportunity to test a condition that was simulated in our in-house dryer model (Figure 6). The model predicted that, under moist conditions, we could regenerate a small region of the dryer and switch back and forth to gradually expand that region. The change in the dryer configuration completed earlier in the project helped to make this possible, and as the run continued, the dryer fully recovered.

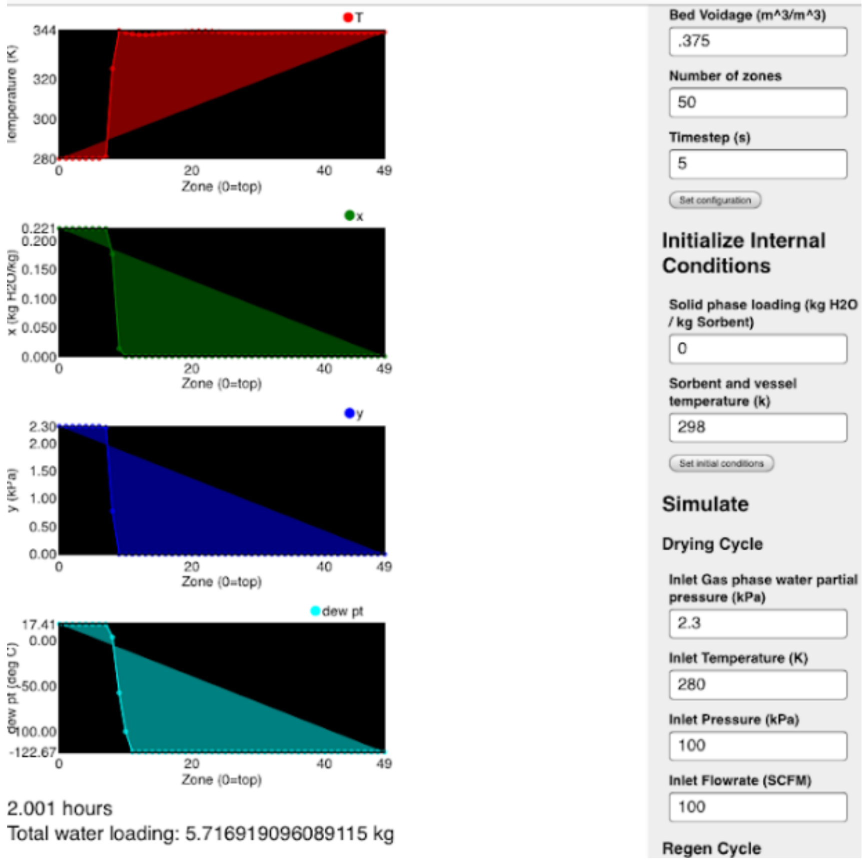


Figure 6. Screenshot of SES's in-house dryer software EDDY.

Running tests with real flue gas has provided valuable validation of the dryer model and has helped make sure the dryers will work for testing at the Hunter Power Station later this year.

During the tests in Alabama, we appreciated being closer to sea level. Even though the gas temperature was high, we didn't have any issues with the blower because the suction pressure was good. We have done preliminary design work on a booster blower and have purchased parts. Over the next few months, we will put the booster blower together for use at the Hunter Power Station.

Separations

During this quarter, new filters for the dual screw presses were constructed and tested. The new, more rigid filters prevent filter-mesh deformation. The new filters also decrease the tolerance between the filters and the screws. Testing with these filters showed an increase in the filter flow rate and screw press reliability. The screw presses with the new filters operated with real flue gas from the MFR, and at the Argos cement plant in Alabama. In addition, we have become very proficient at operating the two screw presses in parallel, thus increasing the overall stability of the system and providing greater confidence in longer-term test runs.

The tests during this past quarter have shown both good results for the filter design and for process stability; however, based on these preliminary results, the dual augers will likely not process sufficient CO_2 for a full 1 tonne CO_2/day process. Thus, we have begun construction on a larger machine using the lessons learned from operating the dual screw presses and from current filter construction.

The new press will have a 6 in. diameter screw and have nearly twice the filter area as the dual 4 in. screws combined. Lessons learned from operation and design changes to the 4 in. presses will be incorporated into the 6 in. design. One such modification is that the solid outlet for the 6 in. machine will have more open area than the 4 in. presses. In previous experiments, we found that CO_2 would plug between the outlet and the wall of the outlet vessel on the 4 in. machines. We were able to mitigate this problem by directly injecting warm liquid CO_2 on the solid outlet to melt the solids. More area on the outlet will address this problem directly without the need to warm the solids outlet area, thus reducing overall heat load.

Another change we will make based on our experience with the dual screw presses is moving the screw bearings to the outside of the pressure vessels. This will enable us to provide an unrestricted path for the solid CO_2 to extrude out of the back of the machine. The 4 in. machines require the bearing supports to pass through the solid CO_2 path, and we had problems with these supports causing plugging early in our testing. The problem was solved by minimizing the number and profile of the supports, but we will now be able to eliminate the supports on our next iteration.

The current design of the larger 6 in. machine that incorporates lessons learned from the dual 4 in. presses is shown below in Figure 7.

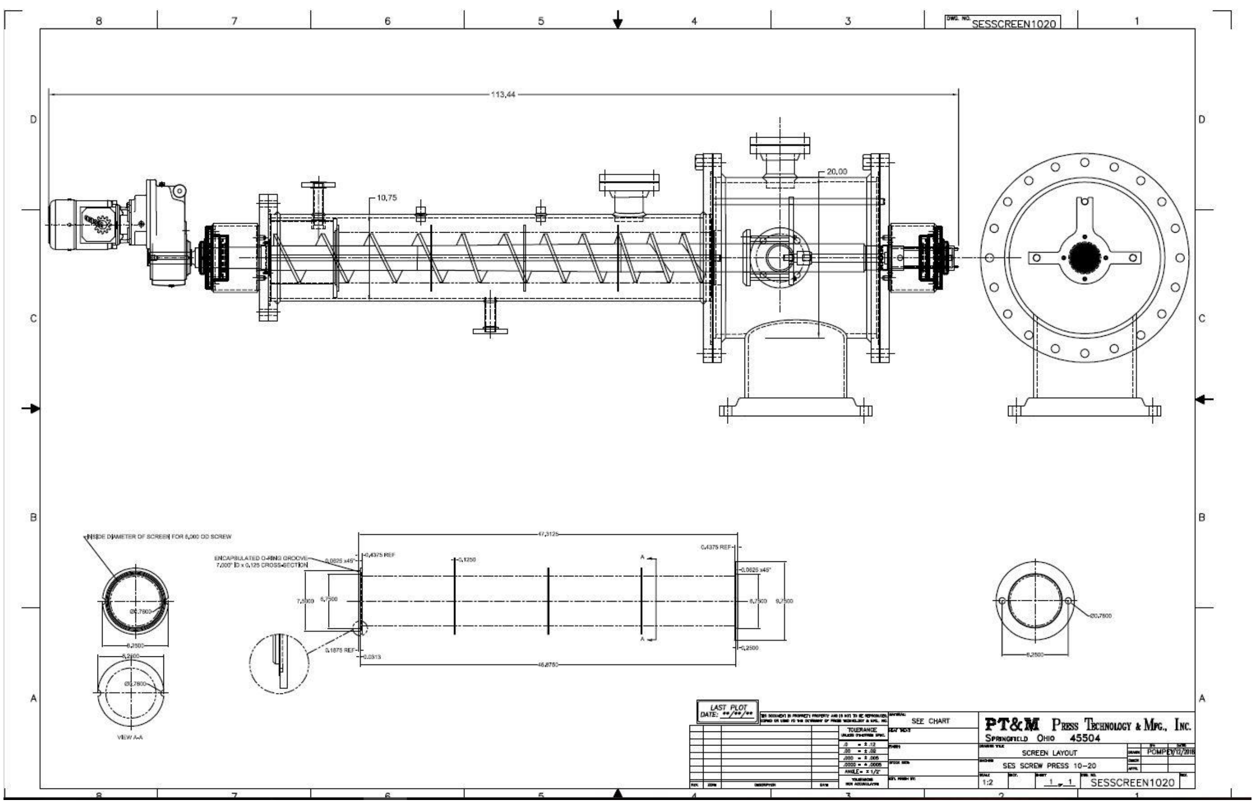


Figure 7. Final design for larger 6 in. screw press system.

Klaren Heat Exchanger

During this quarter, SES worked toward integrating the fluidized bed heat exchanger from Klaren International. This heat exchanger continuously cleans itself using small particles that scour the heat exchange surface. The unit uses a single tube and provides a proof of concept for the Cryogenic Carbon Capture™ (CCC) process. This single-tube heat exchanger also scales modularly to higher flow rates. A finalized P&ID of this heat exchanger and how its integration with the equipment at SES appears as Figure 8~~Figure 8~~~~*Figure 8*~~ and the construction drawing in Figure 9 shows the locations of the process connections as well as the support points.

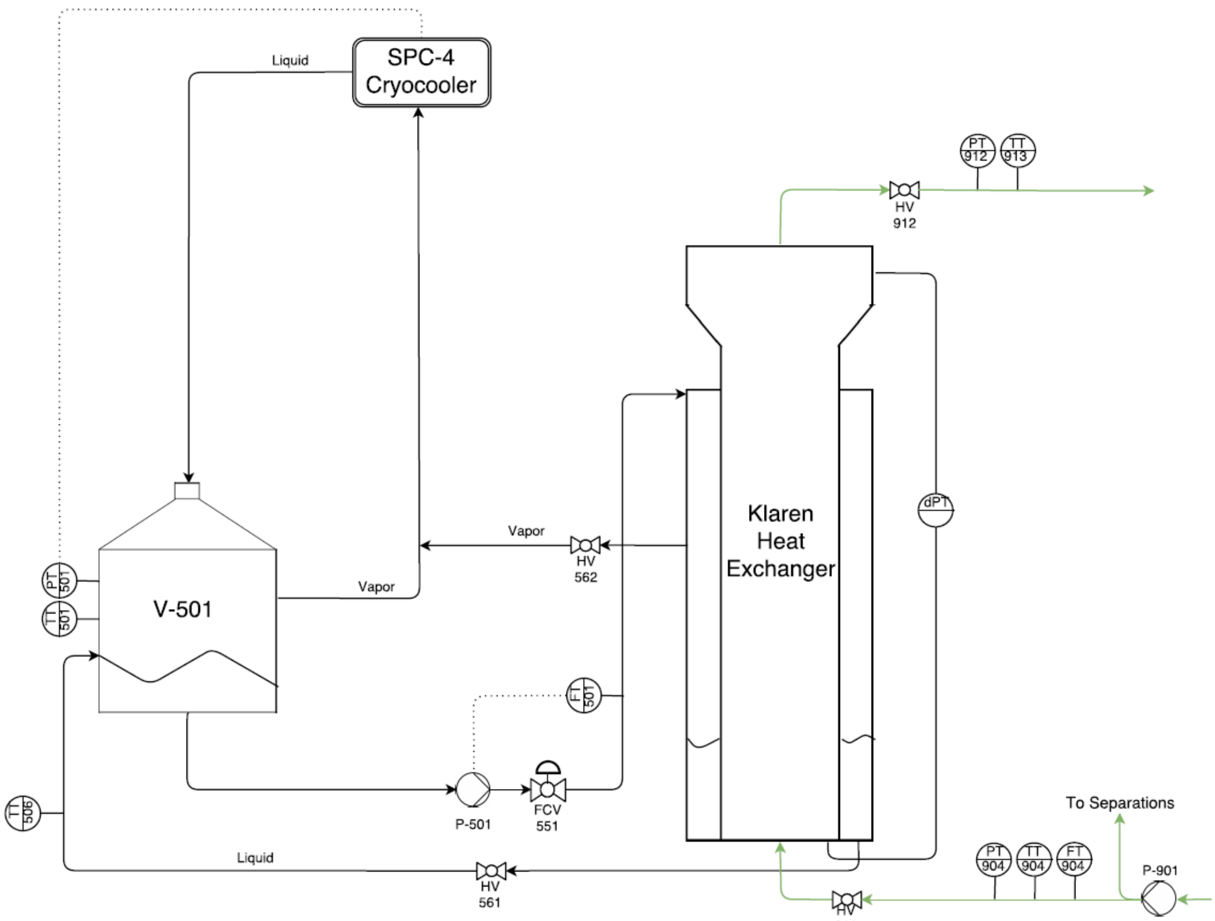


Figure 8. Finalized P&ID of the self-cleaning heat exchanger integrated with SES equipment.

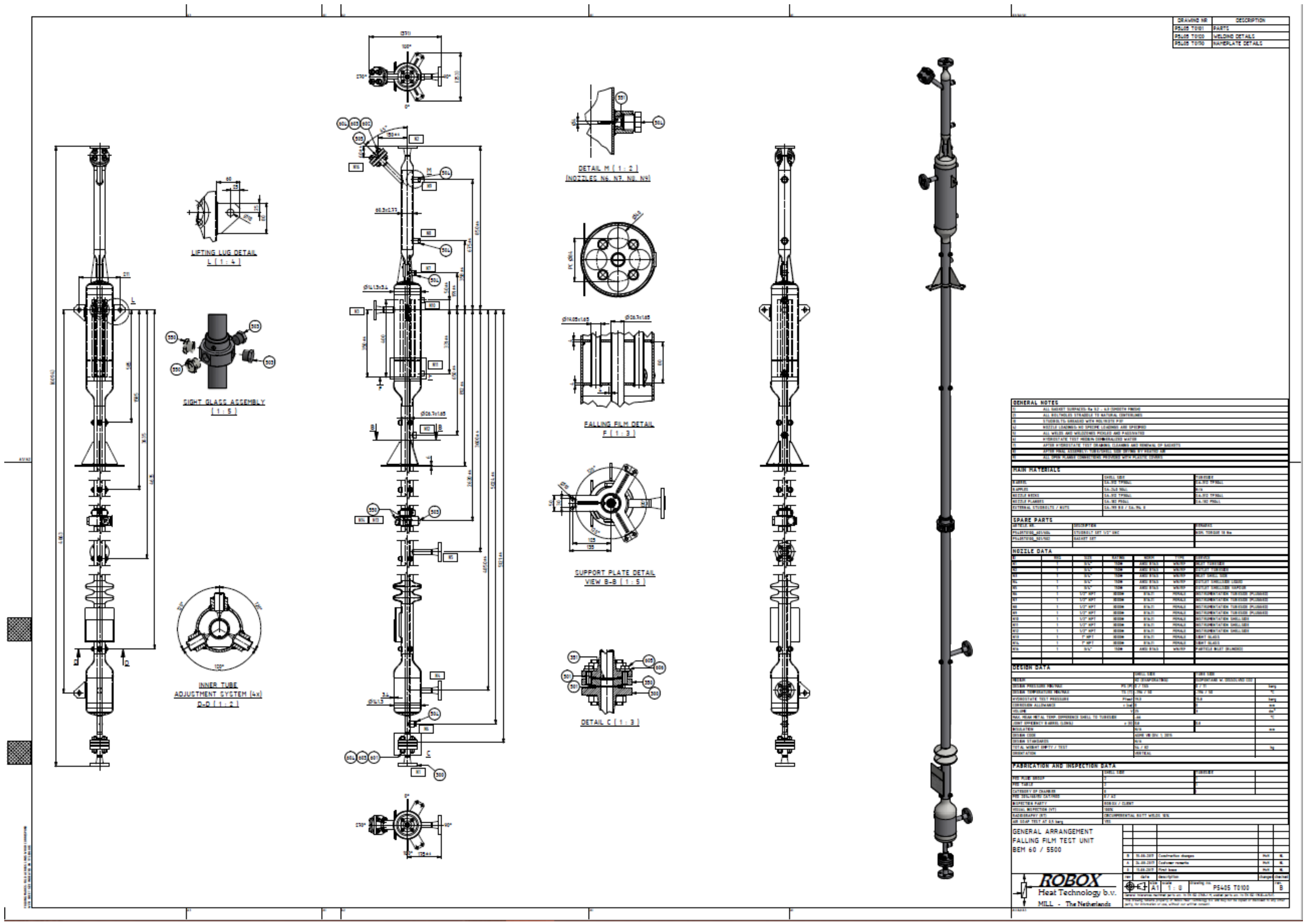


Figure 9. Finalized drawing of the self-cleaning heat exchanger made by Klaren International.

SES designed a frame that will provide a means for supporting, lifting, and insulating the heat exchanger. The frame will be constructed from aluminum with two steel lifting bars and will rest on a steel base. Figure 10 shows a rendering of the frame with all cover panels in place as well as a rendering with the panels removed to expose the heat exchanger.

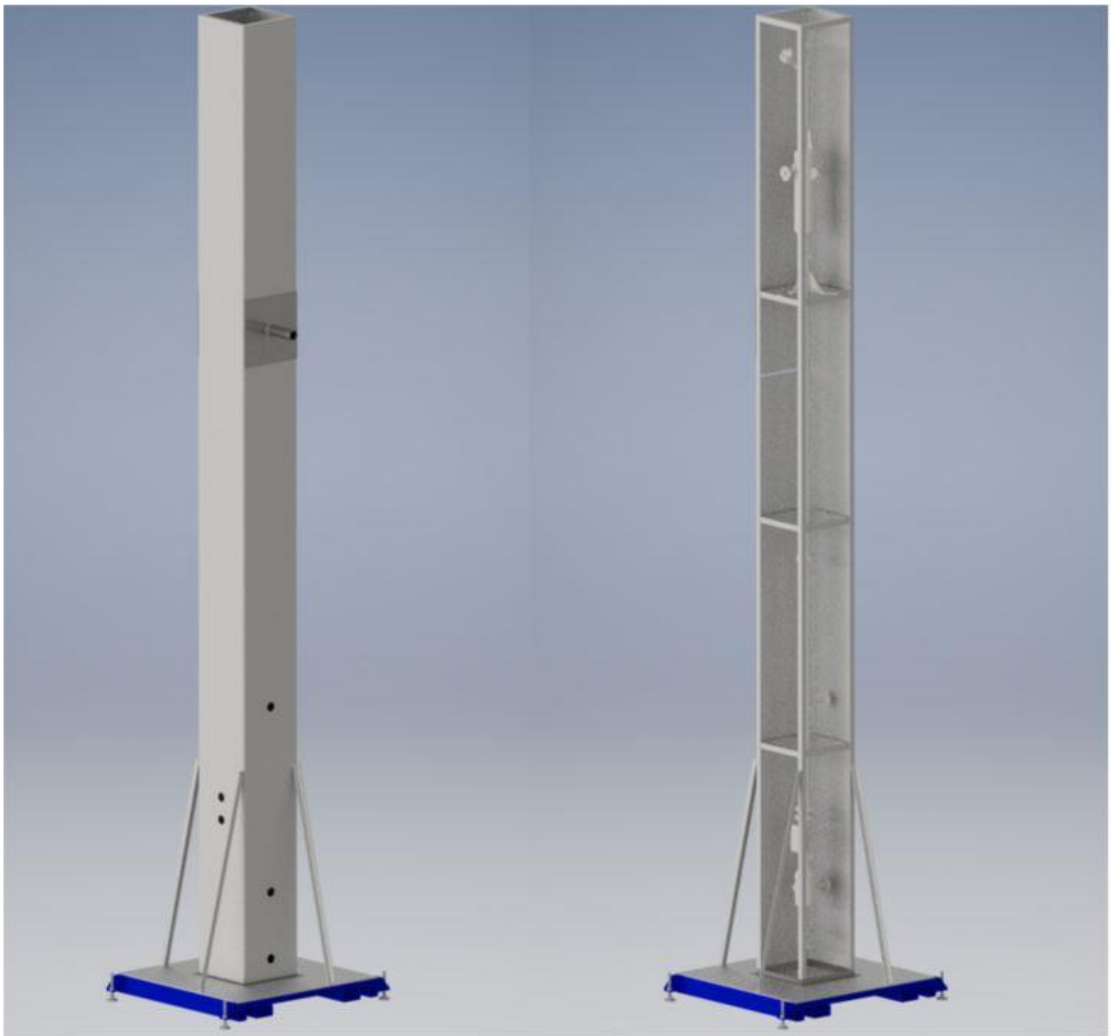


Figure 10. Renderings of the Heat exchanger with and without aluminum panels.

The frame will contain expanded perlite to provide insulation and all process connections will run through access ports on the bottom panels to take advantage of the perlite insulation. Refrigerant will flow between the heat exchanger and the refrigerant dewar via two vacuum-jacketed hoses, as shown in Figure 11. Vacuum-jacketed hose improves heat exchanger location flexibility and insulation performance compared to foam-insulated tubes. A cryogenic refrigerant pump, as described in the next section, overcomes pressure drop caused by the corrugated hose.

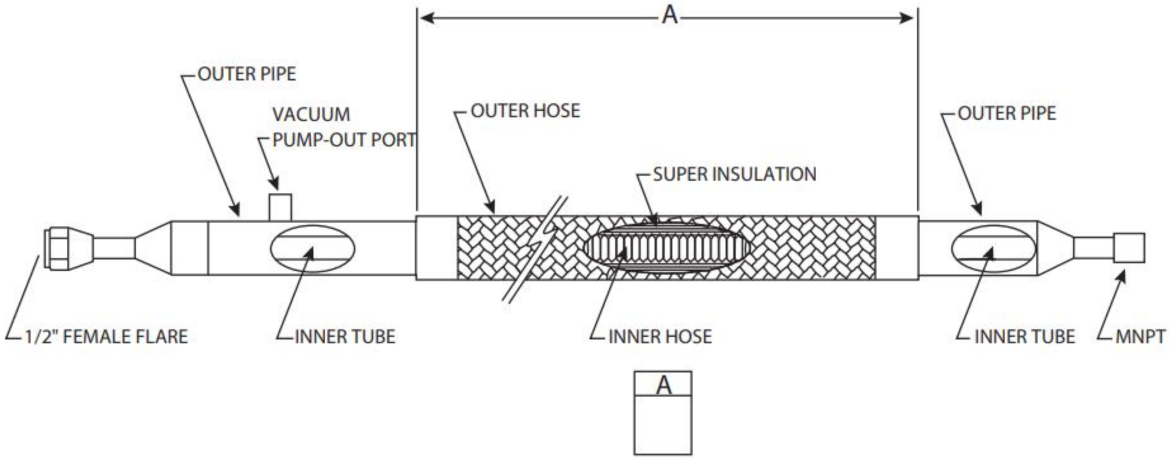


Figure 11. Vacuum jacketed hosing as supplied by Cryofab.

The isopentane-CO_2 slurry tends to foul in corrugated hoses, so the slurry will flow through a smooth stainless tube with Cryogel insulation. SES previously used bent stainless tube to transfer slurry, as shown in Figure 12. Cryogel has a very low thermal conductivity and is installed in layers around the tube until an adequate heat leak is achieved.

Figure 12. Existing stainless tubes insulated with Cryogel used to transfer slurry

Cryogenic Refrigerant Pump

A cryogenic centrifugal pump was purchased this quarter. An image of this pump from Cryostar is shown in Figure 13.

Figure 13: Cryostar CO 120 pump that was purchased in this quarter.

A thorough investigation identified a pump that would work for our application. The current system design feeds small heat exchangers that are well below the height of the dewar that holds the refrigerant. Thus, no pump was required, and the system feed operated by gravity. The Klaren fluidized-bed heat exchanger contains a single tube with the same diameter as an individual tube in a larger pilot-scale heat exchanger. This single tube height is impractical for our gravity-driven system. The previous gravity-fed system ran on saturated refrigerant. A saturated liquid will cavitate in the pump inlet where the pressure drops. The height of the liquid on the suction side of the pump can prevent cavitation if sufficient height could be obtained in our existing dewar. The selected pump has the lowest net positive suction head (NPSH) – only 3 to 4 inches of water. A cutaway shows the dewar (left) and the pump (right) in Figure 14.

The pressure loss from all the plumbing between the dewar and the pump determines if this system will avoid cavitation. The calculations indicate that 5 inches of refrigerant in the dewar suffices to prevent cavitation.

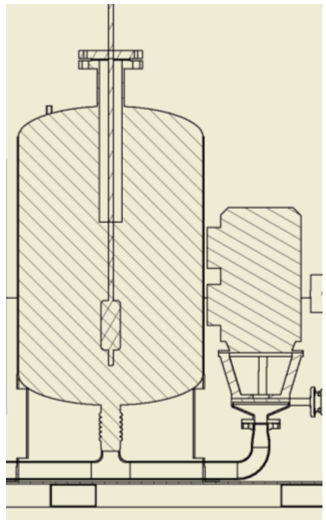


Figure 14. Dewar and pump plumbing cutaway. The pressure loss through the plumbing was determined so the depth of refrigerant required to prevent pump cavitation could be calculated.

Shell-and-Tube Heat Exchanger

In past quarters, the shell-and-tube heat exchanger was designed with polished tubes to prevent the buildup of solid CO_2. As a reminder, a drawing of this heat exchanger is shown in Figure 15.

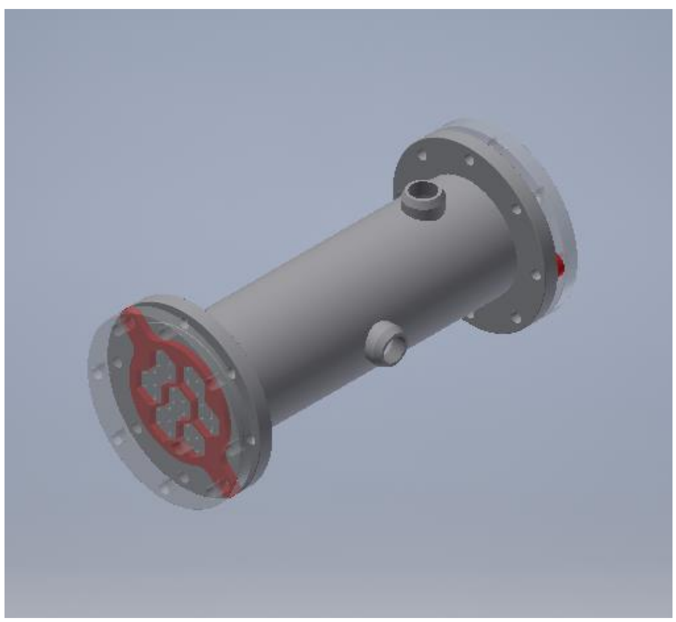


Figure 15. CAD rendering of shell-and-tube heat exchanger.

During the design process, we worked closely with WSA Engineered Systems. WSA has developed a line of valves and cleaning systems for heat exchangers. The valves reverse the flow through a heat exchanger. Reversing the flow alone could cause the buildup on the heat exchanger walls to dislodge and leave the heat exchanger. WSA has also developed a line of cleaning brushes, scrapers, and balls that can traverse back and forth through the tubes as the flow is reversed. Some of these items can be seen in Figure 16. The image on the left shows the brushes and balls that are currently produced by WSA. The image on the right shows an SES-produced mockup of a scraper. Currently, we have prioritized exploring the scraper and brushes over the ball cleaning method. The ball cleaning method requires more hardware, and WSA typically makes balls out of rubber, which is not flexible at the temperatures associated with CCC.

Figure 16. (left) Brushes and (right) scraper to be used in the shell-and-tube heat exchanger. The photo on the left also contains rubber cleaning balls, which would not work at the cold temperatures required by CCC. Constructing these balls from Teflon may be something that SES pursues in the future.

As this system is modular in nature, we are pursuing a variety of these options in parallel. Testing results and a more complete comparison of these options will be reported in the next quarter.

Direct Contact Cooling Heat Exchanger (Reverse Bubbler)

Preliminary studies done during previous quarters indicated that the reverse bubbler will likely not be the optimal heat exchanger for this project. We were able to successfully cool the contact liquid stream, but it absorbed higher-than-expected amounts of liquefied natural gas.

References

[1] R Core Team, *R: A language and environment for statistical computing,* Vienna: R Foundation for Statistical Computing, 2017.

SUPPLEMENTAL QUARTERLY REPORT AND MILESTONE SUBMISSION

Nov 1, 2018

Submitted by

SUSTAINABLE ENERGY SOLUTIONS

Submitted to

ROCKY MOUNTAIN POWER

Sustainable Transport and Energy Plan (STEP)

Overview

This project modifies specific unit operations in an existing research and demonstration unit (the ECL skid) provided by Sustainable Energy Solutions (SES) to improve process efficiency, reliability, or overall performance. These modifications include experimental systems developed by SES. This first project development phase includes skid preparations for later long-term, on-site testing at an RMP facility. This report details the work not previously completed towards the fifth milestone of this project, specifically regarding delayed testing for 1 tonne/day CO_2 capture. This work was completed by October 31, 2018.

Quarterly Milestones

As indicated in the Scope of Work for this project, the fifth milestone involves ordering of parts for the modified skid-scale system that will undergo testing at the Hunter plant, as well as shakedown testing of the unit ops in the upgraded system with tests up to 1 tonne/day. The exact wording of the milestone is below.

Q5	**SES will deliver a report containing the following:** **- Documentation of parts ordered for permanent skid-scale unit ops and skid integration (COMPLETED PREVIOUSLY)** **- Results of testing the permanent skid system with simulated flue gas at 1 tonne/day** **- Shakedown testing completed (COMPLETED PREVIOUSLY)**	**5/15/2018**	**75% Paid $25,241.25 Remaining**

Completed Milestone for 1 Tonne/Day Testing

Due to delays in receiving the larger scale solid–liquid separations equipment, and delays in receiving the cryogenic refrigerant pump, we did not report on the final milestone for testing capturing 1 tonne of CO_2/day in the original quarterly report. This report is a follow up to the testing of the full 1 tonne/day capture, as well as the shakedown of the screw press solid-liquids separation system.

The milestone was not achieved during the timeframe of the original report due to delayed shipping of the larger, higher capacity screw press used in solid-liquids separations. In this report, this new, improved screw press was the primary focus of our testing. During these tests we also increased the simulated flue gas flow rate through the system until we were achieving 1 tonne/day capture. This allowed us to test all components of the system at full capacity. Figure 1 shows flowrates of CO_2 for the total flow through the system, called the "Processed Rate", and the CO_2 captured by the system, or "Capture Rate". The capture rate is the metric we are using for indicating whether we were achieving the full 1 tonne/day capture. On an hourly basis, the required captured rate is 41.66 kg/hour, and as you can see from the figure the rate is consistently above this required rate after the initial startup.

We were able to achieve the full 1 tonne/day capture for multiple runs. These runs did not appear to be limited by the cooling capacity of the shell and tube heat exchanger or the screw press in the solid-liquid separations system. SES is continuing to optimize issues such as melter concentration, CO_2 loading in the slurry, and the rate of CO_2 clearing in the shell and tube heat exchanger.

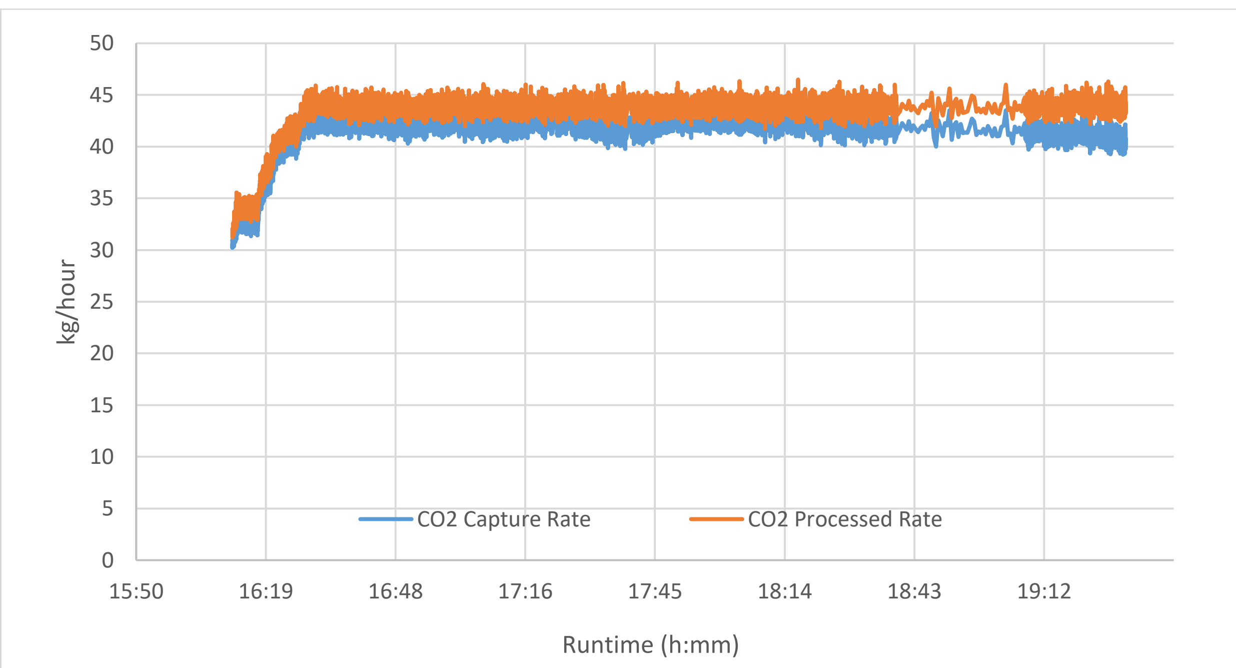


Figure 1. CO2 processing rates during 1 tonne/day test.

Another key variable we examined during these runs was the CO_2 loading in the slurry. Being able to maintain a consistent and low mass fraction in the slurry is critical to steady state operation and is indicative of a well operating screw press. Figure 2 shows this mass fraction over time during a 1 tonne/day test run, with a consistently maintained CO_2 concentration in the slurry.

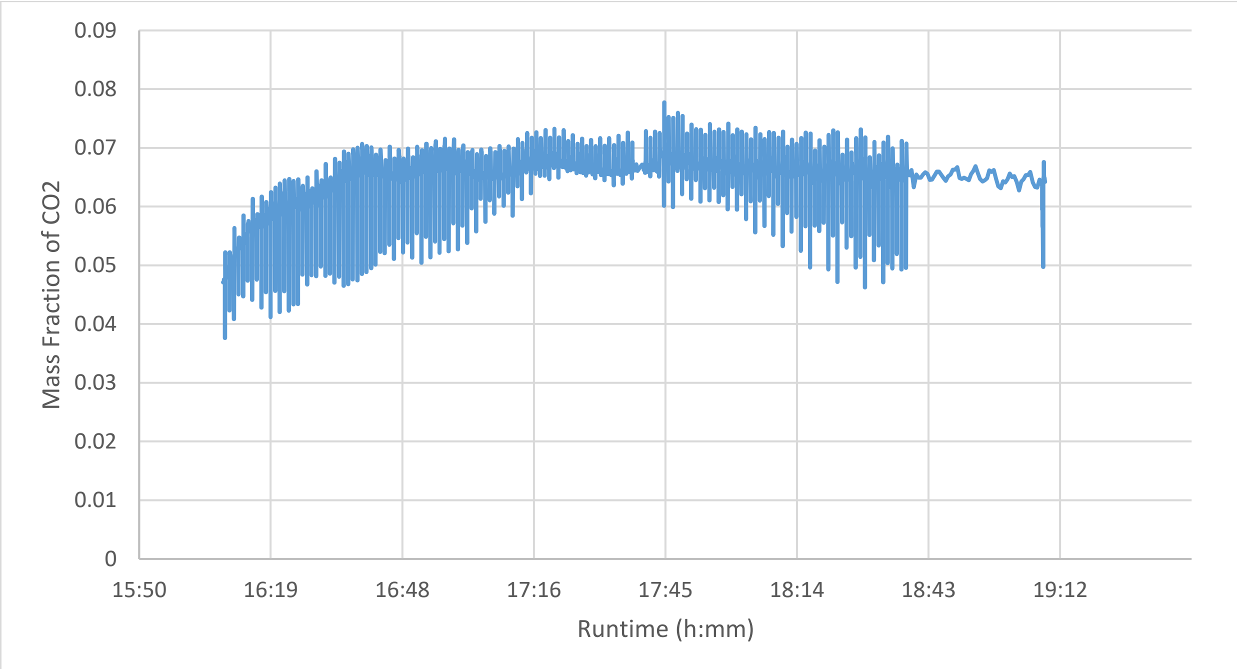


Figure 2. Mass fraction of CO2 during 1 tonne/day test. Mass fraction in the slurry is an indicator of solid-liquid separations effectiveness.

The final focus of the testing during the 1 tonne/day runs was the pressure drop across the shell and tube heat exchanger, as this is also indicative of whether or not we can achieve steady state operation at the full flow rate. Figure 3 shows this pressure drop over the same time period as the previous figures.

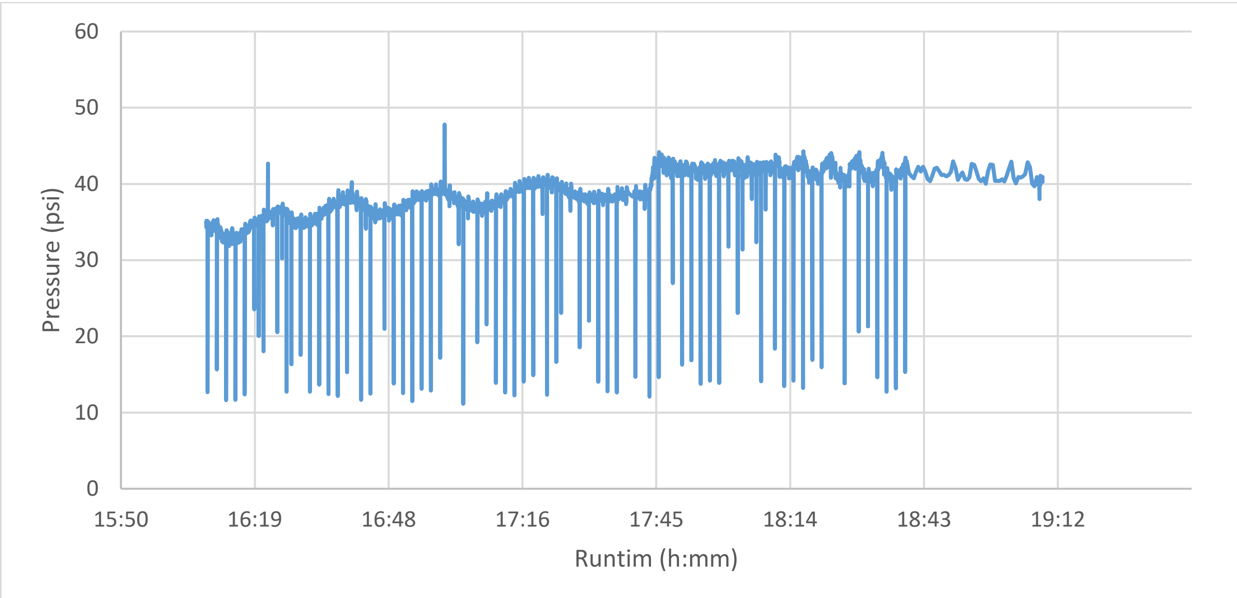


Figure 3. Delta P across the shell and tube heat exchanger during a 1 tonne/day test. The pressure drop is an indicator of fouling in the heat exchanger.

Additional Modifications and Testing

Experiments are continuing at SES with some modifications being made to improve long term reliability for the extended test runs. One challenge being faced is the long term cooling load capability of the system when we are running at 1 tonne/day, as it appears our ability to cool the contacting liquid stream decreases over time. We have been able to mitigate this with some operational changes to the system, especially in how we operate our cryocoolers. We are also making significant improvements to the insulation of the system before we ship it to the plant, which we believe will fully mitigate these problems.

QUARTERLY REPORT AND MILESTONE SUBMISSION

May 15, 2018

Submitted by

SUSTAINABLE ENERGY SOLUTIONS

Submitted to

ROCKY MOUNTAIN POWER

Sustainable Transport and Energy Plan (STEP)

Overview

This project modifies specific unit operations in an existing research and demonstration unit (the ECL skid) provided by Sustainable Energy Solutions (SES) to improve process efficiency, reliability, or overall performance. These modifications include experimental systems developed by SES. This first project development phase includes skid preparations for later long-term, on-site testing at an RMP facility. This report details the work done towards the fifth milestone of this project.

Quarterly Milestones

As indicated in the Scope of Work for this project, the fifth milestone involves ordering of parts for the modified skid-scale system that will undergo testing at the Hunter plant, as well as shakedown testing of the unit ops in the upgraded system with tests up to 1 tonne/day. The exact wording of the milestone is below.

Q5	**SES will deliver a report containing the following:** **- Documentation of parts ordered for permanent skid-scale unit ops and skid integration** **- Results of testing the permanent skid system with simulated flue gas at 1 tonne/day** **- Shakedown testing completed**	**5/15/2018**	**$100,965**

Preparation for Setup at the Hunter Power Station

This quarter, engineers from SES and the Hunter Power Station collaborated to choose the location where the Cryogenic Carbon Capture™ (CCC) skid will operate during testing this fall. Ports were prepared and/or added to to the stack for the flue gas to be removed and processed. Gas composition, pressure, and temperature are being discussed and the skid layout next to the tower are being determined. A possible configuration that is likely to be used is shown in Figure 1.

The Hunter Power Station has several ports with varying gas temperature, pressure, and composition. The port from which the skid will sample gases is still under discussion. A 70-ton crane must fit in the "courtyard" area shown below for unloading and loading the skid units.

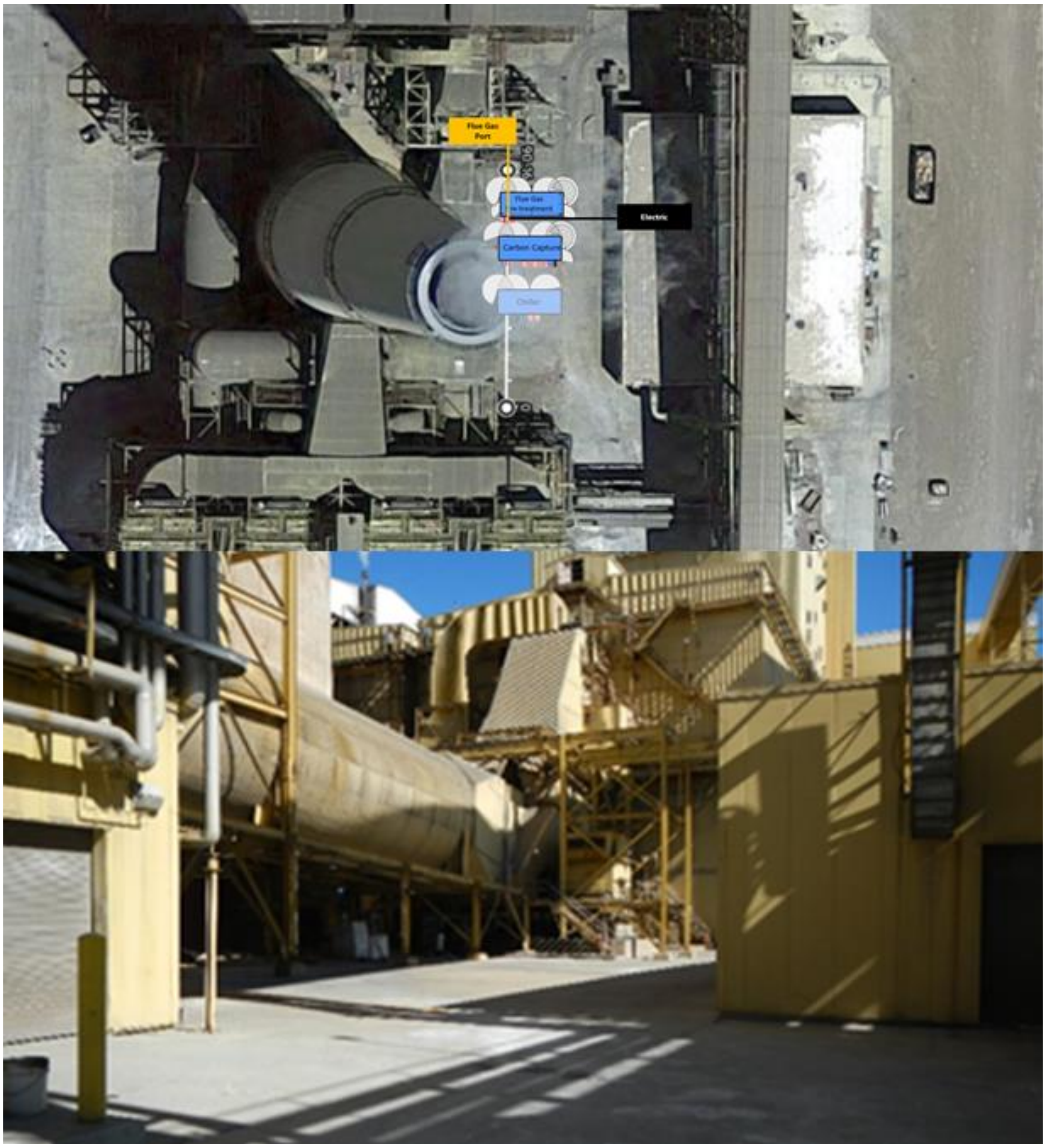


Figure 1. (top) Aerial and (bottom) ground views of area for possible placement of the containers at the Hunter Power Plant site.

Cryogenic Refrigerant Pump Installation

During this quarter, SES modified the skid to accommodate the cryogenic pump and to accommodate both the shell and tube heat exchanger and a fluidized bed heat exchanger. Figure 2 shows the regions of the modified design. The cryogenic pump appears in grey-scale in the back and the shell and tube system is in the front with some color highlights, with the unmodified sections rendered as partially transparent.

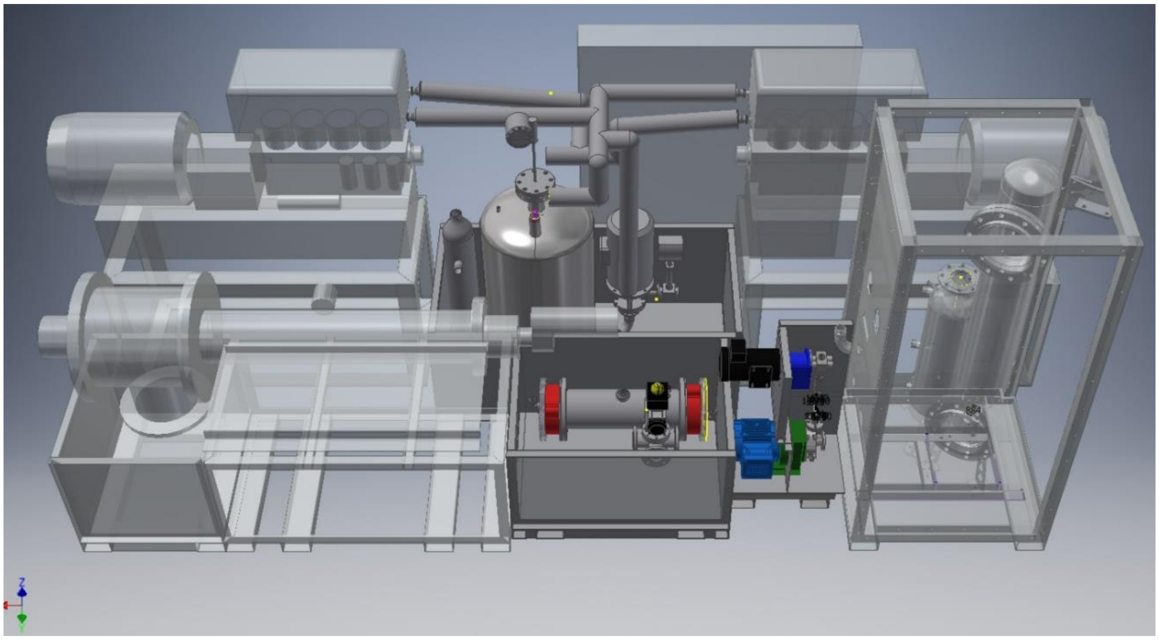


Figure 2. CAD models for the placement of the pump, shell and tube heat exchanger, and other new components in the ECL skid. Objects that were not modified are translucent.

During the previous quarter, the changes reflected in the above CAD drawing were nearly completely implemented. Figure 3 shows the new configuration of the cooling section of the ECL skid. The blue pump motor in the back is partially obscured by a section of vacuum-jacketed pipe.

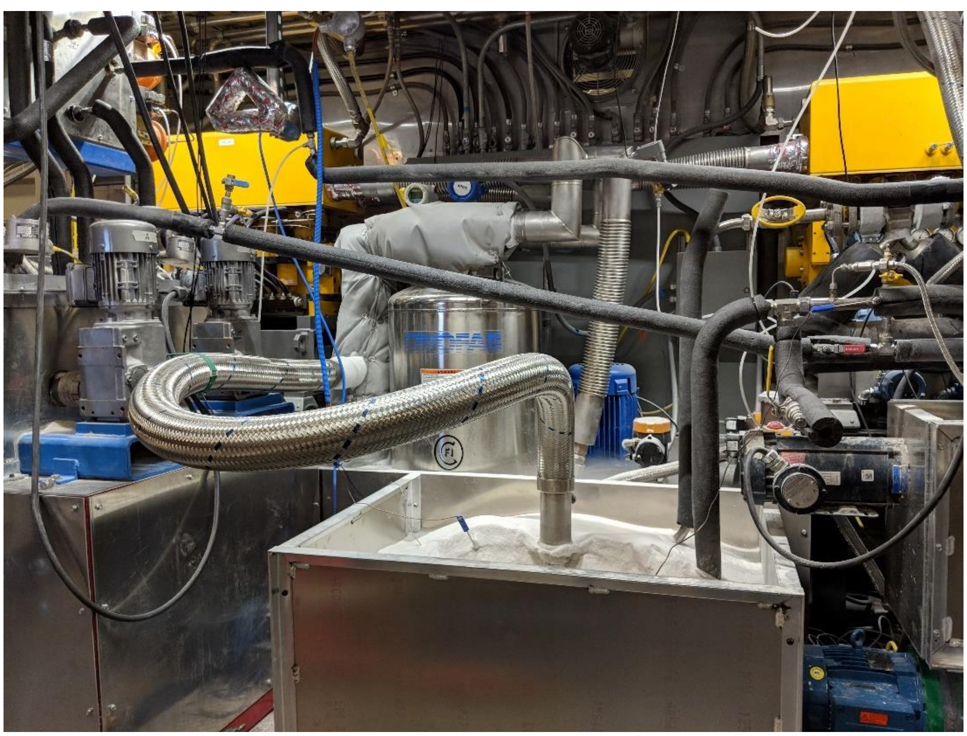


Figure 3. The shell and tube heat exchanger in place with the cooling system.

Shell-and-Tube Heat Exchanger

SES tested the shell and tube heat exchanger using the previous gravity-feed system prior to modifying the skid with the cryogenic pump. The gravity-feed system regulated the refrigerant by a level difference using a proportional control valve into the heat exchanger. These tests showed that the thermal resistance on the refrigerant side of the heat exchanger inhibited cooling and maintained capture at less than 1 tonne/day of CO_2. The cryogenic pump should increase cooling and therefore throughput. These tests also showed that the shell and tube heat exchanger is more resistant to fouling than other heat exchangers, but there was still enough fouling to require the use of brushes or scrapers for long-term operation. Figure 4 shows the shell and tube heat exchanger installed in the skid.

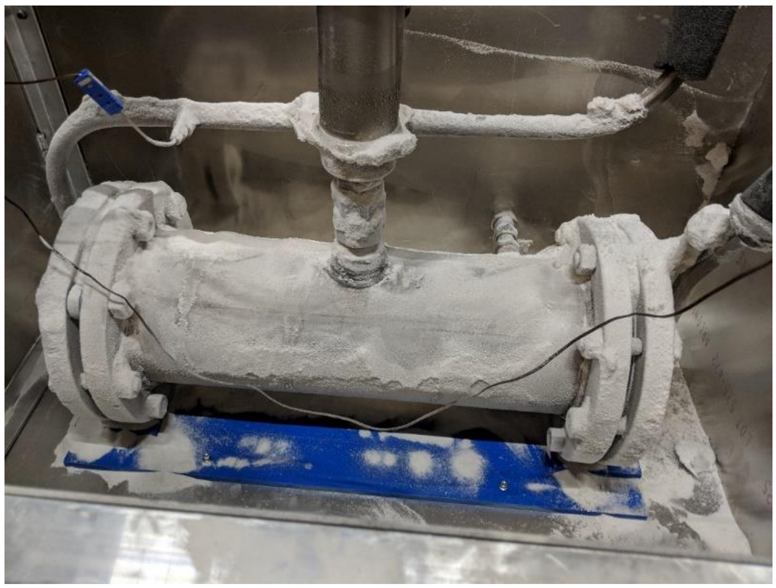


Figure 4. Shell and tube heat exchanger after initial testing.

Testing of the shell and tube heat exchanger with the refrigerant pump is ongoing. Future work will also include the addition of a back flush valve that will change the direction of the flow in the shell and tube heat exchanger, which should decrease fouling when used alone and is necessary for using brushes or scrapers. The brushes for cleaning the tubes have been ordered and all the hardware for implementing this change will arrive in the next few weeks.

Backflush Valve

The backflush valve mentioned in the previous section arrived in the last quarter. This valve reverses flow through the heat exchanger, possibly dislodging deposits on heat exchange surfaces. If changing the flow direction alone is not enough, brushes or scrapers can traverse the length of the tube each time the flow is reversed.

Figure 5 shows the basic operation of the backflush valve. The bottom of the figure shows how the flow reverses by changing the valve position. This reversal will not impact the operation of the remainder of the process and should result in breaking up solids formed on the surface of the heat exchanger. If flow reversal is insufficient to clean the heat exchanger, the backflush action will drive a brush or scraper back and forth through the heat exchanger tubes. Figure 6 shows the backflush valve in the SES lab.

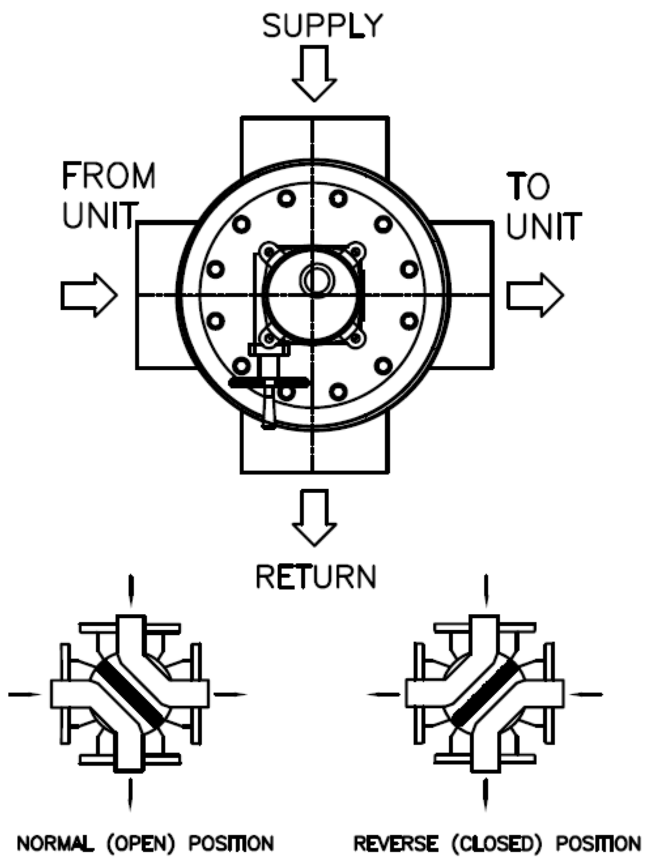


Figure 5. Basic operation of the backflush valve.

Figure 6. Actuated backflush valve ready to be installed in the system.

Klaren Heat Exchanger

SES has continued work toward integrating the fluidized bed heat exchanger from Klaren International. During this quarter, we finalized the instrumentation and flow diagram for the system and how the various unit operations connect. A finalized P&ID of this heat exchanger, including its integration with the equipment at SES, is shown in Figure 7. Of note is the added a vapor–liquid separator, which allows the Klaren heat exchanger to be flooded with liquid nitrogen, as any two-phase liquid returns will be separated before reaching the cryochillers.

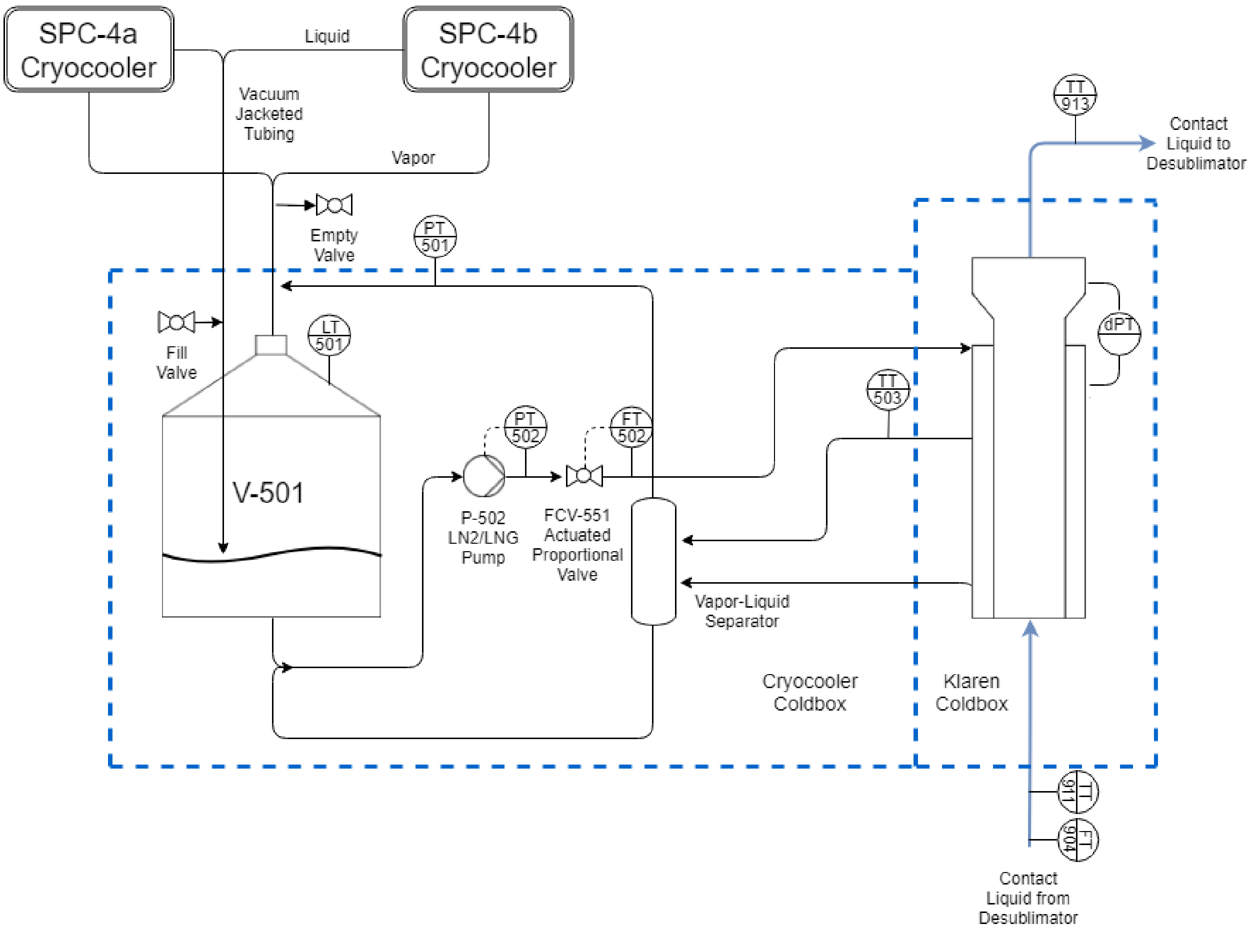


Figure 7. P&ID of the self-cleaning heat exchanger with coldboxes and new instrumentation emphasized integrated with SES equipment.

The construction drawing in Figure 8 appeared in previous reports and shows the locations of the process connections as well as the support points. During this quarter, we modified the Klaren system slightly by adding a sieve plate to the top of the column, as shown in Figure 9. This will prevent any particles used for clearing the walls of CO_2 from entering the remainder of the flow and exiting the system.

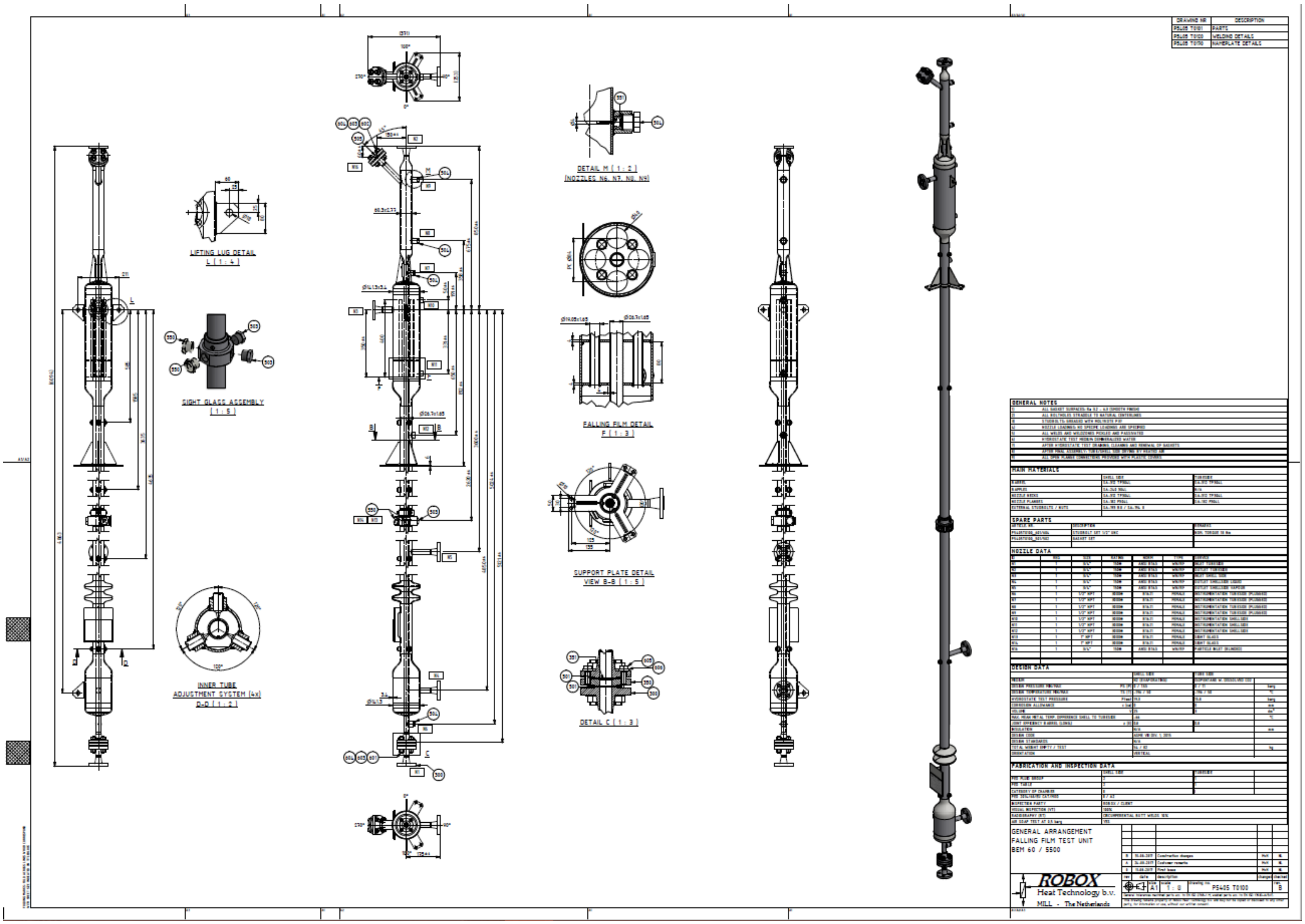


Figure 8. Finalized drawing of the self-cleaning heat exchanger made by Klaren International.

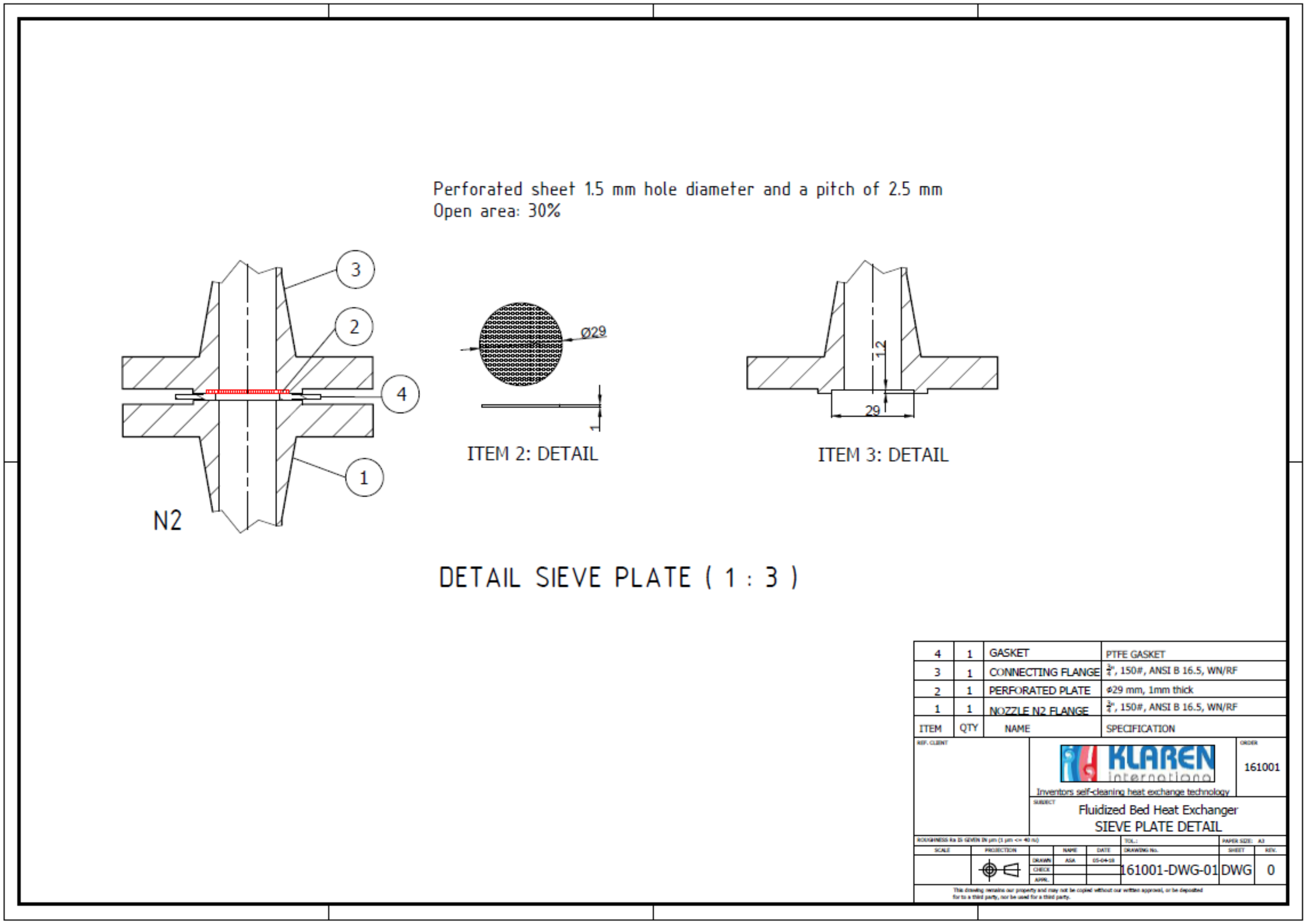


Figure 9. The new sieve plate that will prevent any particles from exiting the heat exchanger.

SES designed a frame for supporting, lifting, and insulating the heat exchanger. The aluminum frame has two steel lifting bars and rests on a steel base. Figure 10 shows the constructed frame without the cover panels.

Figure 10. Klaren heat exchanger frame without aluminum panels.

The frame will hold expanded perlite to provide insulation and all process connections run through access ports on the bottom panels to take advantage of the perlite insulation. Refrigerant flows between the heat exchanger and the refrigerant Dewar via two vacuum-jacketed hoses (Figure 11). Vacuum-jacketed hose provides some flexibility for heat exchanger location and increases insulation performance compared with foam insulation on tubes. A cryogenic refrigerant pump, as described in the previous section, overcomes the pressure drop caused by the corrugated hose.

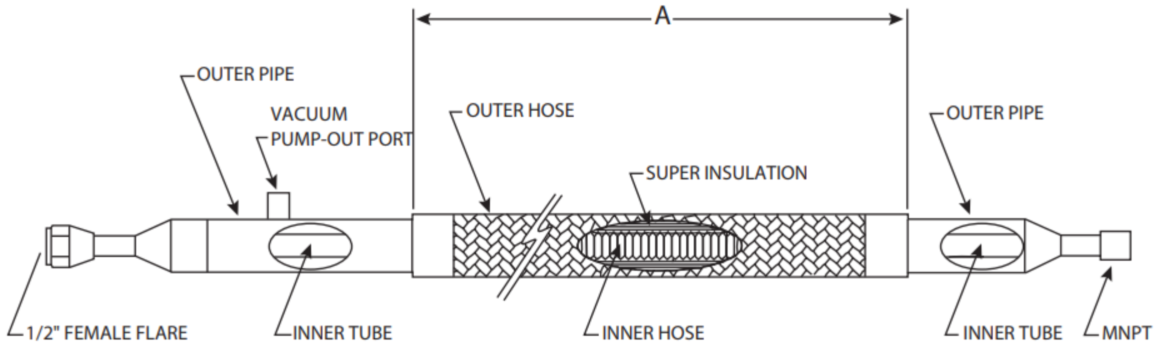


Figure 11. Vacuum jacketed hose (Cryofab).

The cryogenic hoses performed as expected in the skid system, thus significantly reducing the heat load along these lines. Figure 12 shows a section of this vacuum jacketed hosing in place with the rest of the system.

Figure 12. One section of flexible vacuum jacketed hosing in place (stainless hose with blue stripes).

The isopentane-CO_2 slurry tends to foul in corrugated hoses, so the slurry will flow through a smooth stainless tube with Cryogel insulation. Cryogel has a very low thermal conductivity and forms layered insulation around the tube until achieving acceptable heat loss.

Reverse Bubbler using Alternate Liquids including Methanol

We made significant strides this quarter in the thermodynamic modeling of the reverse bubbler using methanol as a non-soluble cooling medium for the contact fluid. We performed a thorough investigation of multi-component liquid–liquid and vapor–liquid–liquid phase equilibria across the temperature and pressure ranges possible for operation in CCC.

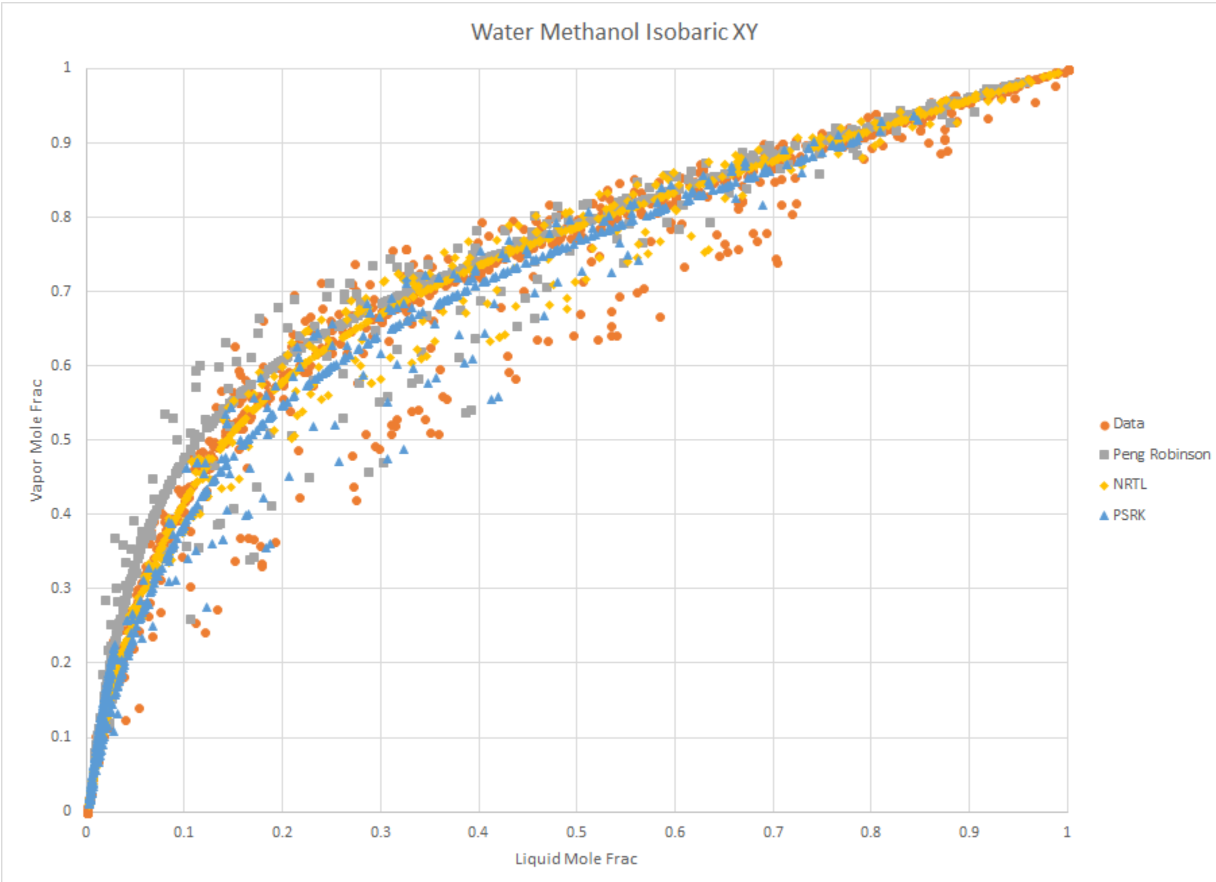


Figure 13. Water–methanol isobaric XY

It appears that the components are very immiscible and very high purity could be achievable with minimal energy investment. This would create a contact liquid cooler where all nucleation sites would be inside the cooler itself and not on the heat exchanger surface. This is, in principle, the same concept used in our desublimating heat exchanger in which nucleation occurs in the liquid phase and the solid surfaces do not foul. Systematic experiments will test this heat exchange at a small scale in the future. Preliminary experiments verify the freezing point of the methanol-water eutectic. We also mixed the chilled methanol solution with contact fluid to verify that the components were immiscible and to see how fast they separate after thorough mixing. All results were positive (note the meniscus between the upper and lower liquids in Figure 14).

We will continue testing this methanol reverse bubbler in the coming months.

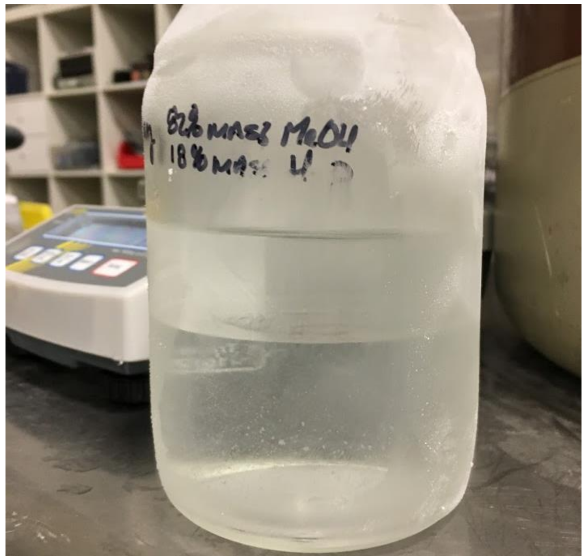


Figure 14. Methanol–water/contact fluid mixture showing meniscus between the 2 phases.

Skid-Scale System Testing

The majority of the skid testing this quarter was shakedown testing related to the new equipment detailed above. As discussed above, the shell-and-tube heat exchanger was installed and tested for the first time using a gravity-fed system. The main purpose of testing this particular heat exchanger was to establish its efficacy to mitigate fouling compared with previous braised-aluminum heat exchangers that had been tested. Most of the heat exchangers tested to date had a tendency to foul after operation for 2–6 hours, depending on running conditions, before they were rendered unusable due to buildup of solid particles in the heat exchanger.

First fouling Test

The first test to determining the fouling rate of the shell-and-tube heat exchanger was a 10-hour test run at conditions that would typically foul a braised-plate heat exchanger in 3-4 hours. We measured the pressure drop across the heat exchanger to determine the rate of fouling. The base pressure drop is approximately 10 psi, most of which actually occurs across the desublimating tower spray head that is in series with the heat exchanger. We were able to run for almost 10 hours continuously; while the pressure drop did increase, it did so at a rate that was significantly lower than that observed in the braised-plate heat exchangers (Figure 15).

There was a significant increase in the pressure drop towards the end of the run. However, this could mostly be explained by a large increase in the solids loading of the slurry that was being processed. Due to abnormalities in the CO_{2-} recycle system, the inlet concentration of CO_2 spiked and caused a corresponding increase in the solids concentration of the slurry. This eventually led to the shutdown of the run. The spikes that you see in the pressure drop are operator-run interventions to curtail fouling problems. These mitigation techniques were developed previously and have shown to be effective in the braised-plate heat exchanger tests and were tested here for the first time on the shell-and-tube heat exchanger.

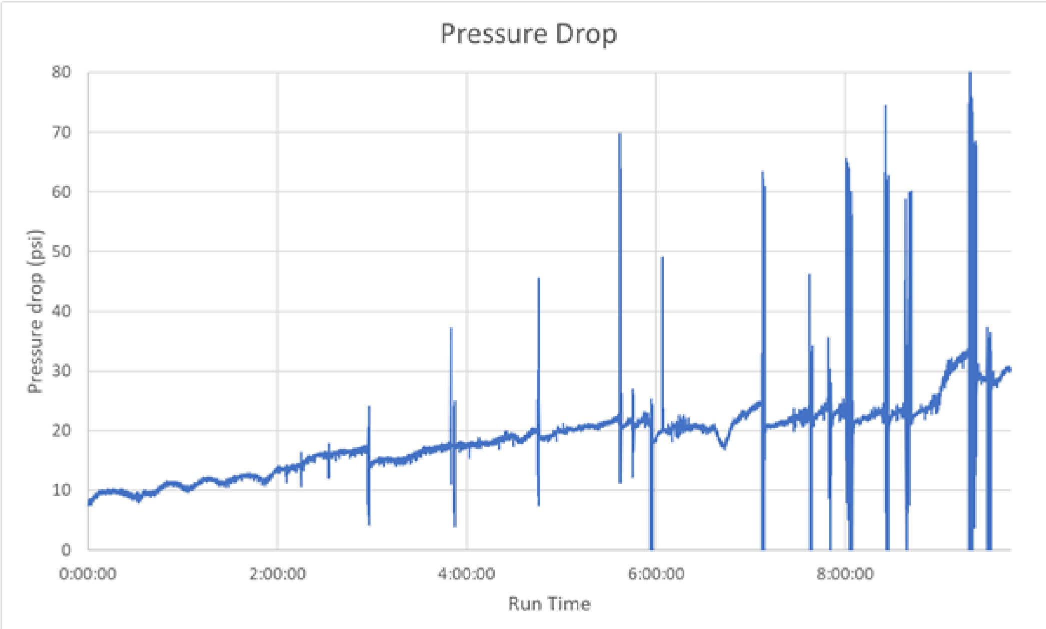


Figure 15. Pressure drop results over the course of the first fouling test.

Second Fouling Test

Since the results from the initial fouling test were positive, we decided to attempt another run at the same conditions. Although test conditions were nominally the same as in the previous run, the results were worse. We believe that this is due to CO_2 that was already dissolved into the contact liquid at the beginning of the run. However, having run the test twice and seen fouling both times, we established that the shell-and-tube heat exchanger, on its own, is not able to maintain stead-state operation without additional mitigation techniques, such as the use of brushes or scrapers, as mentioned above. The results are presented in Figure 16.

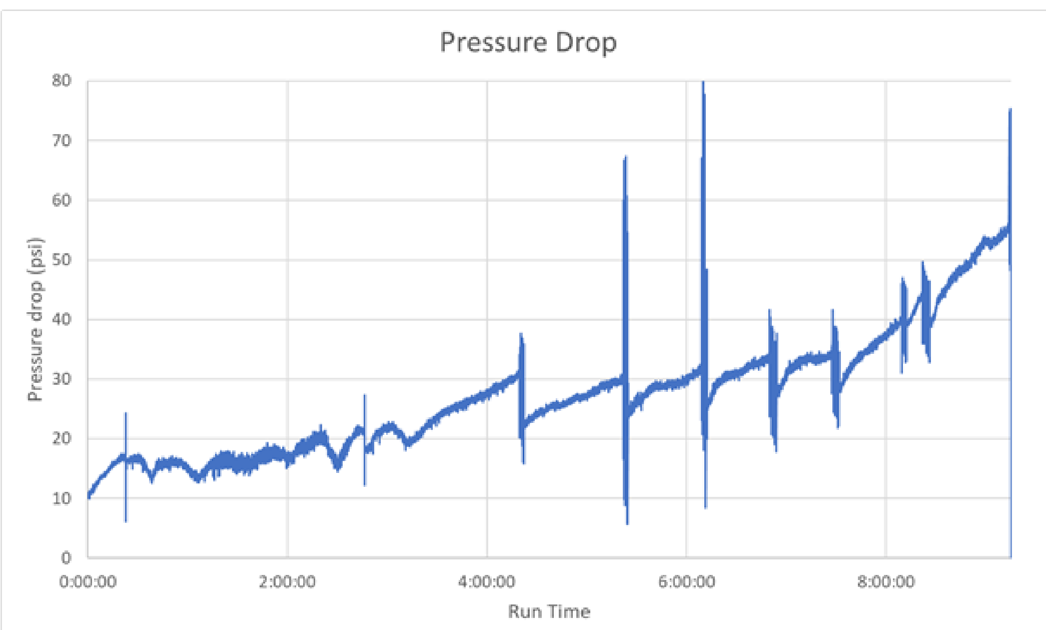


Figure 16. Pressure drop results over the course of the second fouling test.

Shell and Tube Load Test

We also ran a load test to determine if the heat exchanger had sufficient heat exchange area to capture 1 tonne of CO_2/day. The system underwent a stress test to determine the possible upper cooling limit and the location of the bottleneck. The possible limiting factors were cryocooler capacity, tube-side convection, and shell-side convection. We determined that we could capture approximately 600 kg/day with the system as it was tested, and that the coefficient of the shell-side refrigerant was the limiting factor for further cooling. The cryocoolers still had extra capacity that was not being used. Changes to the tube-side slurry, such as increasing or decreasing the flowrate, did not change the cooling load delivered. However, changes to the shell-side operation, such as changing the height of the liquid column present in the dewar, resulted in a measurable change in the cooling load. We think, therefore, that adding the refrigerant pump should allow us to increase the cooling capacity of the shell-and-tube heat exchanger.

Initial Tests of the Cryogenic Refrigerant Pump

Our most recent tests have been two short-term test runs utilizing the new cryogenic refrigerant pump. These tests have been run over the past three days. While we are still sorting through the data and process control strategies, our initial impressions are positive. The pump should allow us to better control our cooling load and increase the overall capacity of the system.

Delayed Milestone for 1 Tonne/Day Testing

Due to delays in receiving the larger scale solid–liquid separations equipment, and delays in receiving the cryogenic refrigerant pump, we did not achieve the final milestone for testing capturing 1 tonne of CO_2/day in this quarter. We anticipate this milestone being completed shortly as we test this equipment, and a follow up report will be sent with those results.

QUARTERLY REPORT AND MILESTONE SUBMISSION

August 15, 2018

Submitted by

SUSTAINABLE ENERGY SOLUTIONS

Submitted to

ROCKY MOUNTAIN POWER

Sustainable Transport and Energy Plan (STEP)

Overview

This project modifies specific unit operations in an existing research and demonstration unit (the ECL skid) provided by Sustainable Energy Solutions (SES) to improve process efficiency, reliability, or overall performance. These modifications include experimental systems developed by SES. This first project development phase includes skid preparations for later long-term, on-site testing at an RMP facility. This report details the work done towards the sixth milestone of this project.

Quarterly Milestones

As indicated in the Scope of Work for this project, the sixth milestone involves preparation and modification at the Hunter PP site, preparation for transport from SES and any requirements of SES employee while at the Hunter PP site, and continued shakedown testing of the ECL ski. The exact wording of the milestone is below.

Q6	**SES will deliver a report containing the following:** **- A description of the preparations and modifications at the Hunter PP site.** **- Documentation of insurance, transport, personnel trailer, and other on-site needs.** **- A description of the ongoing on-site setup and shakedown of the ECL testing skid.**	**8/15/2018**	**$218,008**

Preparations and Modifications at the Hunter Power Station (Aaron)

Over the last several months, we have worked closely with engineers at the Hunter Power Plant to verify the location on the stack where the flue gas slip stream will be drawn and returned. On July 19th, we took measurements and finalized the location for each of the ECL testing skid units to be placed. We prepared an unloading plan and checked measurments for flue gas ducting and electrical cables. Currently, we are planning on placing the skids in the “courtyard” area that was selected earlier this year (see Figure 1).

Figure 1. Courtyard at Hunter Power Plant where SES will locate the ECL testing skid.

This area is preferred for us and the plant because in addition to being in close proximity to the stack, the ECL testing skid will be out of the way of plant workers and contractors during fall maintenance. The skids will be placed in the configuration pictured below, which is different from previous plans (Figure 2). This configuration facilitates unloading when the ISO-sea container skids are delivered. It also provides access to the main doors if any maintence requiring a forklift is needed during the deomonstration.

Electrical routing from the breaker in the power building can be routed multiple ways (Figure 2). The preferred route exits the building and follows the building wall then crosses the courtyard on the ground through a protected cover. An alternate route runs the cable through existing cable trays from the power room to a wall near the ECL testing skid.

In preparation for testing, employees at the Hunter Power Plant had multiple ports installed for gas sampling. Our current plan is to use two ports that are after the flue gas desulfurization unit where the flue gas stream temperature is typically near 45 °C (Figure 4–Figure 6). The gas will be drawn through a 4” stainless steel ball valve (Figure 5) and conveyed through a 3” or 4” hose or duct down to the side of the walkway, across the header and down to the skid (Figure 4). Figure 5 shows the 4” port.

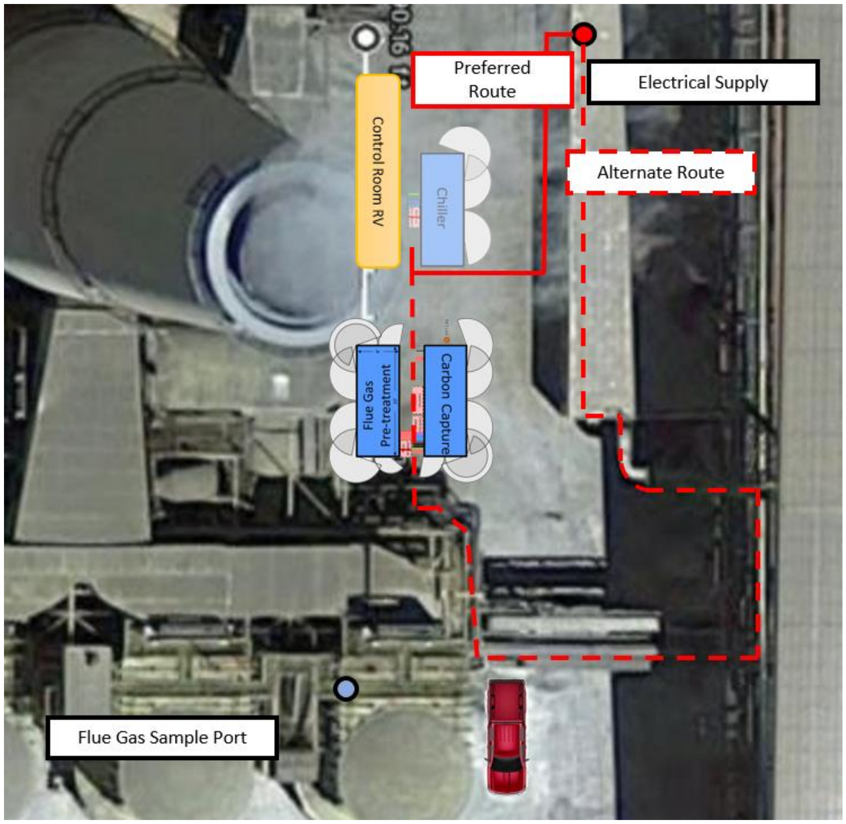


Figure 2. Configuration of the ECL testing skid with electrical routing diagram

Figure 3. Preferred electrical route.

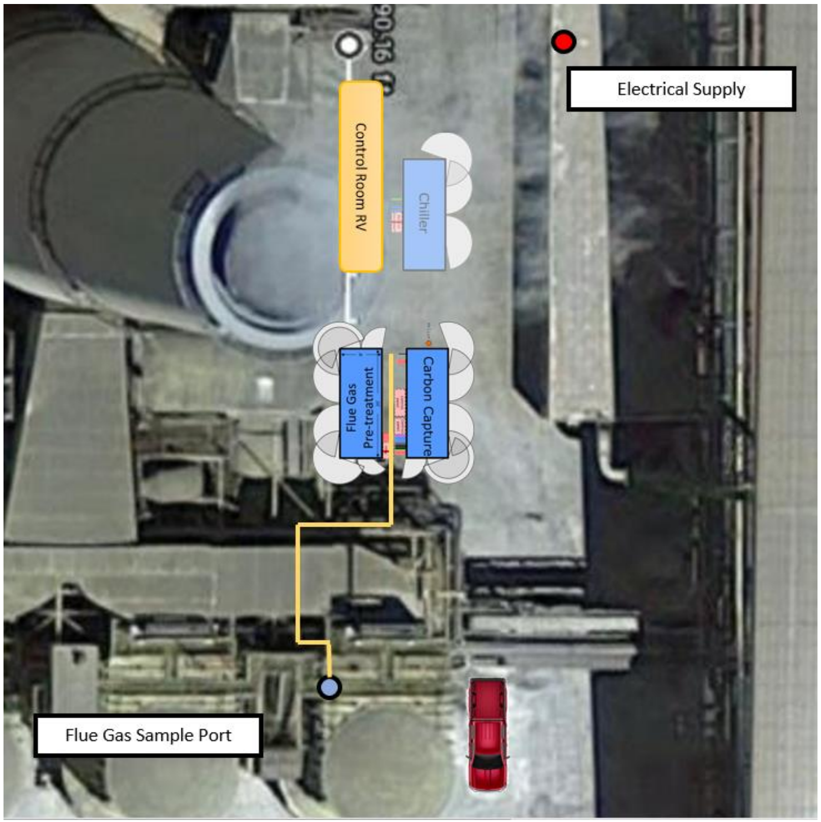


Figure 4. Gas port location and ducting to and from the ECL testing skid.

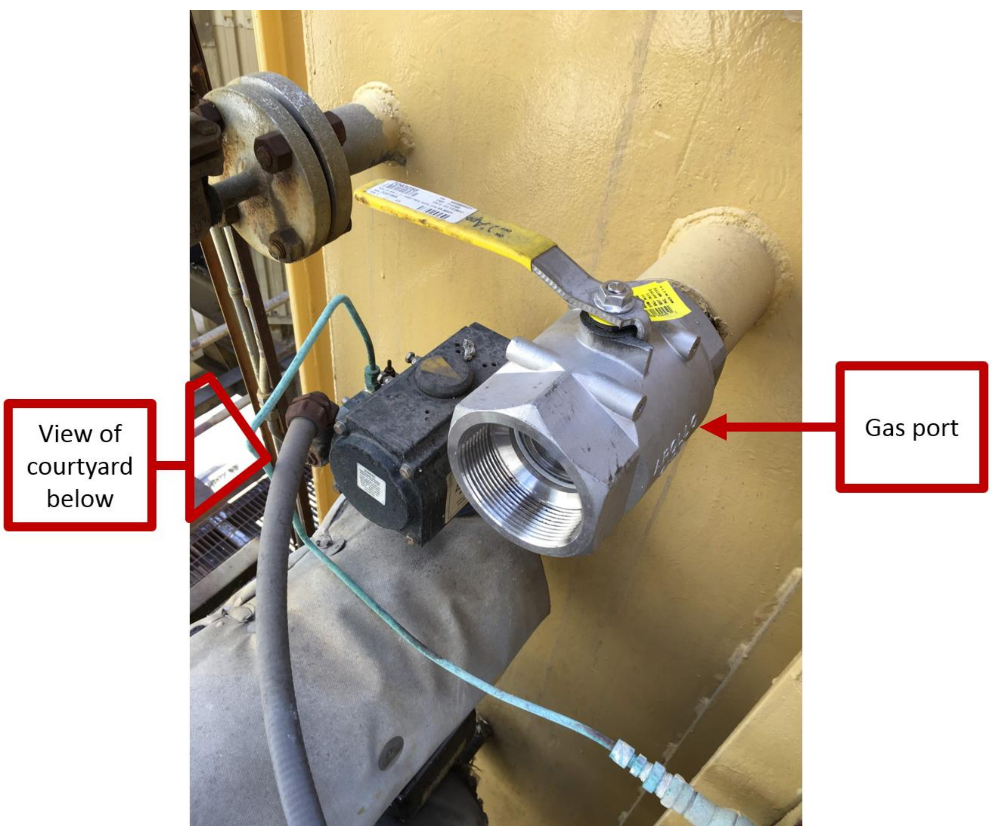


Figure 5. Gas port location.

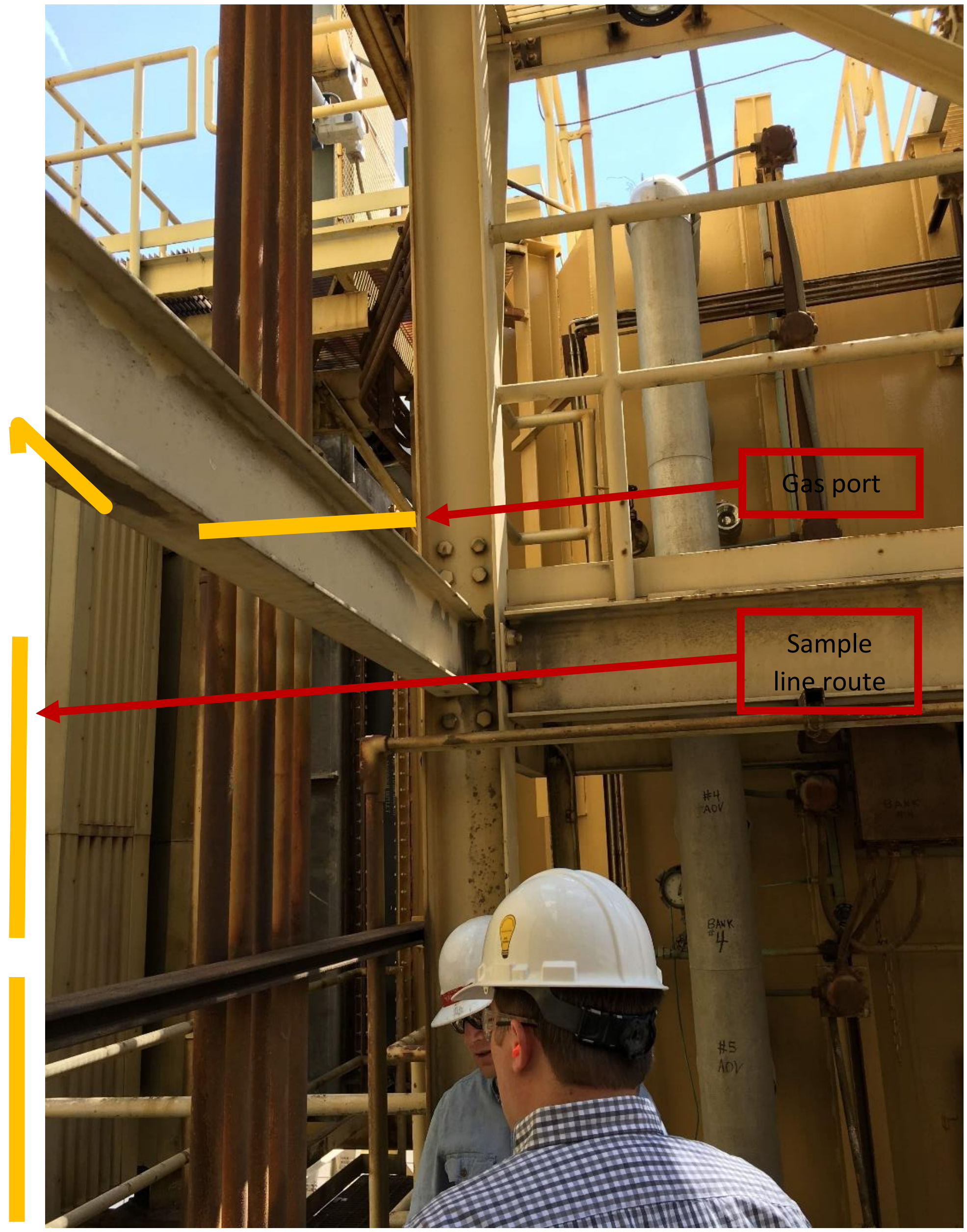


Figure 6. Gas port location and start of sample line to ECL testing skid.

Over the next several weeks, we will finish arranging the piping and electrical layout so we are ready for testing in October.

Documentation of Insurance, Transport, Personnel Trailer, Other On-site Needs

Insurance

Find below relevant pages for insurance currently in place or that will be activated before we arrive on site. This includes workers compensation, general liability, excess liability, and auto. More documentation is included as a separate attachment.

EMPLOYERS

EMPLOYERS PREFERRED INS. CO.
A Stock Company

Workers' Compensation and Employers Liability Insurance Policy

Policy Number	Policy Period From	To
EIG 2110803 04	05/25/2018	05/25/2019
	12:01A.M. Standard Time at the address of the Insured as stated herein	

Transaction		
AMENDED DECLARATIONS	Effective: 05/25/2018	
NCCI Carrier # 31283 **WCIRB CARRIER#**	**PRIOR POLICY NUMBER** EIG211080303	

1. Named Insured and Address	Agent
SUSTAINABLE ENERGY SOLUTIONS 1489 WEST 105 NORTH OREM UT 84057	TRUSTCO INC 1362000 2735 E PARLEYS WAY STE 305 SALT LAKE CITY, UT 84109-1666 Telephone: 8012785341

Customer #	Carrier #	FEIN #	Risk ID #	Entity of Insured
	31283	261659060	430422049	LIM LIABILITY CO

Additional Locations:

2. The Policy Period is from 05/25/2018 to 05/25/2019 12:01 a.m. Standard Time at the Insured's mailing address.

3. A. Workers Compensation Insurance: Part ONE of the policy applies to the Workers Compensation Law of the states listed here: UT

B. Employers Liability Insurance: Part TWO of the policy applies to work in each state listed in Item 3A. The limits of our liability under Part TWO are:

Bodily Injury by Accident	$	1,000,000	each accident
Bodily Injury by Disease	$	1,000,000	policy limit
Bodily Injury by Disease	$	1,000,000	each employee

C. Other States Insurance: Part THREE of the policy applies to the states, if any, listed here:
All states except AK, DE, HI, ND, NH, OH, RI, WA, WV, WY and states listed in item 3.A.

D. This policy includes these endorsements and schedules: See attached schedule.

4. The premium for this policy will be determined by our Manuals of Rules, Classifications, Rates, and Rating Plans. All information required below is subject to verification and change by audit.

SEE EXTENSION OF INFORMATION PAGE

ACORD®

CERTIFICATE OF LIABILITY INSURANCE

DATE (MM/DD/YYYY): 07/27/2018

THIS CERTIFICATE IS ISSUED AS A MATTER OF INFORMATION ONLY AND CONFERS NO RIGHTS UPON THE CERTIFICATE HOLDER. THIS CERTIFICATE DOES NOT AFFIRMATIVELY OR NEGATIVELY AMEND, EXTEND OR ALTER THE COVERAGE AFFORDED BY THE POLICIES BELOW. THIS CERTIFICATE OF INSURANCE DOES NOT CONSTITUTE A CONTRACT BETWEEN THE ISSUING INSURER(S), AUTHORIZED REPRESENTATIVE OR PRODUCER, AND THE CERTIFICATE HOLDER.

IMPORTANT: If the certificate holder is an ADDITIONAL INSURED, the policy(ies) must have ADDITIONAL INSURED provisions or be endorsed. If SUBROGATION IS WAIVED, subject to the terms and conditions of the policy, certain policies may require an endorsement. A statement on this certificate does not confer rights to the certificate holder in lieu of such endorsement(s).

PRODUCER Daniel Murray(762432M) 68 W Center St Midvale UT 84047-7388	CONTACT NAME: Daniel Murray		
	PHONE (A/C, NO, EXT): 801-569-2886	FAX (A/C, NO): 801-568-1320	
	E-MAIL ADDRESS: dmurray@farmersagent.com		
	INSURER(S) AFFORDING COVERAGE		NAIC #
INSURED SUSTAINABLE ENERGY SOLUTIONS, 1489 W 105 N OREM UT 84057	INSURER A: Truck Insurance Exchange		21709
	INSURER B: Farmers Insurance Exchange		21652
	INSURER C: Mid Century Insurance Company		21687
	INSURER D:		
	INSURER E:		
	INSURER F:		

COVERAGES CERTIFICATE NUMBER: REVISION NUMBER:

THIS IS TO CERTIFY THAT THE POLICIES OF INSURANCE LISTED BELOW HAVE BEEN ISSUED TO THE INSURED NAME ABOVE FOR THE POLICY PERIOD INDICATED. NOTWITHSTANDING ANY REQUIREMENT, TERM OR CONDITION OF ANY CONTRACT OR OTHER DOCUMENT WITH RESPECT TO WHICH THIS CERTIFICATE MAY BE ISSUED OR MAY PERTAIN, THE INSURANCE AFFORDED BY THE POLICIES DESCRIBED HEREIN IS SUBJECT TO ALL THE TERMS, EXCLUSIONS AND CONDITIONS OF SUCH POLICIES. LIMITS SHOWN MAY HAVE BEEN REDUCED BY PAID CLAIMS.

INSR LTR	TYPE OF INSURANCE	ADDTL INSD	SUBR WVD	POLICY NUMBER	POLICY EFF (MM/DD/YYYY)	POLICY EXP (MM/DD/YYYY)	LIMITS	
	COMMERCIAL GENERAL LIABILITY ☐ CLAIMS-MADE ☐ OCCUR GEN'L AGGREGATE LIMIT APPLIES PER: ☐ POLICY ☐ PROJECT ☐ LOC OTHER:						EACH OCCURRENCE	$
							DAMAGE TO RENTED PREMISES (Ea Occurrence)	$
							MED EXP (Any one person)	$
							PERSONAL & ADV INJURY	$
							GENERAL AGGREGATE	$
							PRODUCTS - COMP/OP AGG	$
								$
C	AUTOMOBILE LIABILITY ☐ ANY AUTO ☐ OWNED AUTOS ONLY ☒ SCHEDULED AUTOS ☒ HIRED AUTOS ONLY ☒ NON-OWNED AUTOS ONLY	N		606675062	07/01/2018	07/01/2019	COMBINED SINGLE LIMIT (Ea accident)	$ 1,000,000
							BODILY INJURY (Per person)	$
							BODILY INJURY (Per accident)	$
							PROPERTY DAMAGE (Per accident)	$
								$
	☐ UMBRELLA LIAB ☐ OCCUR ☐ EXCESS LIAB ☐ CLAIMS-MADE DED ☐ RETENTION $						EACH OCCURRENCE	$
							AGGREGATE	$
								$
	WORKERS COMPENSATION AND EMPLOYERS' LIABILITY ANY PROPRIETOR/PARTNER/EXECUTIVE OFFICER/MEMBER EXCLUDED? (Mandatory in NH) Y/N ☐ If yes, describe under DESCRIPTION OF OPERATIONS below	N/A					☐ PER STATUTE ☐ OTHER	$
							E.L. EACH ACCIDENT	$
							E.L. DISEASE - EA EMPLOYEE	$
							E.L. DISEASE - POLICY LIMIT	$

DESCRIPTION OF OPERATIONS/LOCATIONS/VEHICLES (ACORD 101, Additional Remarks Schedule, may be attached if more space is required)

2003 CHEVROLET SILVERADO; VIN: 1GCHK23153F168909

Kinsale Insurance Company

A.M. Best Company Rating: A- (Excellent)
Financial Size Category: VIII

QUOTE

RE: Sustainable Energy Solutions LLC
1193 South 1480 West
Orem, UT 84058

Submission #: 01243163
Quote Letter #: 03869263
Quote Date: 06/27/2018

We are pleased to offer the following quote. This quote is valid until 07/27/18. Please read carefully as the terms and conditions of coverage may differ from those requested. THIS IS NOT A BINDER OF INSURANCE.

Company: Kinsale Insurance Company

Policy Term: 10/01/2018 - 10/01/2019

Retro Date: n/a

Limits of Liability:

$5,000,000 Each Occurrence
$5,000,000 Annual Aggregate

Business Description: Design, build and operation of experimental CO2 separation technology

Schedule of Underlying Insurance:

General Liability:

Carrier:	Kinsale Insurance Company	Each Occurrence	$1,000,000
Policy Term:	10/01/2018 - 10/01/2019	General Aggregate	$2,000,000
Coverage Form:	Occurrence	Products / Completed Operations	$2,000,000
		Personal and Advertising Injury Limit	$1,000,000

Contractors Pollution Liability:

Carrier:	Kinsale Insurance Company	Each Occurrence	$1,000,000
Policy Term:	10/01/2018 - 10/01/2019	General Aggregate	$2,000,000
Coverage Form:	Occurrence		

Professional Liability:

Carrier:	Kinsale Insurance Company	Each Occurrence	$1,000,000
Policy Term:	10/01/2018 - 10/01/2019	General Aggregate	$2,000,000
Coverage Form:	Claims Made (Retro Date: Inception)		

Kinsale Insurance Company

A. M. Best Company Rating A- (Excellent)

Financial Size Category: VIII

QUOTE

RE: Sustainable Energy Solutions LLC
1193 South 1480 West
Orem, UT 84058

Submission #: 01242857
Quote Letter #: 03869189

Coverage Form: Commercial General Liability - Occurrence

Policy Period: 10/01/2018 - 10/01/2019

Retro Date: n/a

Description of Operations: Design, build and operation of experimental CO2 separation technology

We are pleased to offer the following quote which will remain valid until 07/27/18 unless extended and agreed to in writing by us. Please read carefully as the terms and conditions of coverage may differ from those requested. THIS IS NOT A BINDER OF INSURANCE.

Limits:	LIMITS OF INSURANCE
Each Occurrence Limit	$1,000,000
Damages to Premises Rented to You Limit	$100,000
Medical Expense Limit	Excluded
Personal & Advertising Injury Limit	$1,000,000
General Aggregate Limit	$2,000,000
Products / Completed Operations Aggregate Limit	$2,000,000
Additional Coverages:	**LIMIT OR AMOUNT**
Contractors Pollution Liability OCC	$1MM / $2MM
Contractors Professional Liability	$1MM / $2MM
Deductible:	
Per Occurrence	$5,000
Contractors Pollution	$10,000
Contractors Professional	$10,000
** All Deductibles include ALAE,BI and PD	

Page **2** of **8**

Transport

The three skid containers will be loaded onto two trailers for transport. As one of the containers has extra equipment on the roof, one trailer will be a double drop. We have verified that the trailers will be able to back into the space required where they will be unloaded. We have also verified the pricing for this transport and it will be within what was originally projected. After speaking with the personnel at Hunter Power Plant we have also received the contact for crane companies that have done work on the site in the past, and initial contact has been made with them for scheduling.

We will also be transporting up to two smaller modular units in the form of the distillation column and the Klaren Heat Exchanger. Each of these has been designed with transport in mind, and can fit side by side in the remaining space on the double drop trailer. We will also be able to lift both with the crane that will be unloading the containers.

SES has also confirmed with the site that we will be able to ship some of our cables and hoses previous to shipping the containers, to allow for easier setup on site and more flexibility for the plant's schedule during setup.

Two vehicles will be maintained near the plant for most of the testing period. This includes a truck owned by SES and a rental vehicle under a long-term rental agreement. The rental vehicle will largely transport SES employees to and from the Castle Dale area while the truck will be used for work on site and movement of the personnel trailer.

Personnel Trailer

The trailer has been purchased (Figure 7) and is being modified to be used as a control room and personnel trailer.

Figure 7. Personnel trailer to be used as the control room while testing at the Hunter Power Plant.

Ongoing Shakedown Skid-Scale ECL System Testing

Shell-and-Tube Heat Exchanger

The shell-and-tube heat exchanger is being tested as this is written. SES has been working closely with WSA engineered systems to find a solution for fouling in the shell-and-tube heat exchangers. It was hoped that because the geometry of this heat exchanger is so simple, the buildup of CO_2 on the surfaces may just flake off into the flow. This was shown in previous tests not to be the case. Future work will be completed as follows

1. Reverse the flow using a flow reversal valve provided by WSA - These test have already been completed with partial success. When brazed plate heat exchangers were being used in the ECL

skid, several mitigation strategies were developed to reduce the impact of fouling. These same strategies are being brought to bear on the shell-and-tube heat exchanger. It is hoped that these strategies in combination with the flow reversal valve will result in a heat exchanger that can be cleared and thereafter can be operated continuously.

2. Shuttle brushes or scrapers cleaning the heat exchanger - Should these strategies and flow reversals prove insufficient, a secondary approach will be used. WSA has developed shuttles in the form of brushes or scrapers that can traverse the length of each tube in the heat exchanger and can scrape the buildup off the walls. A cutaway of a single tube in the shell-and-tube heat exchanger is shown in Figure 8 and a photograph of a brush made for our shell-and-tube heat exchanger is shown in Figure 9. To describe how this works, imagine that there is flow passing through the tube labeled “Heat Exchange Tube” in Figure 8. When the fluid is flowing from left to right, the brush is held in the position shown at the end of the heat exchanger. The fluid can flow through slots and around the brush. When the flow is reversed, the brush is pushed through the tube to the other end of the heat exchanger. Thus, the tube is brushed clean of any deposits and the heat exchange can continue unimpeded.

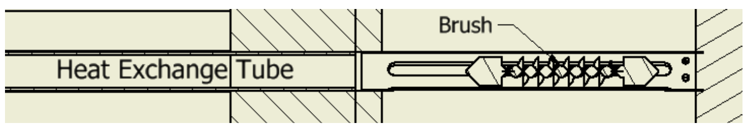


Figure 8. Cutaway of a single tube in the shell-and-tube heat exchanger.


Figure 9. Photograph of brush made to clean the SES heat exchanger.

One preliminary test with the brushes has been completed, but this test was inconclusive and will have to be repeated. Current testing is focusing on the first strategy with no scrapers, but the scrapers will be used as necessary.

Falling Film Fluidized Bed Heat Exchanger

SES recently installed and commissioned the falling film fluidized bed heat exchanger (FBHX). The FBHX is a vertical shell-and-tube heat exchanger (Figure **10**,Figure **11**). Liquid nitrogen is pumped to the top of the shell side, and is distributed around a single tube, forming a falling film that cools the process liquid flowing upward within the tube. A bed of fluidized particles suspended within the tube continually scours the walls of the tube, preventing build-up of solid CO_2. In traditional heat exchangers, this build-up of CO_2 causes a rapid increase in pressure drop and eventual failure due to insufficient fluid flow and heat transfer.

Figure 10**. The FBHX enclosed within its insulating coldbox, being moved into position**

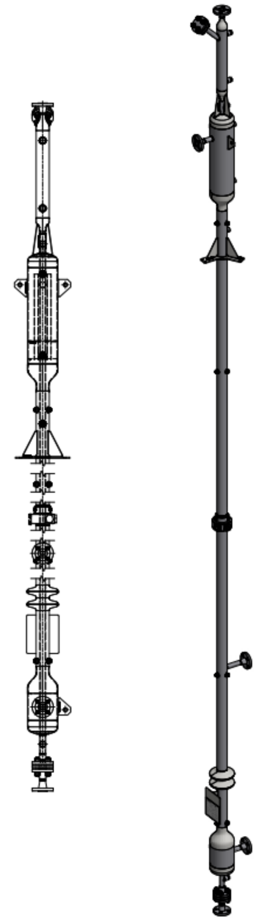


Figure 11**. Drawing of FBHX supplied by Klaren International.**

The FBHX was designed and built by Klaren International. Klaren sized the heat exchanger to deliver approximately 10 kW of cooling at −140 °C with liquid nitrogen as the shell side refrigerant. This sizing was based on our best estimates of viscosity and other fluid properties of the slurry, which have historically been very difficult to obtain.

SES completed installation including instrumentation, coldbox design and construction, and plumbing. SES tested the FBHX over the course of about six weeks. Initial tests were promising, as there was no rapid increase in pressure drop during a 7-hour run on June 21 (Figure 12) and a 5-hour run on June 26 (Figure 13). (The gradual upward trend in pressure drop is due to the increasing concentration of solid CO_2 within the slurry phase and is an expected occurrence during startup.) Unfortunately, the FBHX was not able to deliver the heat transfer required to desublimate one tonne per day of CO_2. Nevertheless, SES gained valuable experience and data that, in the future, may inform the sizing of a larger heat exchanger. One simple way of sizing up the heat exchanger would be to add a second tube, for example. Such a heat exchanger would occupy roughly the same footprint.

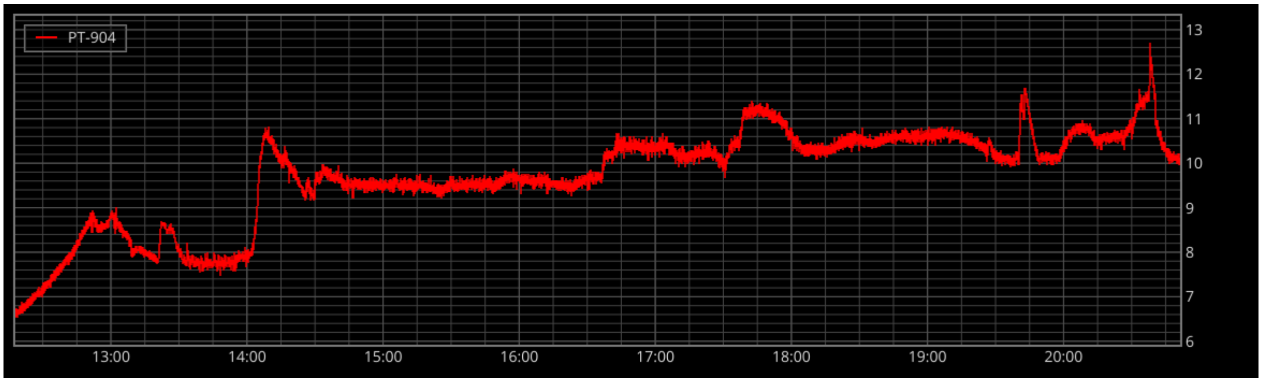


Figure 12. Pressure-drop data from June 21, 2018.

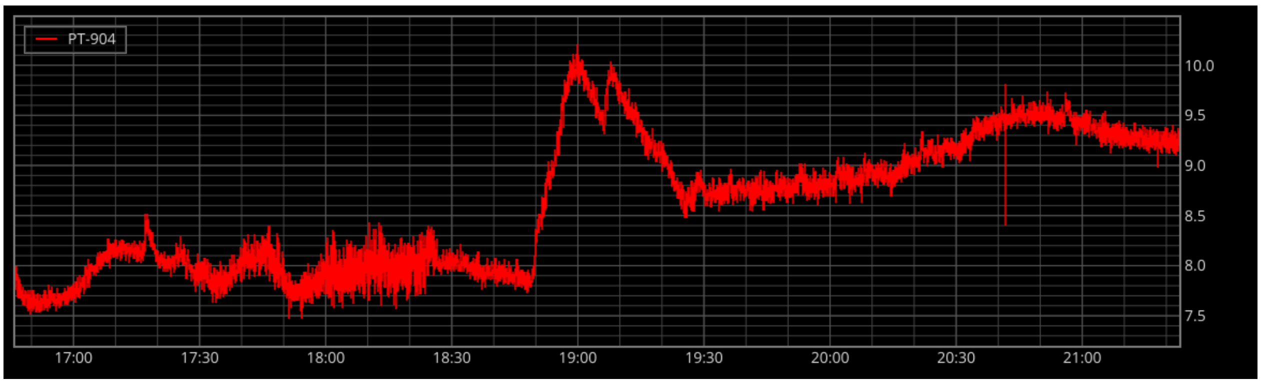


Figure 13. Pressure-drop data from June 27, 2018

QUARTERLY REPORT AND MILESTONE SUBMISSION

February 26, 2019

Submitted by

Submitted to

Sustainable Transport and Energy Plan (STEP)

Overview

This project modifies specific unit operations in an existing research and demonstration unit (the ECL skid) provided by Sustainable Energy Solutions (SES) to improve process efficiency, reliability, or overall performance. These modifications include experimental systems developed by SES. This second project phase includes skid transportation, on-site testing at an RMP facility and any modification during that time. This report details the work done towards the seventh milestone of this project.

Quarterly Milestones

As indicated in the Scope of Work for this project, the seventh milestone involves setting up the ECL skid on site at the Hunter Power Plant, as well as a report of testing to date. This milestone was delayed from its original projected date due to delays from equipment manufacturers and some additional modifications that were required to be done to the skid before going on site. The exact wording of the milestone is below.

Q7	**SES will deliver the following:** **- Finalized setup and operation of the ECL Skid at the Hunter PP.** **- A full report of the testing to-date under RMP funding, with continued testing occurring under the NETL contract.**	**11/15/2018**	**$ 309,118**

Finalized Setup of the ECL Field Test Units at the Hunter Power Plant

On December 17th, the three ECL field test skids were loaded onto two trailers for transport. We used a double drop trailer in order to transport the chiller skid, which has extra equipment on the skid roof. We had originally contracted one company to supply both trucks and drivers but, at the last minute, they were unavailable, and we were forced to acquire the services of two other drivers with their trailers, which ended up being much cheaper than originally planned.

We also transported our distillation column and several smaller pieces of equipment (additional cables, hoses and a liquid storage tank) using a SES-owned pickup truck and a rented flatbed trailer.

Upon arriving at the plant, we were met by a crane that had been contracted to unload the skids and place them in a small courtyard near one of the smokestacks, according to the unloading plan that was agreed upon by us and plant personnel (see Figure 1).

Figure 1. The SES Carbon Capture skids located in a courtyard at the Hunter Power Plant.

A slight change was made to the original placement plan: the chiller skid is now behind the RV control room instead of in front of it to avoid having to move the crane once it was in place (Figure 2). This also made it easier to run electrical power from the plant to the chiller skid. We required the use of a forklift to place the distillation column after it was unloaded, which was provided asnd operated by plant personnel.

A cable providing electrical power to our skids was routed by plant personnel prior to our arrival. It was suspended overhead across an existing metal scaffolding around the courtyard to a pillar next to the smokestack (Figure 2). SES had previously shipped some of our cables and hoses to the site, to allow for easier setup on site and more flexibility for the plant's schedule during setup. We used one of our extension cables to hook our skid directly to the power cable run by Hunter personnel. We also used hoses to run plant water to our skids for our cooling systems, as shown in Figure 2.

In preparation for testing, employees at the Hunter Power Plant had multiple ports installed for gas sampling. We hooked our hoses into two ports that are after the flue gas desulfurization unit where the flue gas stream temperature is typically near 45 °C (Figure 4–Figure 6). The gas will be drawn through a 4" stainless steel ball valve (Figure 5) and conveyed through a 4” hose down to the side of the walkway, across the header and down to the skid (Figure 4). The treated gas is then run back through a 3” hose to a second sample port very near to the first. The flue gas hoses were hooked into the gas sample port (Figure 5) by plant personnel and then we connected the other end of the hoses to our gas pre-treatment skid.

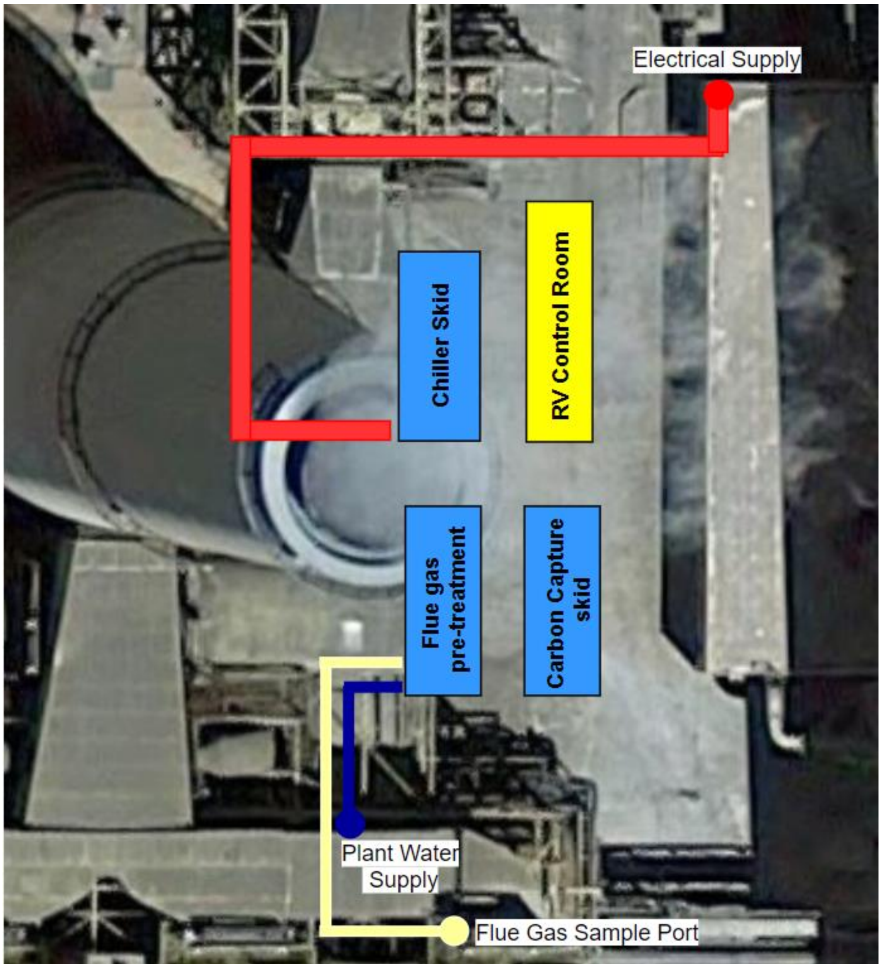


Figure 2. Configuration of the ECL testing skid with electrical routing diagram.

Figure 3. Electrical, gas sampling and water lines run from metal scaffolding (left) to the blue ECL skids.

Figure 4. Flue gas lines from gas pre-treatment skid heading to gas sample port.

Figure 5. Gas Port and 4" Hose

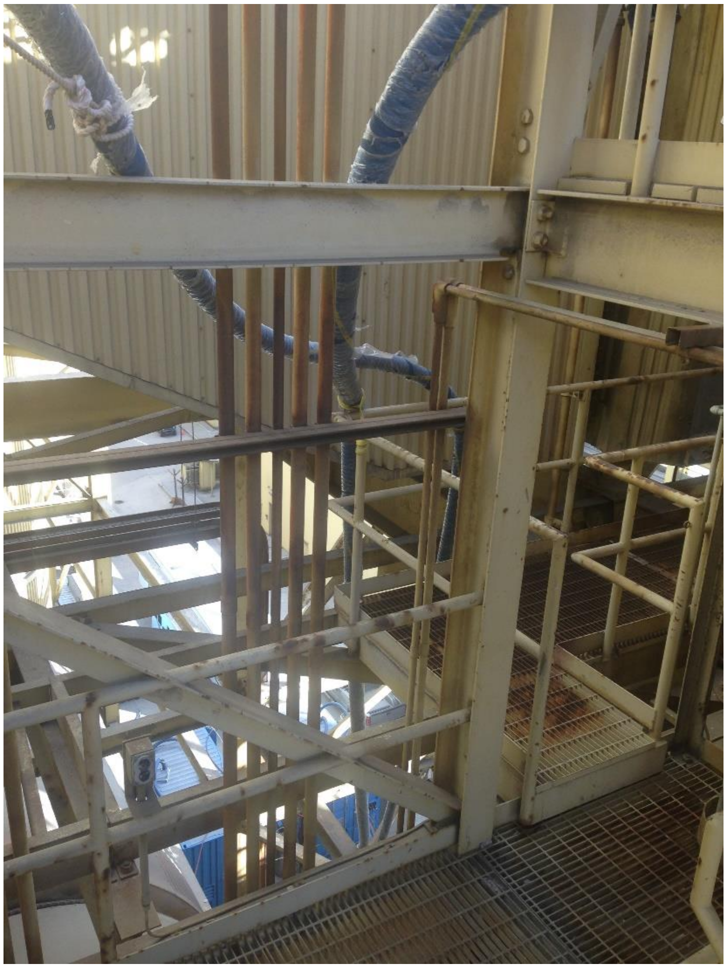


Figure 6. Sample lines to ECL testing skid (blue skids in the bottom left of the photo).

Personnel Trailer

The RV trailer (Figure 7) was purchased and modified to be used as a control room and personnel trailer. It was transported to the plant several days before transporting the skids and parked on-site at a place previously agreed upon with plant personnel. It was backed into place after all the skids were in place and then hooked into the plant electricity via the powered skids.

Figure 7. Personnel trailer to be used as the control room while testing at the Hunter Power Plant.

Early On-site Testing and Additional Modifications

On December 20th, after the skids were connected to power, water, and flue gas, we performed an initial cool down test without running flue gas. We were successfully able to cool down to our target temperature of –130 °C with all our equipment functioning correctly and without any problems. The following day, we performed a full test, including cool down and running flue gas. The test was successful but had to be shut down because of what appeared to be water accumulation in the recuperating heat exchanger, which led us to make the changes outlined in the section below: “Removal of Water from Flue Gas”. Unfortunately, because of the malfunction of one of our valves during this shutdown, water and contact liquid travelled into the gas pre-treatment lines and we were forced to drain the system and do a complete purge, which took several days, and we were unable to resume testing until early January 2019. During the system downtime and continuing during testing in January, we performed the following modifications to our system.

Removal of Water from Flue Gas

Upon initial testing of our carbon capture process on-site at the Hunter Power Plant, it was discovered that our current systems for draining water from the precooler and aftercooler during gas pre-treatment were insufficient, causing water to buildup and freeze in the recuperating heat exchanger. To improve water removal, we added a second cyclonic separator (Figure 8) after the precooler and decided to hook up a peristaltic pump (Figure 9) to a tube coming from the bottom of the separator (see #4 in Figure 8) to pull water out and to drain it more effectively.

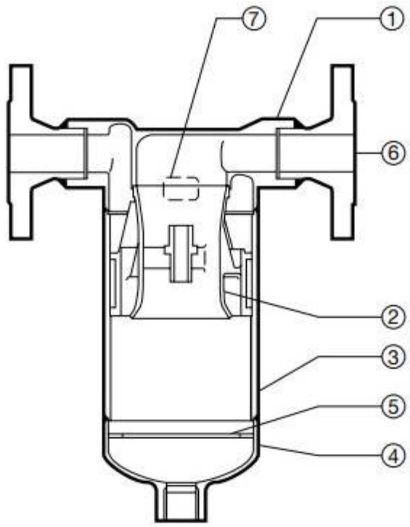


Figure 8. An example of the cyclonic separators used to separate water droplets from the flue gas stream during gas pre-treatment.

Figure 9. Peristaltic pump for draining the precooler cyclonic separator.

Upon initial testing of the separators and the new peristaltic pump, 6 gallons per hour were being drained through the pump and there was no evidence of water droplets in the gas after the second cyclonic separator.

Flue Gas Bypass

After testing resumed in January 2019, it became apparent that our system was not able to handle the high flow rates of flue gas with which we were dealing. Because it was not possible decrease the speed of the blowers (and therefore the flue gas flowrate) we installed a gas bypass (Figure **10**) that would allow us to take a slipstream of our current gas flow to be processed, with the rest of the gas being sent back up to the smokestack. The red globe valve pictured allows us to control the flow rate of the gas being processed.

While operating our process at SES headquarters, normal operation involved operating in a "closed loop" mode, circulating nitrogen gas through the system to reach thermal equilibrium before beginning to process CO_2. A second gas bypass (Figure **11**) was installed to allow us to run the system in this "closed-loop" mode, where we charge the system with nitrogen while we cool down the entire system before beginning to process flue gas.

Figure 10. **Flue gas bypass to allow us to decrease gas flow rate of gas to be processed.**

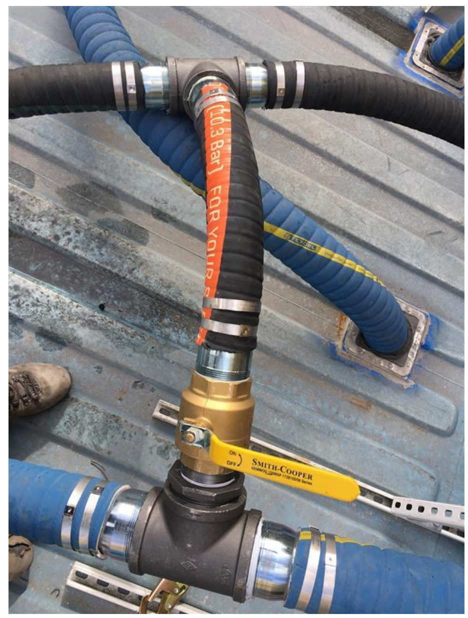


Figure 11**. Second flue gas bypass.**

Early Testing

Testing on-site from January 1, 2019 to the present has followed a very similar pattern. As we begin to process flue gas through the Carbon Capture skid, the pressure drop increases due to an increasing concentration of solid CO_2 in the slurry phase. Figure 12 shows negligible pressure drop over the course of 1.5 hours, as is to be expected and is what we normally seen during operation. Figure 13 also shows pressure drop over a period of 1.5 hours, in this case increasing much more rapidly than we have seen before, an indication of the buildup of solid CO_2 in the shell and tube heat exchanger. This fouling occurs even while employing flow reversal fouling mitigation measures (these measures cause the vertical lines in the data in Figure 13). We think that maybe some contaminant (probably water) was introduced into the contact liquid at a point between December 21, 2018 and January 12, 2019 that is causing this severe fouling. As this report is being written, we are in the process of filtering and purging the entire system to remove the contaminant.

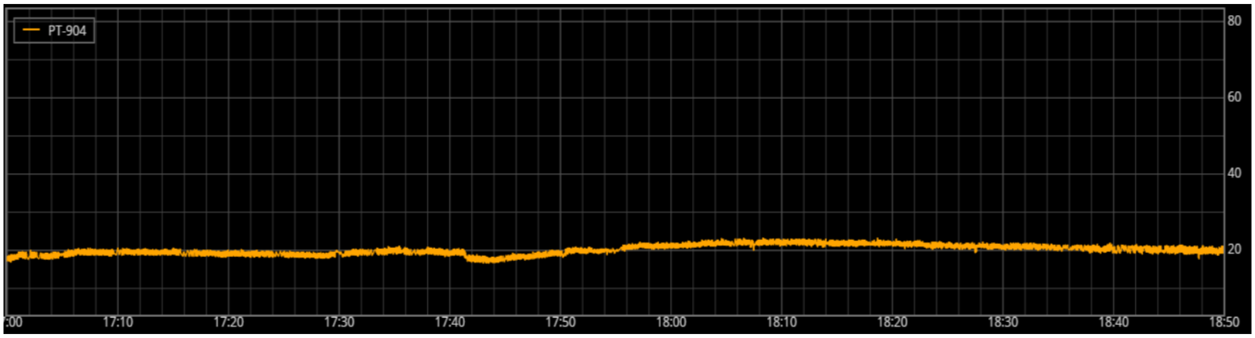


Figure 12. Pressure-drop data from December 21, 2018.

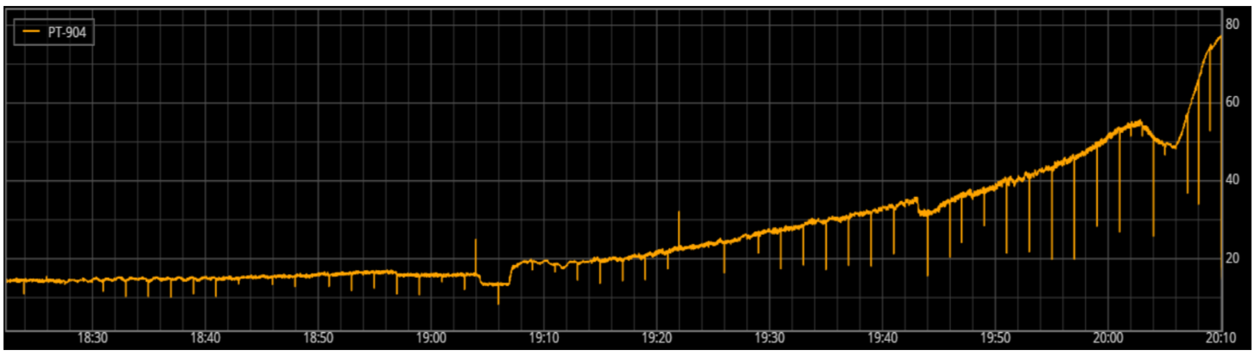


Figure 13. Pressure-drop data from January 12, 2019.

QUARTERLY REPORT AND MILESTONE SUBMISSION

November 13, 2019

Submitted by

SUSTAINABLE ENERGY SOLUTIONS

Submitted to

ROCKY MOUNTAIN POWER

Sustainable Transport and Energy Plan (STEP)

Overview

This project modifies specific unit operations in an existing research and demonstration unit (the ECL skid) provided by Sustainable Energy Solutions (SES) to improve process efficiency, reliability, or overall performance. These modifications include experimental systems developed by SES. This second project phase includes skid transportation, on-site testing at an RMP facility and any modification during that time. This report details the work done towards the seventh milestone of this project.

Quarterly Milestones

The eighth quarter for this project fell between two phases of the project, and as such had no milestone associated with it. As a general report, the following occurred during that time period.

Modifications made to the ECL Field Test Units at the Hunter Power Plant

Some of the pumps used during the initial phases of the testing showed higher than expected rates of wear. This was especially prevalent in the bearings of the pumps, which also created issues with contaminants downstream of the pumps. Senior engineers from the pump manufacturer and SES reviewed carbon 60, silicon carbide (SiC) bearings, bronze, graphite-impregnated bronze, PTFE-plug bronze bearings, needle roller bearings, and other options, and ultimately selected carbon 60 and a pump with larger bearings that runs at lower speed. The larger bearing surface now shows promise of wearing significantly slower.

Previous reports discussed the possibility of using scrapers or brushes to mitigate fouling. SES hypothesized that scrapers were keeping the tubes clean, but that the ends of the heat exchanger were allowing the accumulation of solids, which eventually blocked flow. SES designed and built inserts that direct the flow, and seemed to have significantly improved operation in the shell and tube heat exchanger.

Two newly designed in-line settling tanks remove SO_2, NO_x, and solid particulate matter (pollutants) from the process stream. Results confirmed that significant amounts of both water,solid particles, and SO_2 accumulated in the tanks from approximately 24 hours of operation. Hand valves on the tank drains to allow sample and drain the tanks. FTIR analysis of these materials will be in the report next quarter.

Skid Operation and Shakedown

Shakedown testing initially focused on water removal from flue gas before it reached the desiccant dryers. An additional cyclonic separator reduced the dewpoint to an acceptable level before the blowers and a peristaltic pump removes the condensed water. After these changes were made, the dew point remained consistently in an acceptable range.

Continued shakedown testing indicated that injecting flue gas while the recuperator was warm caused problems with cooling capacity and ultimately resulted in rapid fouling in the heat exchangers. A closed nitrogen recycle loop resolved this issue by establishing an appropriate temperature, after which CO_2 could be injected without causing the contact liquid to warm drastically.

SES continued to test the ECL unit using the Test Plan developed to structure the on-site testing as well as provide a framework for experimentation with the Skid ECL System. From the Test Plan, the field test is divided into three general periods. Objectives for these periods include:

On-site shakedown – This was the primary focus of the Q8 time period

- On-site quality check to evaluate leaks, structural issues, equipment alignment, or other problems that occurred during transport and setup.
- Integration and acceptance testing of power plant flue gas stream, process water, and electrical systems and connections.
- Process test runs to make sure all safety and controls systems are operational.
- Thorough testing and setup of pre-treatment systems that could not be tested in a laboratory setting.

Process optimization

- Test runs will use lessons from experiments done on the integrated system in the lab and will include longer test runs to ensure that the full system is operating as expected.
- The method for operating the system may change during this time to adapt to power plant conditions, including temperature and pressure of the flue gas stream and the total available cooling that we are able to achieve.

Long-term testing

- This period of testing is focused on achieving long-term runs and gathering data, including at least one 500-hour test run at nominal 1 tonne CO_2/day at above 90% capture.

Both shakedown and process optimization took longer than expected and delayed the start of the attempts at long-term testing. During this period SES also optimized multiple operating parameters for real flue gas, as listed in the test plan previously prepared by SES. These tests helped create more stable operation. For example, SES has created a new method for screw press operation based on the differential pressure between the melter and the outlet from the slurry pump, which provides a more accurate prediction of slurry behaviour than previous parameters.

QUARTERLY REPORT AND MILESTONE SUBMISSION

April 15, 2019

Submitted by

SUSTAINABLE ENERGY SOLUTIONS

Submitted to

ROCKY MOUNTAIN POWER

Sustainable Transport and Energy Plan (STEP)

Overview

Sustainable Energy Solutions (SES) worked through several modifications to the existing Cryogenic Carbon Capture™ (CCC) process under DOE and RMP support over the last year. These modifications improve the reliability, and in some cases, decrease the energy and economic costs of the process. SES is currently demonstrating these changes with a field test at an RMP site (Hunter Power Station).

As SES improved the reliability of these unit operations, SES also innovated technologies that have the potential to replace existing unit operations with reliability and energy efficiency benefits. SES is also actively planning for the next scale of CCC operation and will explore the scalability of these and related unit operations as part of this investigation. These include:

1. Simultaneously drying and cooling the flue gas to the CO_2 frost point.
2. An alternative cooling and solid–liquid separation system for the contact liquid. This will also include the development of a pollutant removal system for SO_x and NO_x built into this separations system and the CO_2 purification system.
3. Investigate unit operation scalability

Quarterly Milestones

As part of this project, SES reports quarterly on the progress made towards the above objectives. The exact wording of the milestones for this quarter are as follows:

Q9	SES will deliver a report containing the following: Task A1 – Finalized integrated dryer design. Results of experiments used to validate design. Equipment sourced. Task A2 – Final selection of the solid–liquid system, or other	4/15/2019	$ 95,249

system designed to meet the same requirements, which will be tested. Initial long lead time parts ordered. Assessment of pollutant removal options and modeling of basic design of system.

Task A1. Gas drying and cooling

Objective

The objective of this task is to mature the direct-contact cooling and drying systems to the point they can be tested in the skid.

Experimental Work

During the last few months, SES has tested its direct-contact phase-change (DCPC) dryer concept using two bench-scale proof-of-concept prototypes and the results from these tests are promising. This dryer works by cooling the gas in a direct-contact heat exchanger; as the gas cools, water vapor is condensed and dissolved in the heat exchange liquid (DCPC liquid) leaving a cold dry stream for further processing. In pilot- and full-scale CCC processes, the gas from the dryer enters a desublimator and is cooled further to separate CO_2. The light gases (N_2 and O_2) that leave the CCC process are used to chill the DCPC liquid (currently a methanol–water mixture) through a reverse bubbler, spray tower, or other direct-contact heat exchanger (see Figure 1). As the mixture is chilled in the reverse bubbler some of the water in the water–methanol mixture freezes and is filtered out of the stream, thus maintaining the concentration of the mixture.

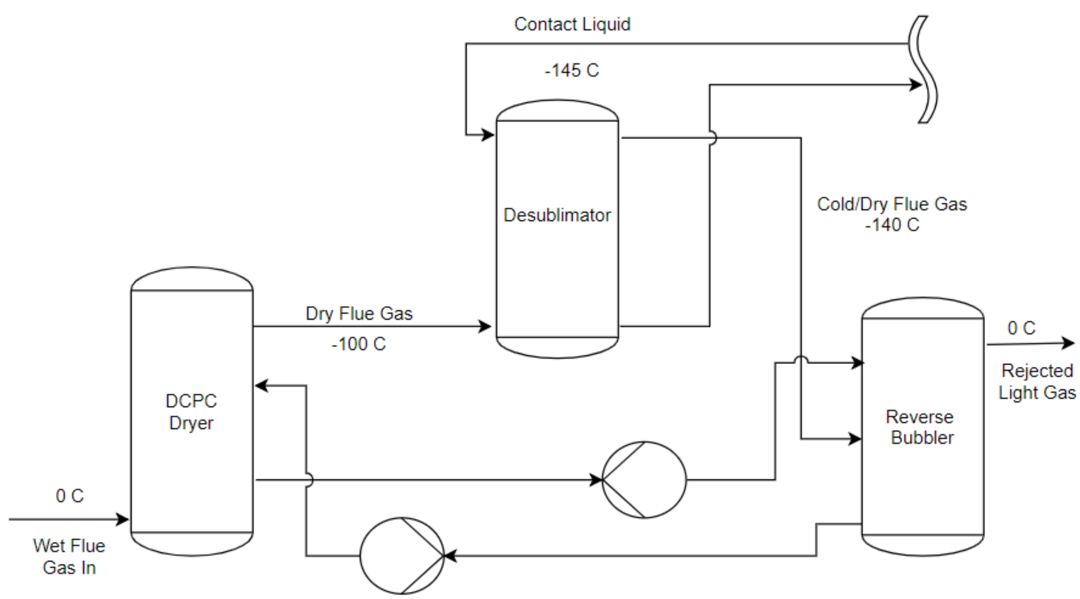


Figure 1. Simple process flow diagram showing the current process for drying and capturing CO_2 from CO_2-rich light gas streams.

Cooling for the DCPC dryer was provided using a Polycold industrial refrigeration system with temperature control and data logging using an existing bench-scale unit operations test stand (see Figure 2 and Figure 3).

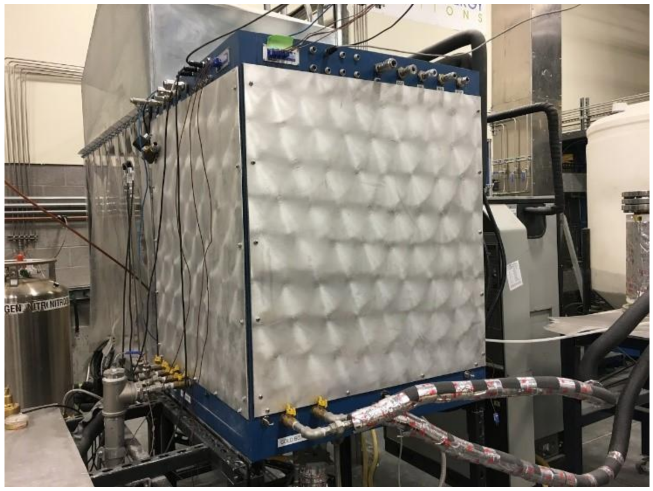


Figure 2. Bench-scale unit operations test stand at SES

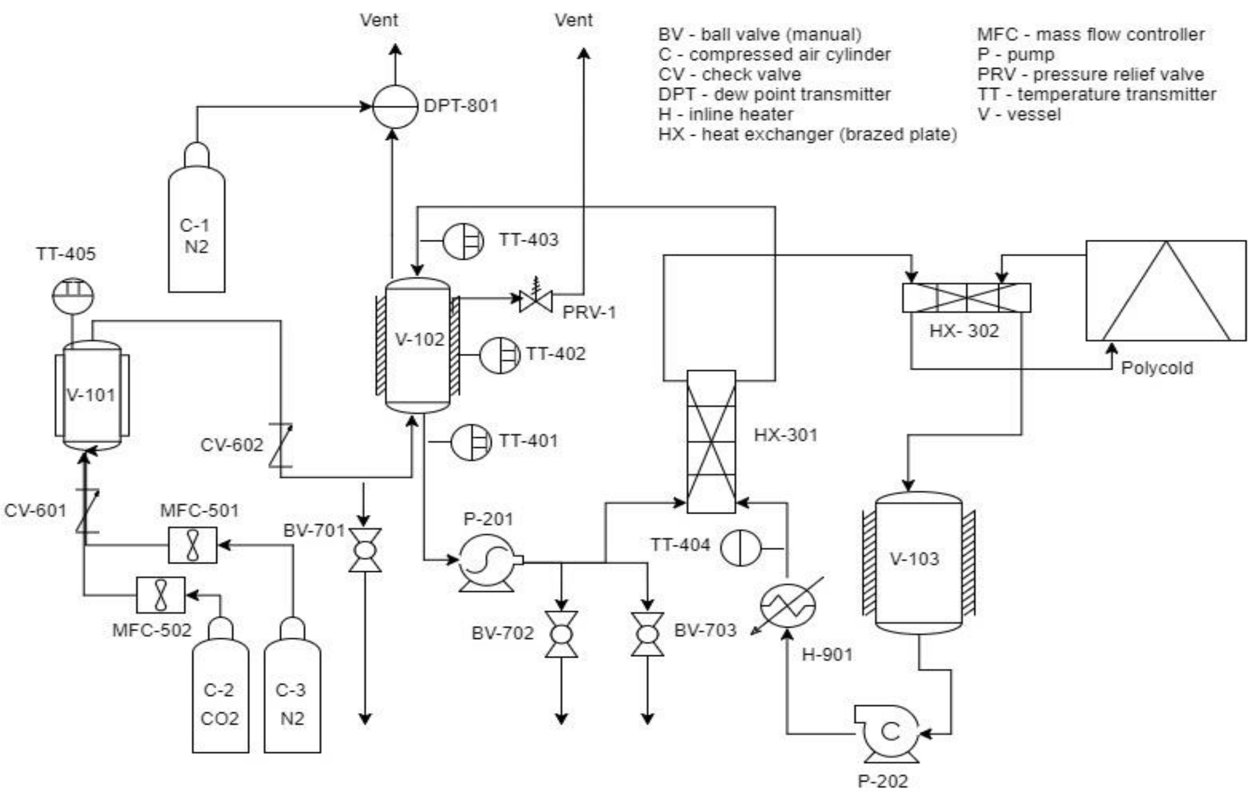


Figure 3. P&ID of DCPC dryer setup in bench-scale unit operations test stand at SES.

Design work for the prototype DCPC dryer focused on scaling up to the skid- and pilot-scale systems. The DCPC prototype allows quick changeover for testing spargers in bubbler tests, but it can easily accommodate packing (Figure 4).

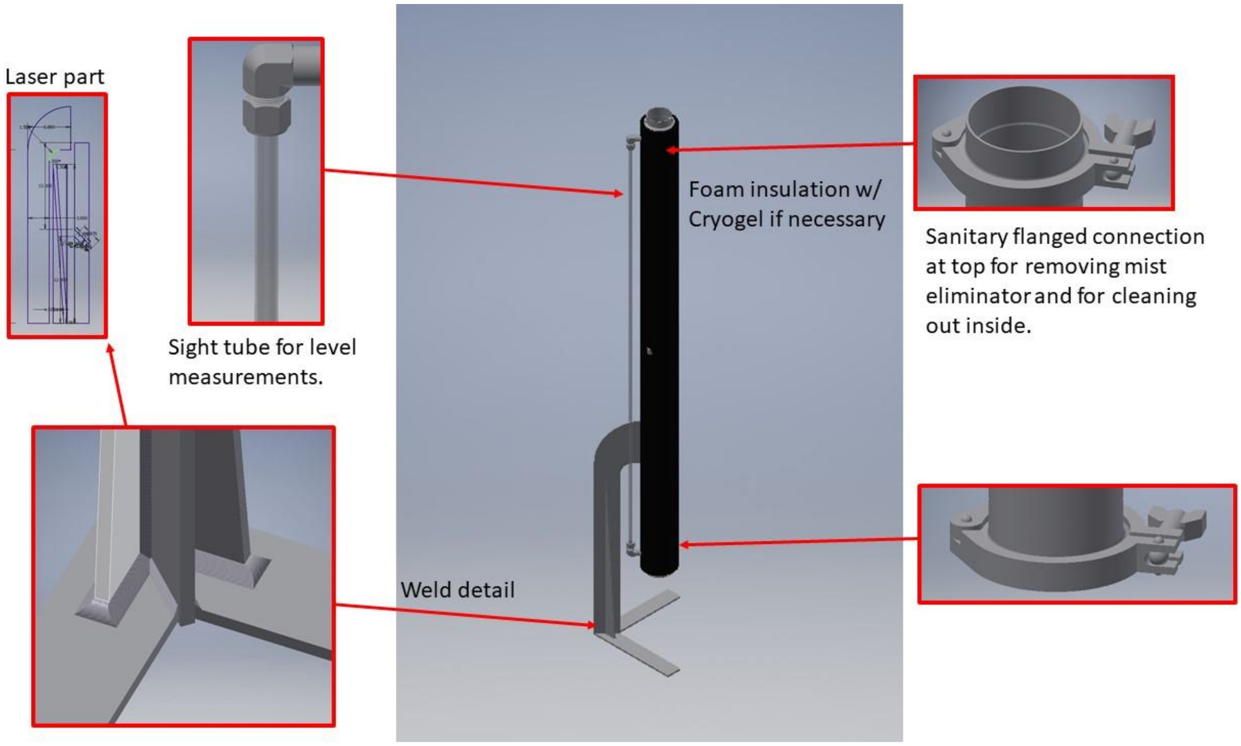


Figure 4. CAD drawings of DCPC prototype.

Results from Testing

Various tests were completed in March and April 2019. In these tests, the DCPC liquid was chilled to a temperature between −60 and −100 °C. A gas stream comprised of nitrogen and water vapor was fed into the heat exchanger with the temperature and dew point measured at the outlet. Water removal was measured using a film-polymer hygrometer (dew point transmitter) in the gas and by measuring the changing composition of the DCPC liquid as the water condenses from the gas phase. In each test, water was effectively removed from the gas and verified using both measurements. Figure 5 shows the liquid temperature of the DCPC liquid as it enters and leaves the dryer.

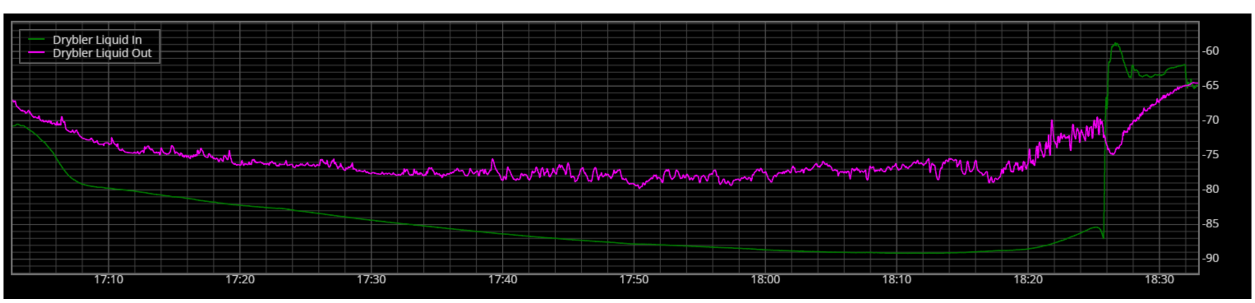


Figure 5. Inlet and outlet DCPC liquid temperatures during testing (4/2/2019).

There is some disagreement between the gas temperature and the dew point measurements during testing on the bench-scale system (Figure 6), but we believe these discrepancies can be reconciled and that we can avoid future discrepancies in skid-scale testing. The first error is in the gas outlet temperature measurement. The test was designed to hydrate and then dry a 1 SCFM stream, but the thermal mass of that stream is so small that heat conduction from the thermowell in the outlet gas line significantly affects that measurement. In tests at the design flow rate, the gas temperature reading is always high. Increasing the flowrate lowers the temperature reading, but causes carryover of the DCPC liquid, which affects the dew point reading. These problems can both be easily mitigated on the skid-scale DCPC design. The current skid-scale design uses a packed column direct-contact heat exchanger to mitigate splashing and liquid carryover with an optional small polishing bed for removing microdroplet carryover if it is observed. The flowrate will also be higher, so conduction through the thermowell into the gas stream will have a much smaller effect.

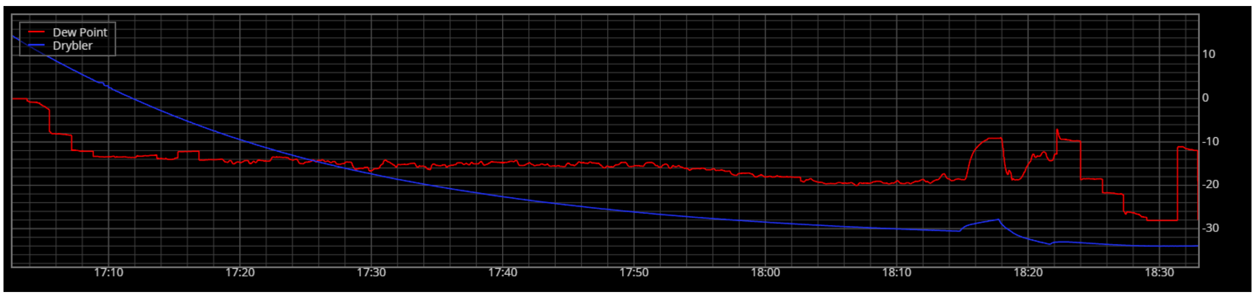


Figure 6. Gas outlet temperature (Drybler) and dew point measured during testing (4/2/2019).

Skid-Scale to Full-Scale Comparison

The full-scale DCPC dryer modifies the flue gas recuperator shown in previous process designs. At skid-scale, it could either replace a two-stream flue gas recuperator and add a small load to the refrigeration system that is already included in the skid system or it could be implemented as a separate system with more limited integration. Figure 7 shows integration with the DCPC dryer replacing the recuperator and Figure 8 shows the DCPC dryer as a stand-alone piece of equipment with limited integration into the process. At this point, both options are feasible, but the stand-alone option is a simpler modification.

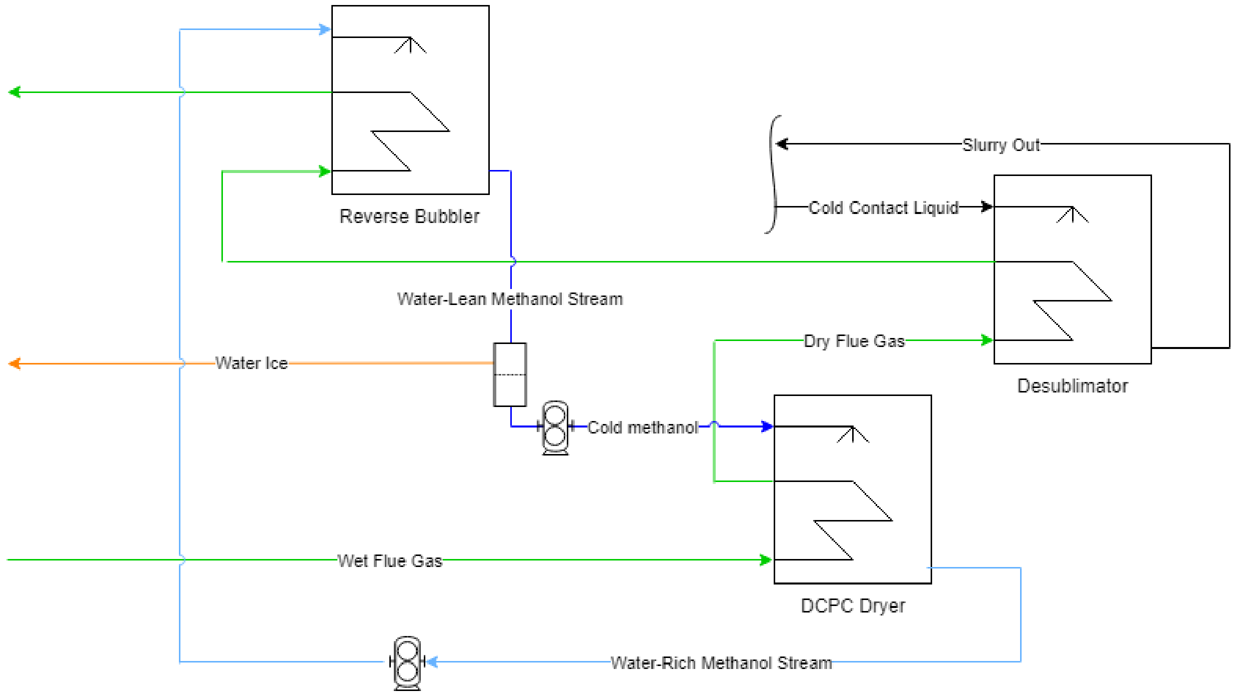


Figure 7. Full integration of DCPC dryer, including the replacement of the recuperating heat exchanger from earlier process designs

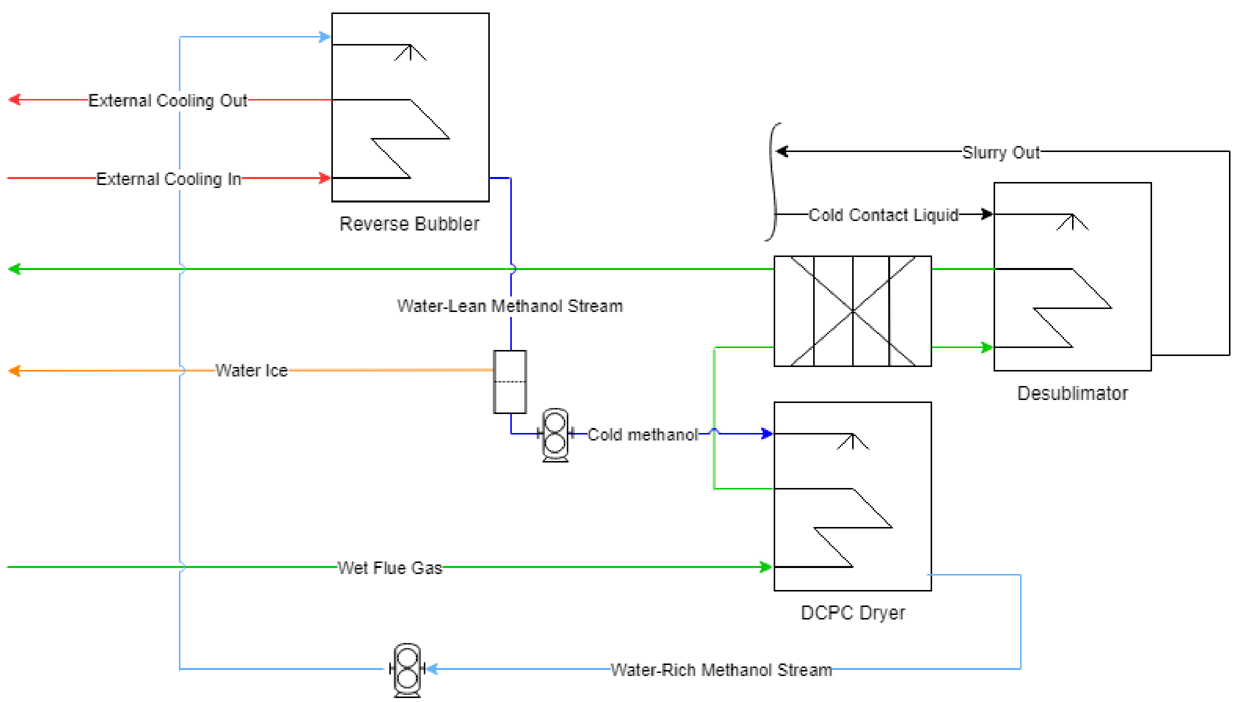


Figure 8. Stand-alone DCPC with limited integration.

Component Sourcing

The skid-scale DCPC dryer will include two fairly standard low-pressure vessels: one vessel where water is removed from the gas and a second where water will be removed from the water–methanol mixture to keep the mixture concentration constant. Two different commercial gear pumps and one disc pump (built in-house at SES) were tested on the DCPC prototype. Each of these pump options is available for the skid-scale DCPC system.

Instrumentation has also been sourced and some has been ordered (Table 1). A low-temperature in situ digital refractometer has been ordered to replace the handheld refractometer in Figure 9.

Figure 9. Hand-held refractometer reading to check water–methanol composition. This instrument will be replaced with a low-temperature digital refractometer for in situ measurement of composition.

Table 1. Equipment for building and testing DCPC dryer.

Equipment	Source
Methanol Slurry Circulation Pump	Discflo 2015-8-2HHD
Reverse Bubbler	Custom vessel – non pressure rated
DCPC Dryer	Custom vessel – non pressure rated
Cryocoolers	Recharged Polycold 4000H and 2500L
Pressure Transducers	Pressure Transducers Direct
Refractometer	Afab PR-1000

Task A2. Solid-Liquid Separation and Contact Liquid Cleaning

Objective

This task develops a liquid–solid separation device that produces high-purity (>90%) solids while cooling and purifying liquids sufficiently that they can be reinjected into the desublimating heat exchanger, including the initial evaluation and design of a pollutant removal system that will be placed in the separations system or in the CO_2 purification system.

Description of Selected Separations System

SES has selected to continue development of the separations device included in the original proposal for this project. The primary focus of this device will be shifted towards designing an experimental apparatus for the sintering aspect of the process, where the actual high-purity CO_2 liquids will form. In addition to this device, SES will also perform experiments on a liquid–liquid extraction process, which cleans the remaining dissolved CO_2 out of the outgoing stream from the solid–liquid separations device. By focusing on these aspects of separations, we should be able to address two of the key challenges we face in our current system.

The primary separations device is comprised of two parts. The first separates the solids from the liquids from the slurry that enters the device. This can be accomplished either with a solid–liquid separator previously developed at SES, or with a novel device that works by positioning the auger at an angle such that liquid flows toward the bottom through the flights while the auger conveys solids toward the top. In either device, the stream pressurizes the solids near the top of device through a tapered bore, change in flights, or extrusion into the next section. The bottom of this device is externally cooled, which cools the contact liquid that exits from the bottom and which precipitates the residual dissolved CO_2. The residual CO_2 forms on the inside walls of the lower section. The screw in this section of the device removes it as it accumulates on the walls.

The second part of the device, and the portion which we will be focusing on for this project (Figure 10), warms the now mostly dry solids as they flow toward the bottom. At the bottom, the solids are near their melting temperature. As the solids warm, residual liquid, which is lighter than the solids, flows out of the increasingly less porous solid block. These liquids eventually join the liquid stream at the bottom of the first device (not shown in the figure) and recirculate to the desublimating heat exchanger.

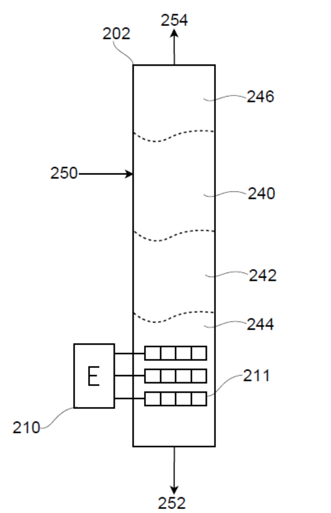


Figure 10. Second stage of the solid–liquid separator. A nearly pure but cold and porous solid enters at 250. The solid is compressed, warmed, and melted as it approaches the exit (252). The lighter liquids separate from the solids as the solids compress and melt, then exit the system near the top (254). Note: the exit is more likely to be on the side than on the top as illustrated.

Description of Experimental Liquid–Liquid System

An additional aspect of the separations and purification system that must be explored is the removal of any remaining CO_2 before it reaches the cooling heat exchangers. Mitigations for the fouling caused by this CO_2 have been developed by SES, however they are currently less efficient and more expensive than desired. A much better solution would be to remove any remaining dissolved CO_2 before it reaches these heat exchangers.

One proposed method for elimination of the dissolved CO_2 is by liquid–liquid extraction. The cold clarified isopentane can be mixed with an immiscible fluid that has a greater affinity for CO_2 than the isopentane. The dissolved CO_2 will preferentially move from the isopentane liquid phase into the other liquid phase. This leaves the isopentane with less dissolved CO_2 than when it entered the unit operation. A single-stage operation should result in isopentane of sufficient purity to mitigate fouling in the subsequent isopentane cooling heat exchanger. If a single stage proves insufficient, a multi-stage liquid–liquid extraction process is also possible. The second liquid phase will then have to be purified via a classical distillation separation. However, the required flow rate of the second liquid phase is much smaller than the amount of isopentane in the system. Additionally, the immiscible liquid can be selected in order to minimize the energy required for distillation. This simply requires a compound to be selected that has a vastly different volatility than CO_2. The small flowrate and volatility difference should lead to a relatively small energy penalty for the distillation process. There are many compounds that could work, but we have identified the ether class as the most promising at this point, specifically dimethyl ether and diethyl ether have favorable properties and are the leading candidates right now.

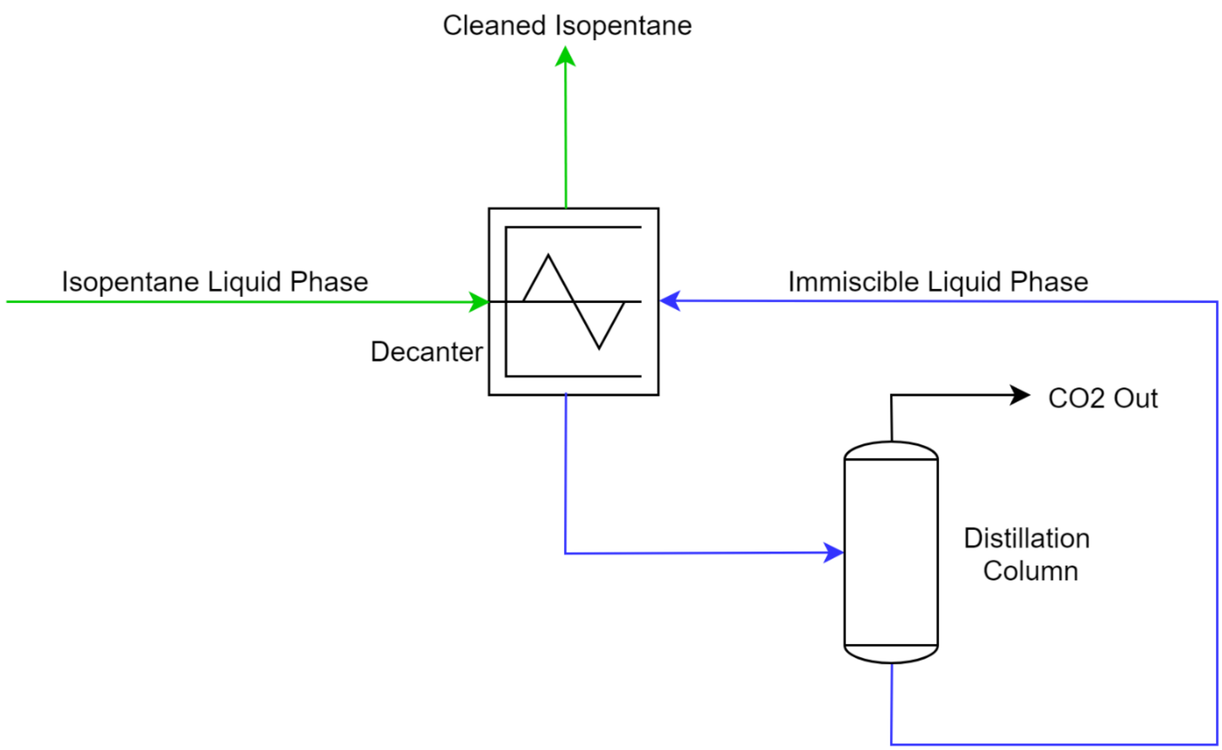


Figure 11. Liquid–Liquid extraction conceptual process

Description of Pollutant Removal System

Included in the exploration of possible separations and purifications technologies are processes for the removal of pollutants such as SO_x and NO_x. These pollutants condense at temperatures higher than CO_2 and will be caught in the overall capture process. Preliminary research has shown that a small portion of these pollutants will exit in the CO_2 stream after the distillation column.

The remaining portion may accumulate in the system over time. Based on our modelling, we believe that that this these contaminants must pass through the distillation column, and therefore we can capture them at this location.

Figure 12 describes one possibility for dealing with pollutants in the recirculating hydrocarbon stream. In this system, a vessel is designed near the distillation section of the process where there can be a quiescent zone. This area allows the heavier pollutants to separate out of the main flow by density and be removed a small amount at a time.

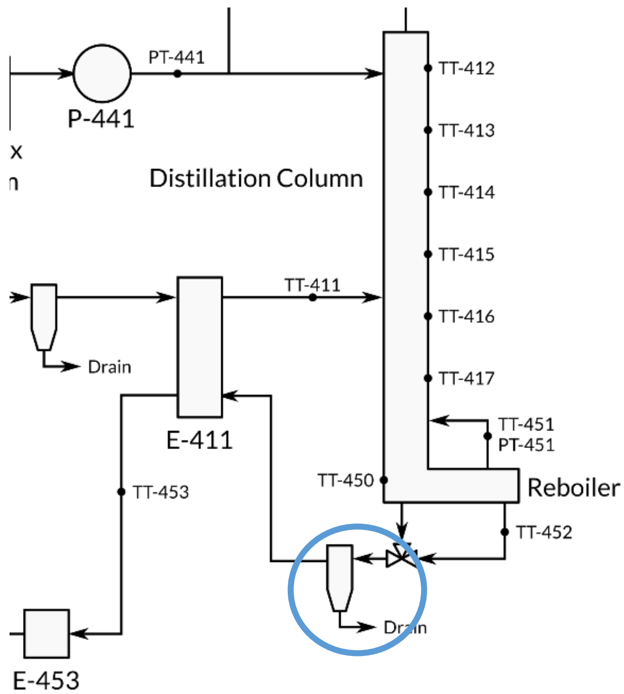


Figure 12. Pollutant removal location using modifications to existing distillation equipment.

QUARTERLY REPORT AND MILESTONE SUBMISSION

July 15, 2019

Submitted by

SUSTAINABLE ENERGY SOLUTIONS

Submitted to

ROCKY MOUNTAIN POWER

Sustainable Transport and Energy Plan (STEP)

Overview

Sustainable Energy Solutions (SES) worked through several modifications to the existing Cryogenic Carbon Capture™ (CCC) process under DOE and RMP support over the last year. These modifications improve the reliability, and in some cases, decrease the energy and economic costs of the process. SES is currently demonstrating these changes with a field test at an RMP site (Hunter Power Station).

As SES improved the reliability of these unit operations, SES also innovated technologies with improved reliability and energy efficiency that have the potential to replace existing unit operations. SES is also actively planning for the next scale of CCC operation and will explore the scalability of these and related unit operations as part of this investigation. These include:

1. Simultaneously drying and cooling the flue gas to the CO_2 frost point.
2. An alternative cooling and solid–liquid separation system for the contact liquid. This will also include the development of a pollutant removal system for SO_x and NO_x built into this separations system and the CO_2 purification system.
3. Investigating unit operation scalability

Quarterly Milestones

As part of this project, SES reports quarterly on the progress made towards the above objectives. The exact wording of the milestones for this quarter are as follows:

Q10	SES will deliver a report containing the following: **Task A1 –** Record of dryer system equipment being ordered. **Task A2 –** Finalized design and record of system ordered. Description of assembled solid–liquid or other separation	7/15/2019	$ 123,522

system. Designs and parts ordered for the pollutant removal system.

Task A1. Gas drying and cooling

Objective

The objective of this task is to mature the direct-contact cooling and drying systems to the point they can be tested in the skid. The quarterly objective is to order the main portions of the dryer system and prepare for future assembly and testing. We also conducted some additional testing of the dryer bench system.

Additional Results from Testing

Last quarter, we reported a difference between the dewpoint measurements and the actual temperature of the gas. One hypothesis for this difference was that liquid was splashing at the inlet and creating microdroplets that were being carried to the dew point transmitter with the exiting gas. We verified that liquid splashing was occurring at the top of the column by running the liquid loop with the column open to see how the liquid behaved internally. The image on the left in Figure 1 shows that there are in fact liquid droplets with velocities high enough that they are ejected from the column. This means that droplets are reaching the height of the gas exit port on the cap of the column during operation.

Figure 1. [Left] liquid enters the column at such a high velocity that droplets are launching out of the column (circled in blue) [right] Added tube diverts the stream by 90 degrees so that instead of hitting the column wall, it drops straight down, eliminating microdroplet creation.

We have attempted to prevent water microdroplets from humidifying the air stream by directing the stream downward instead of towards the side of the column. We added a section of tube inside of the column (pictured Figure 1, right) which successfully prevented liquid droplets from being launched upward toward the column cap. Additional mitigation strategies that may be included on the skid-scale direct-contact phase-change (DCPC) dryer include structured and/or random packing or a chilled splash guard.

Integrating the DCPC dryer with the skid

Figure 2 shows the desublimator coldbox on the skid-scale CCC system as it is currently configured at the Hunter Power Plant in Castle Dale, UT.

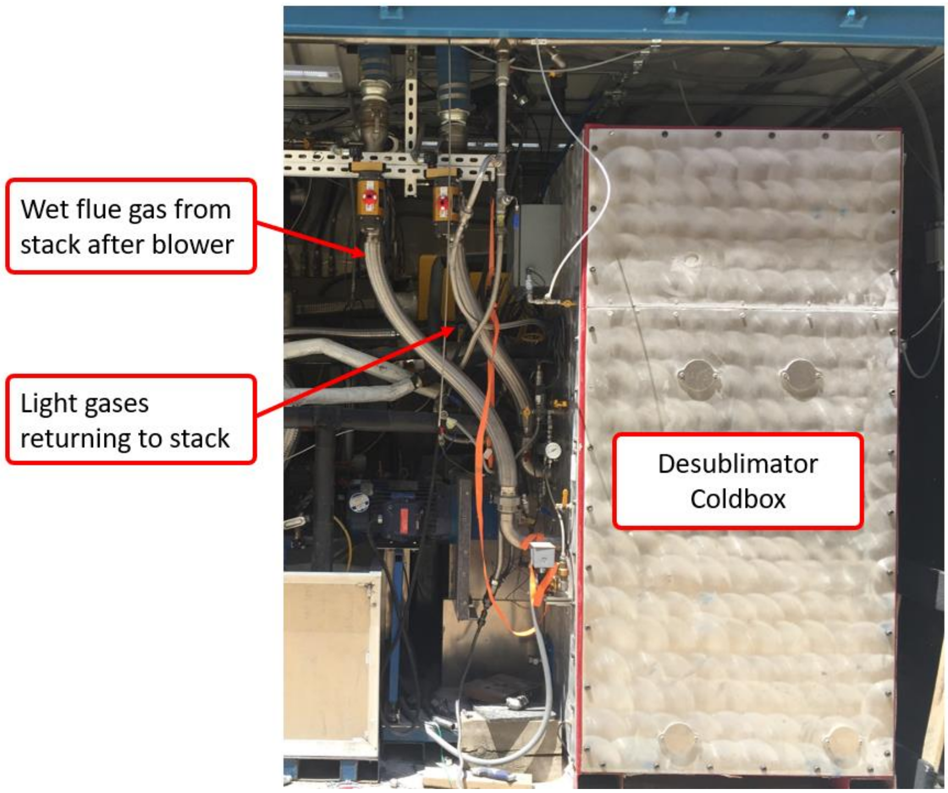


Figure 2. Desublimator coldbox with inlet (wet flue gas from stack after blower) and exit (light gases returning to stack) lines labelled.

The first of two possible configurations for the DCPC dryer is shown schematically in Figure 3 and sketched in Figure 4. This configuration includes the construction of a coldbox, piping, and instrumentation/control equipment with some small modifications to the current desublimator coldbox.

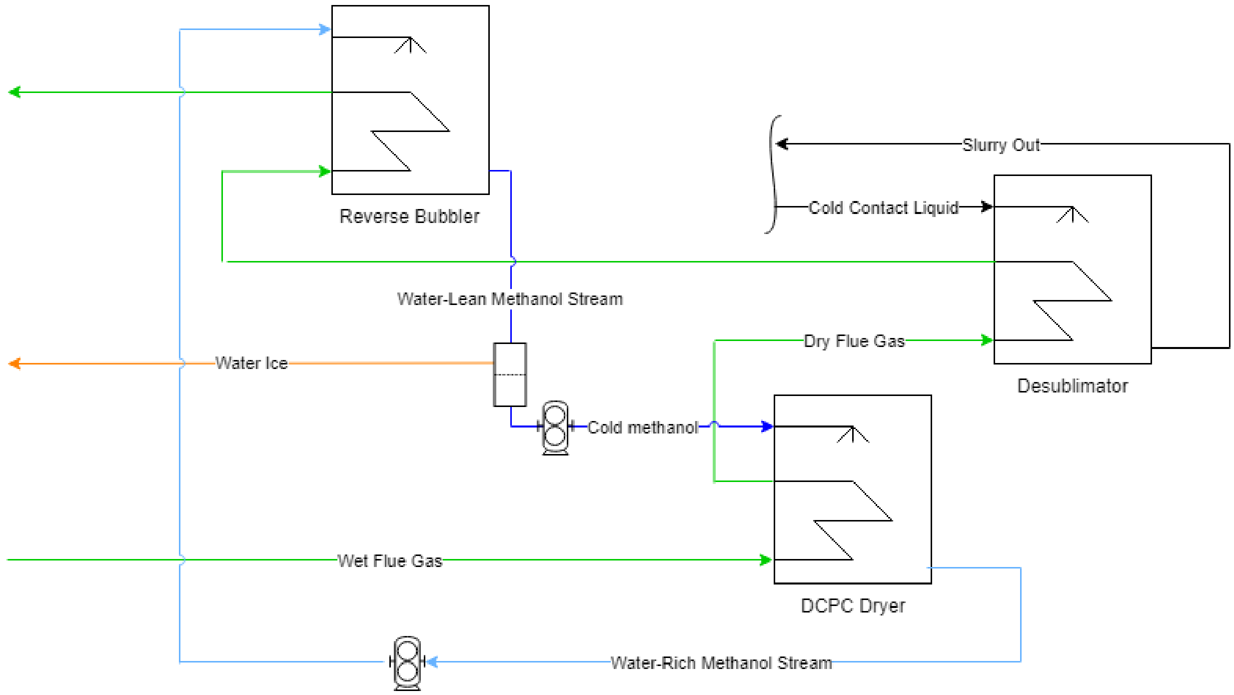


Figure 3. Block flow diagram of DCPC dryer Configuration A.

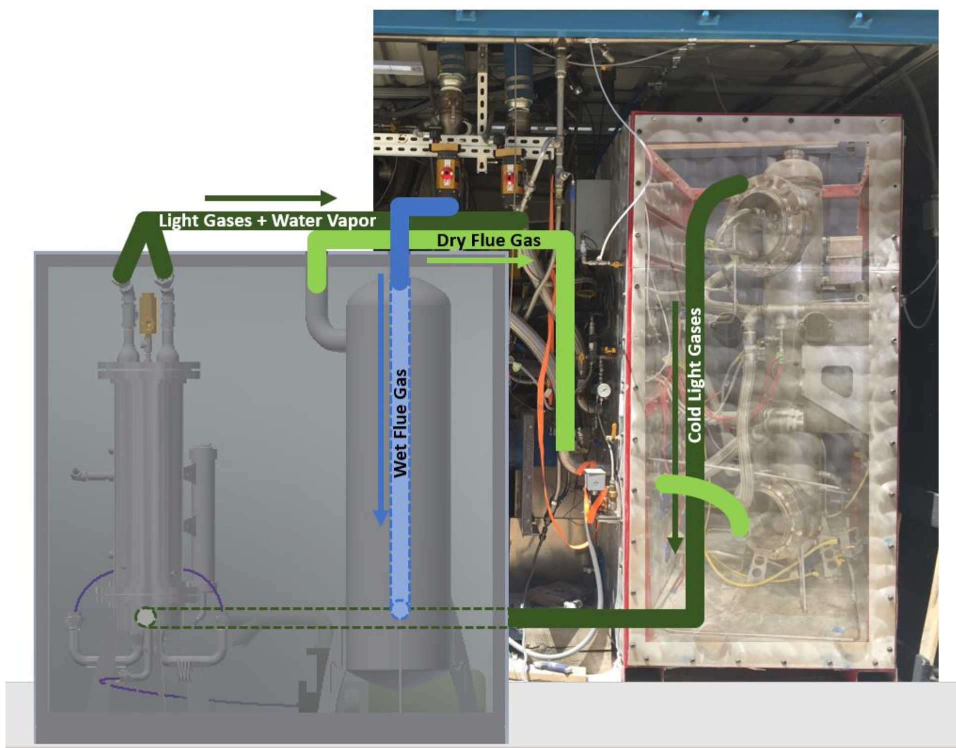


Figure 4. Sketch of DCPC dryer Configuration A.

An alternative configuration that we are still pursuing includes the same equipment for drying the gas, but utilizes an external gas cooling stream in the reverse bubbler for experimental purposes so we can vary flowrates and temperatures to help us optimize this portion of the process independent of the flowrate going through the DCPC dryer. This configuration is shown in the schematic (Figure 5) and sketch (Figure 6) below.

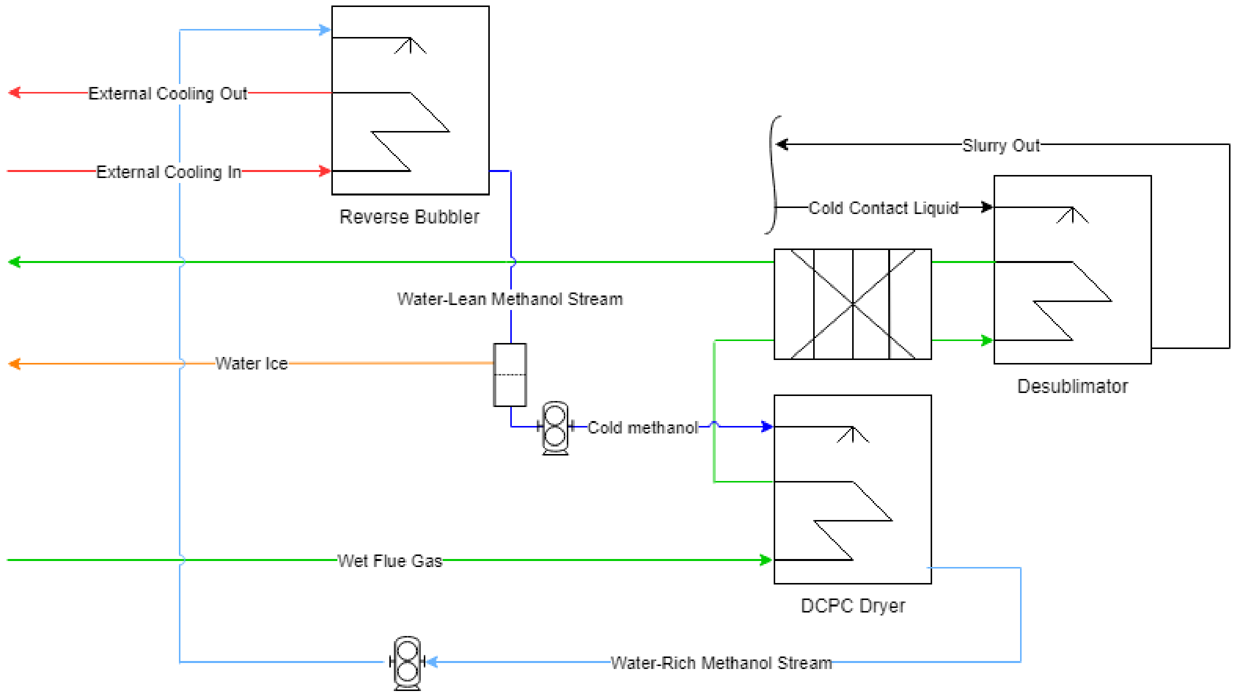


Figure 5. Block flow diagram of DCPC dryer Configuration B.

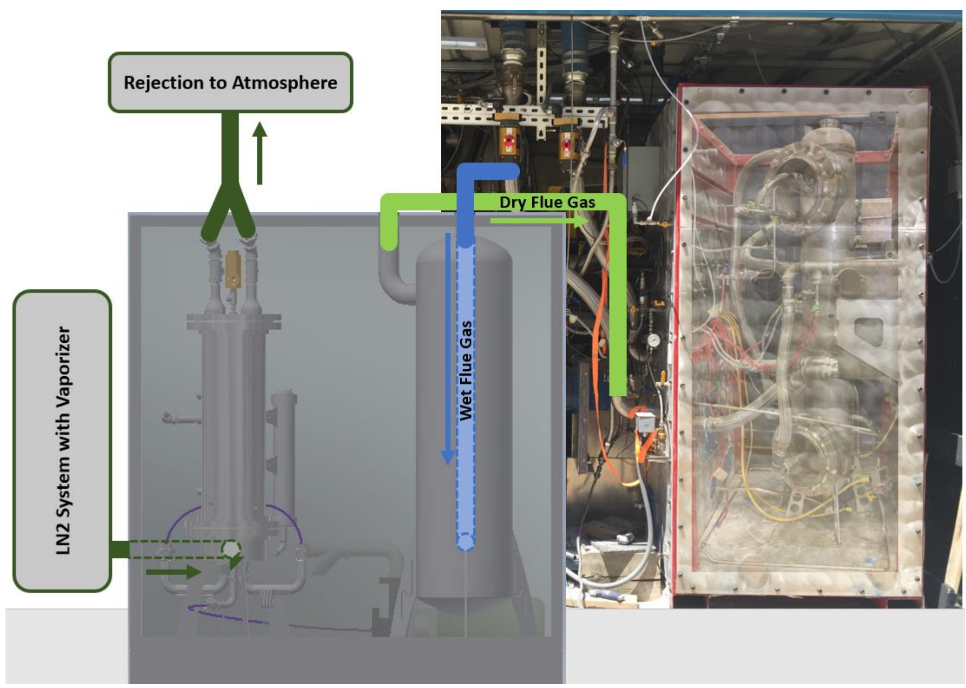


Figure 6. Sketch of DCPC dryer Configuration B.

Major Equipment Order Status

By July 15, the purchase of all major pieces of equipment is complete or pending. The following list shows status of these parts:

Table 1. Ordering status of all major pieces of equipment as of July 15, 2019.

Description	Vendor	Purchased	Installed	Commissioned
Coldbox				
C-Channel for base	Affiliated Metals	Yes	No	No
Base sheet	Affiliated Metals	Yes	No	No
Angle for wall supports	Affiliated Metals	Yes	No	No
Wall sheets	Affiliated Metals	Yes	No	No
Stencil for fork pockets	OSHCut	No	No	No
Perlite ports	OSHCut	No	No	No
Threaded inserts	Available in lab	Yes	No	No
Piping and Vessels				
Reverse bubbler	Available from lab	Yes	No	No
DCPC body	Available from lab	Yes	No	No
DCPC Feet	OSHCut	No	No	No
Instrumentation				
PLC interface module	HEI TEK Automation	Yes	No	No
Analog input module	HEI TEK Automation	Yes	No	No
Thermocouple input module	Available from lab	Yes	No	No
Discrete input module	Available from lab	Yes	No	No
Discrete Output module	Available from lab	Yes	No	No
24VDC power supply	Available from lab	Yes	No	No
Drybler low level switch	McMaster	Yes	No	No
Drybler high level switch	McMaster	Yes	No	No
Reverse bubbler low level switch	McMaster	Yes	No	No
Reverse bubbler high level switch	McMaster	Yes	No	No
Pressure transducer drybler in	Transducers Direct	Yes	No	No
Pressure transducer drybler out	Transducers Direct	Yes	No	No
Pressure transducer reverse bubbler in	Transducers Direct	Yes	No	No
Pressure transducer reverse bubbler out	Transducers Direct	Yes	No	No
Thermocouples	Omega Engineering	No	No	No
Polymer film hygrometer	Viatran	Yes	No	No
Inline refractometer	AFAB Enterprises	Yes	No	No

Coldbox

Both the reverse bubbler (the portion of the process that recovers cooling from the cold light gasses coming out of the CCC process) and the DCPC dryer will operate at temperatures near

−100 °C. We designed an aluminum coldbox (Figure 7) to hold perlite insulation surrounding these pieces of equipment. We purchased 2x6” aluminum C-channel for the base with removable walls for accessing the equipment after perlite is taken out.

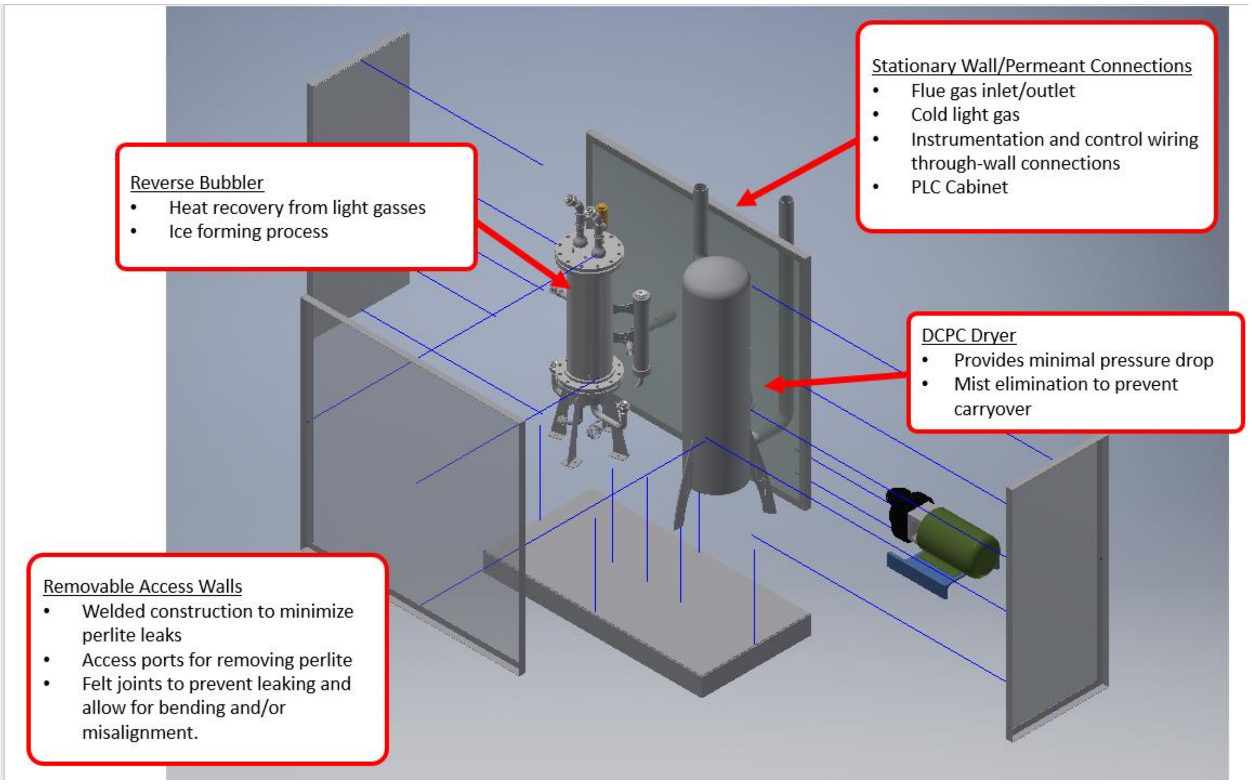


Figure 7. CAD drawing of coldbox for DCPC dryer.

Piping

Piping is 304 or 316 stainless steel rigid tubing and piping with compression fittings and or welded connections meeting or exceeding ASME B31.3 standards.

Instrumentation

The skid currently uses a SIEMENS PLC system controlled by a S7-300 CPU. The DCPC dryer system will have a small control panel mounted on its fixed wall. This control panel houses four IO cards and an interface module that communicates with the PLC using PROFINET protocols over ethernet. This allows the DCPC system to be added or removed without major wiring changes to the skid-scale CCC process.

Task A2. Solid-Liquid Separation and Contact Liquid Cleaning

Objective

This task is to develop a separation system or device for separating CO_2 from a contact liquid stream. Outputs of these potential systems include a low-CO_2 stream that can be reinjected into the desublimating heat exchanger without fouling. This task also includes the initial evaluation and design of a pollutant removal system that will be placed i n the separations system or in the CO_2 purification system. The pollutant removal system was described in the previous quarterly report.

Description of Selected Separations System

Previous reports have explained how this separation system could work, but in the interest of continuity, it will be briefly explained here. The basic idea is that a slurry would enter a chamber, the solids within that slurry would, under specific conditions, coalesce or sinter into a relatively pure solid. That solid would then sink toward the bottom of the vessel where it would be melted and drawn off. In order to complete this action, several difficulties would have to be overcome. First, the solid CO2 would have to be pure enough to overcome thermal stratification of the Liquid. To illustrate this difficulty, consider an isothermal vessel, filled with slurry. Should a heat load be suddenly introduced at the bottom of the vessel, the buoyant forces on the bulk liquid would cause that liquid to rise within the vessel. If, however, the warmth introduced causes the solid particles to sinter together, they would become heavier than the bulk slurry and would sink to the bottom. This solid could then be melted and drawn off. SES has a bench scale cold bath system that can be used to generate the temperatures needed to carry out such an experiment. Figure 8 shows this system.

Figure 8. Cold bath vessel. A smaller vessel is confined within the larger vessel. A window on the outside of each vessel is aligned such that the conditions within can be observed.

Introducing heat to the bottom of the inner vessel will be done with a cartridge heater. The temperature profile within the vessel will be measured and controlled either by adding insulation or additional heaters.

Description of Experimental Liquid–Liquid Extraction System

In the previous report, we identified liquid-liquid separation as a possible method for removing CO_2 from isopentane. The proposed process is shown in the PFD below in Figure 9.

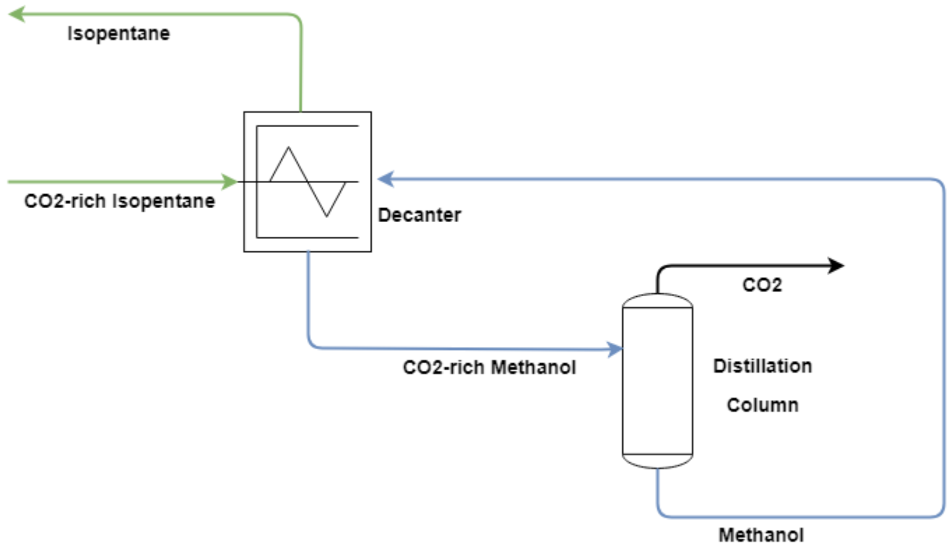


Figure 9. Liquid-liquid extraction of CO2 from isopentane. CO2 rich isopentane and methanol are mixed in a decanter. The methanol stream preferentially absorbs CO2, after which the CO2 is removed in a distillation column.

We tested the solubility of diethyl ether, ethanol, and methanol in isopentane. We found that diethyl ether and ethanol were both soluble in isopentane down to – 40 °C. With Methanol, we saw virtually no separation at 25 °C, but two liquid layers formed when we cooled the mixture down to – 40 °C. We did not achieve full separation; approximately 5 mL of methanol will dissolve in 20 mL of isopentane at – 40 °C. We plan to run tests while cooling the liquids down to – 98 °C (the freezing point of methanol) to see if complete separation can be achieved at a lower temperature. We will also model the dissolution of CO2 in methanol and isopentane to determine the relative solubility of CO2 in each. If model predictions show CO2 preferentially dissolves in methanol, we will determine how best to set up a test apparatus for this liquid-liquid extraction system.

EXTENDED TESTING REPORT SUBMISSION

October 15, 2019

Submitted by

SUSTAINABLE ENERGY SOLUTIONS

Submitted to

ROCKY MOUNTAIN POWER

Sustainable Transport and Energy Plan (STEP)

Summary

This document outlines the work done as part of the extended testing amendment to the existing Rocky Mountain Power (RMP) Cryogenic Carbon Capture™ project.

Sustainable Energy Solutions (SES) worked through several modifications to the existing Cryogenic Carbon Capture™ (CCC) process under DOE and RMP support over the last year. These modifications improve the reliability and in some cases, decrease the energy and economic costs of the process. These modifications culminated in an extended field test at the Hunter Power Station, an RMP site in Castle Dale, UT.

Due to delays in the arrival of key equipment, including a large solid–liquid separations unit provided by a third-party vendor, and subsequent unanticipated modifications to that equipment, arrival at the plant was delayed by almost three months from the original project plan. Additional unanticipated issues occurred with some pieces of equipment and SES replaced or significantly modified several of those pieces.

The additional funding provided by this project extension allowed SES to extend its time on site to test these modifications so that data, information, and analysis of the updated system can be incorporated into the design and analysis of the scaled-up version of the process that could be implemented at a commercial scale on a Rocky Mountain Power Plant.

The exact wording of the deliverable is described below:

SES will deliver a report containing the following: **Task 1** – Analysis of the extended test runs of the small pilot focusing on the benefits gained from recent modifications made to the system.	8/31/2019	$ 75,000

Skid Modifications

Pump

An early failure mode in the field test was faster than expected deterioration of the primary slurry circulation pumps. The deterioration took the form of increased wear on the bearing surfaces, which could contaminate other parts of the system. A larger slurry pump was selected in order to increase the bearing surface size (P-901). Since switching to a new gear pump with larger bearing surfaces, SES has not observed any further deterioration of the bearings or gears in the CO_2 slurry pump. The improved pump performance along with other reliability improvements in the system have allowed the skid to run for longer individual runs.

Both pump heads were originally equipped with 2 HP motors, but it appears that the baseline torque requirement for the new H12R pump head is higher than the pump it replaced. After thorough review of the data and review of the documentation for the pump, a larger motor was installed (see Figure 1). The larger motor allows the pump to handle spikes without slipping.

Figure 1. New P-901 pump motor.

The previous motor for this pump was controlled by a 2 HP sensorless vector variable frequency drive (VFD). This control scheme works well during normal operation, but it doesn't use any feedback from the motor so when the motor slips, the current rises rapidly until the drive breaks the circuit. The new drive uses flux vector control so it can maintain torque at maximum slip (breakdown torque) without tripping.

Screw Press

During testing, solid CO_2 leaking past the screw press filter and eventually plugging downstream was another suspected cause of run failures. Multiple locations were potential causes of the leak problem, including leakage through the mesh due to mesh damage, leakage through the seams on the filter, leakage around the screw press inlet housing, or leakage around the filter/screw press housing joints. Tasks we completed to address each possible leakage location are given below.

- *Leakage through the mesh.* The mesh we are currently using is composed of four sintered layers of wire mesh. The first layer is the filter layer and is a very fine mesh with 0.001 in. openings. The rest of the layers are used to support the filter layer under pressure. After assembling, running, and disassembling the screw press, we noticed more glossy areas of the mesh where the screw likely rubbed on the filter during screw press assembly and disassembly. There was a concern that the fine mesh was damaged, opening larger holes and causing the filter to leak solid CO_2. The mesh was examined under a microscope; the mesh was damaged and smeared together at the high points, but it does not look like larger openings were created in the mesh.
- *Leakage through mesh seams.* The seams of the mesh were sealed with a two-part epoxy. Upon close inspection, we found that the epoxy cracked after extended use. We found a new epoxy that is rated for cryogenic use and has a coefficient of thermal expansion similar to stainless steel and resealed the seams with this epoxy. The new epoxy worked well and showed no signs of cracking.
- *Leakage around the screw press inlet housing.* The inlet housing is a stainless box attached to the inside of the screw press pressure vessel where the slurry enters the machine. A slurry inlet pipe threads into the inlet housing and is then welded to the screw press pressure vessel. The screw passes through the inlet housing, and the inlet housing interfaces with a pressure vessel flange and the filter. Upon close inspection, we found that the inlet housing was not installed straight at Press Technology, and it looked like the pipe threads were leaking. The seal between the inlet housing, flange, and filter could also be leaking due to the misalignment. We removed the inlet housing by cutting away the welded inlet pipe. We then welded a new inlet pipe directly to the inlet housing to prevent possible leakage around the pipe threads. The inlet housing/inlet pipe assembly was then welded into the screw press pressure vessel, and much better alignment was attained.
- *Leakage around the filter/screw press pressure vessel joints.* Due to poor tolerances of the screw press parts, the face seals between the filter, the pressure vessel, and inlet housing did not fit well enough to make a seal. Gaps remained when the machine was assembled, and these gaps allowed slurry to bypass the filter. To solve this problem, gaskets were made from compressible PTFE material to fill the gaps in the face seals.

After making these changes, it appeared that there were still some filter leakage problems with the new larger 6” screw press. As a final resort for this field test, we rebuilt the dual 4” screw presses that we had used in the past and installed them in the skid.

Shell and Tube

Fouling of the liquid cooler heat exchanger has been a key challenge in the past. During the later stages of the field test, inserts were placed into the ends of the shell and tube heat exchanger to better guide the flow and reduce buildup. These changes effectively eliminated the fouling issues we had seen earlier.

Overall Field Test Results

After working through the issues identified above, we were able to achieve significantly longer test runs. By the end of testing in August 2019, we had 12 test runs of 12 hours or longer (Figure 2). These longer test runs helped achieve a total run time of over 600 hours and capture of 6.13 tonnes of CO_2 from flue gas at the Hunter Power Plant.

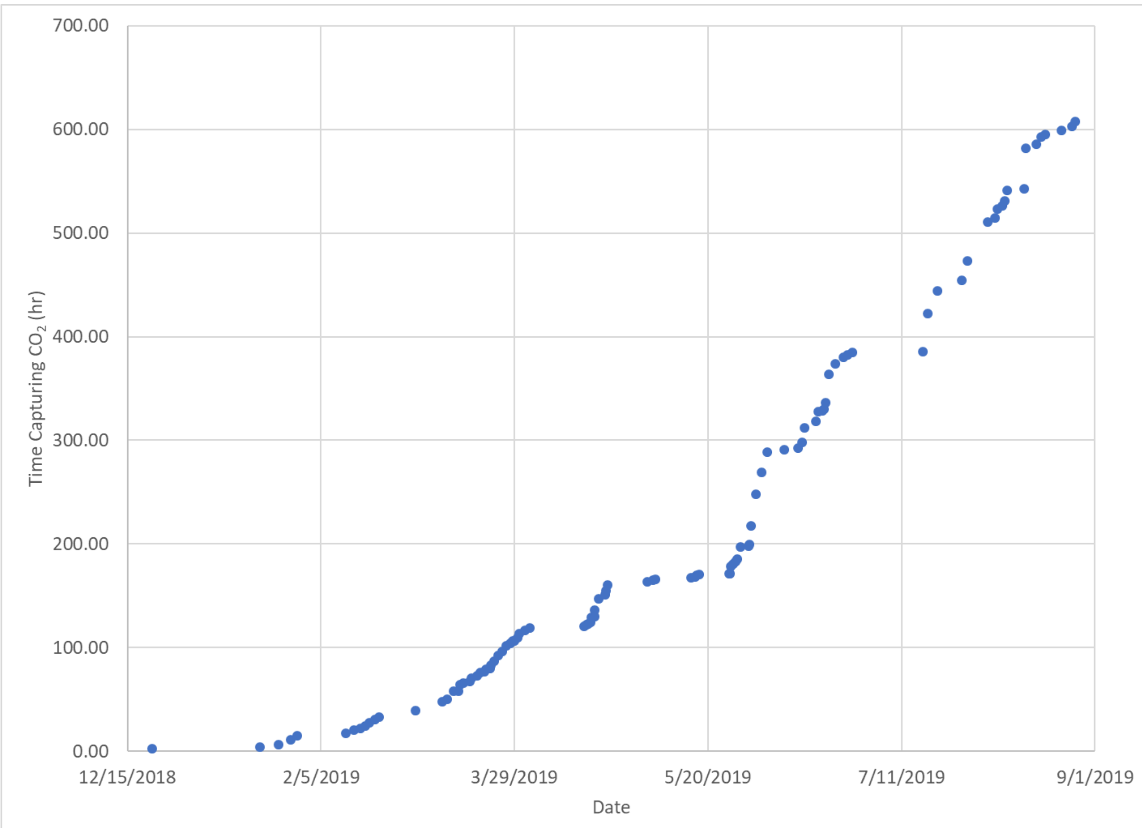


Figure 2. Cumulative hours testing CCC ECL™ skid capturing CO_2 from flue gas at the Hunter Power Plant.

Representative Testing Data

We include here a series of plots showing CCC ECL™ skid performance during representative test runs. For the purposes of this report, we are focusing primarily on the extended test runs conducted under the funding provided by the extension, which is roughly from July 1 to August 31, 2019. When describing the test data below, "steady state" is defined from the perspective of CO_2 capture. There is a time offset between when we see the CO_2 capture efficiency reach steady state and when the CO_2 product reaches steady state. We use the CO_2 capture efficiency to define start and stop times. The distillation column continues to produce CO_2 after a test has ended. For all the following figures, the plots show (from the top): CO_2 capture, flue gas flow rate into the process, flue gas and clean gas CO_2 fraction, temperature into (TT-912) and out of (TT-108.5) the desublimating HX, and the CO_2 capturing rate.

The first test run we will discuss is from July 17–19, resulting in a 40-hour test run, one of the longest conducted at the plant. This was the first significant test after many of the major modifications described above had taken place (Figure 3). It took about 1.75 hours for the process to reach steady state. The mode of failure for this test was plugging on the inlet to the pump, an issue that we were able to resolve operationally in later tests. We captured over 380 kg of CO_2 at an average capture efficiency of above 90%.

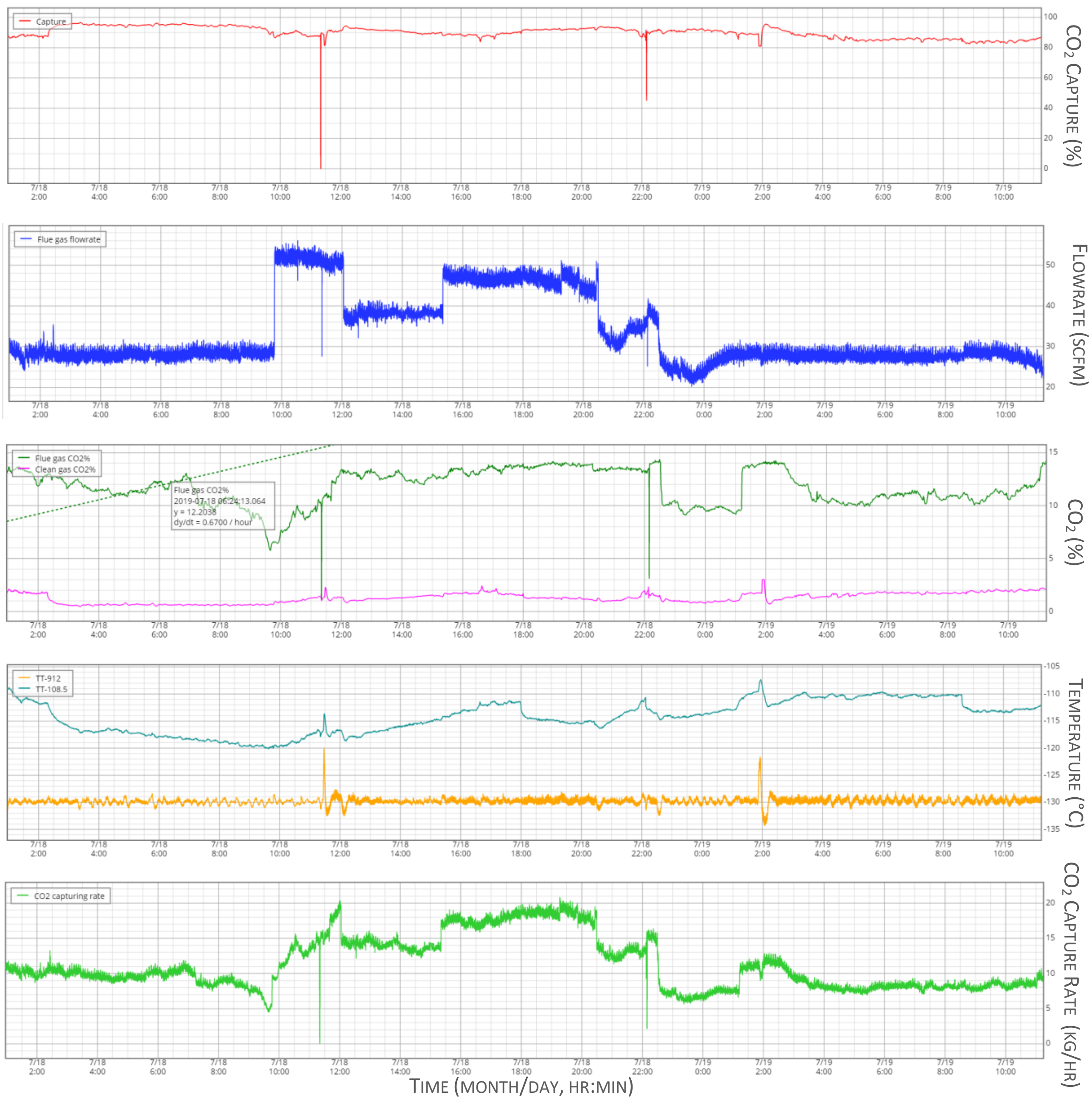


Figure 3. Test data from July 17–19, 2019

The second test run we will discuss is from August 13–15. This was a similarly long test run, at about 37 hours. This test run was operated at a slightly higher capture rate and CO_2 accumulation rate, resulting in more CO_2 captured for a shorter time period (Figure 4). The mode of failure for this test was operator error when switching between heat exchangers. Improved procedures have reduced the future likelihood of this event. We captured over 390 kg of CO_2 at an average capture efficiency of above 95%.

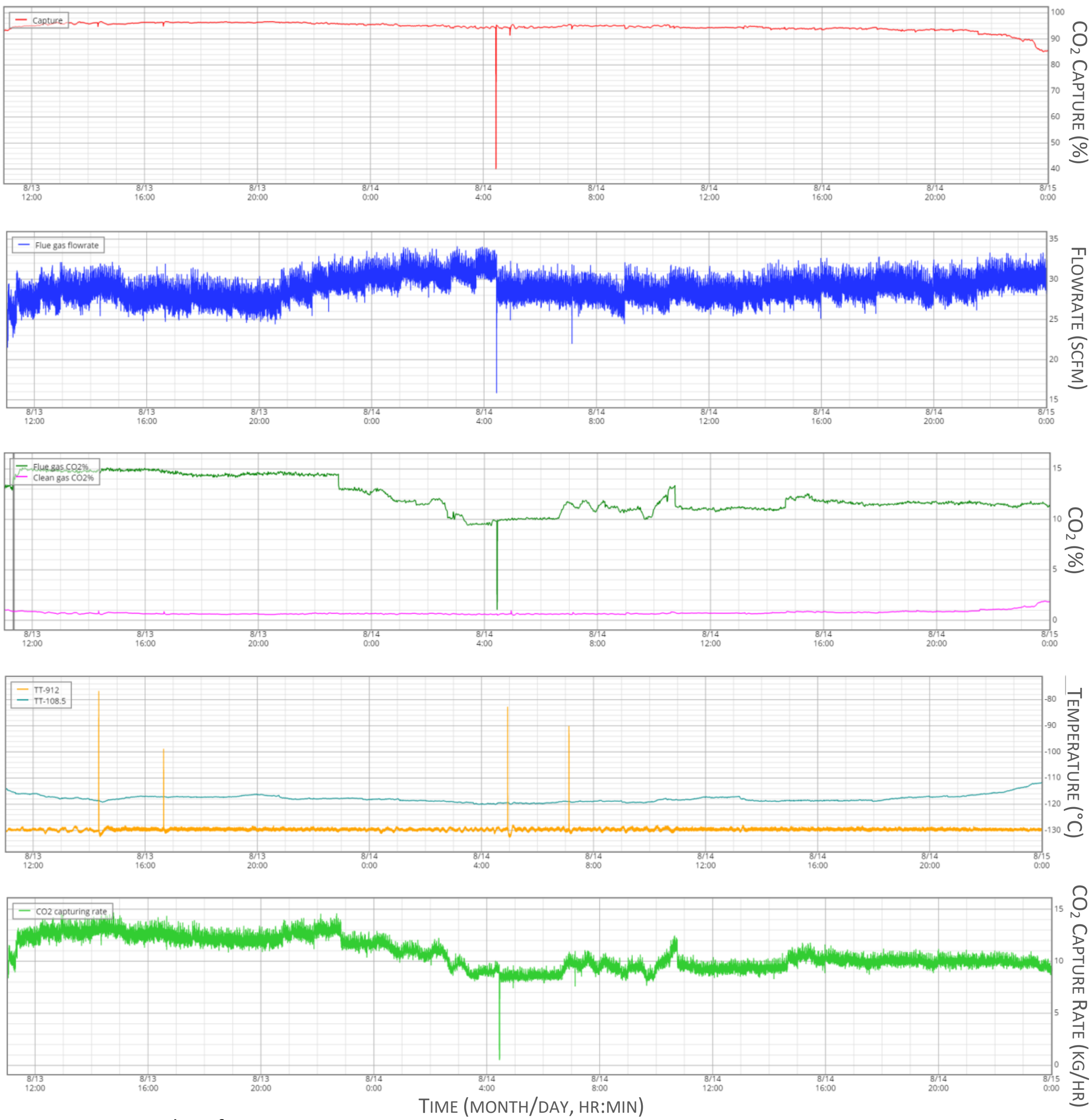


Figure 4. Test data from August 13–15, 2019

Contaminants

Over time, despite our attempts to restart quickly, we noticed a degradation in performance. To restore performance after an extended test period, we replaced the contact liquid in the system and purged each unit with nitrogen. While draining the system, we also recovered a foreign contaminant that appears to be oily liquid that is discussed more below. We have concluded that this substance was detrimental to our testing because we were able to have a successful period of testing immediately following each time the system was cleaned and purged, but the performance of the CCC ECL™ skid would degrade with time.

The most common symptoms of contaminated contact liquid were dramatic increases in pressure throughout the contact liquid heat exchanger at normal operating temperatures (−130 ± 10 °C). Figure 5 shows an unsuccessful test during cool down caused by contaminants in the cooling loop.

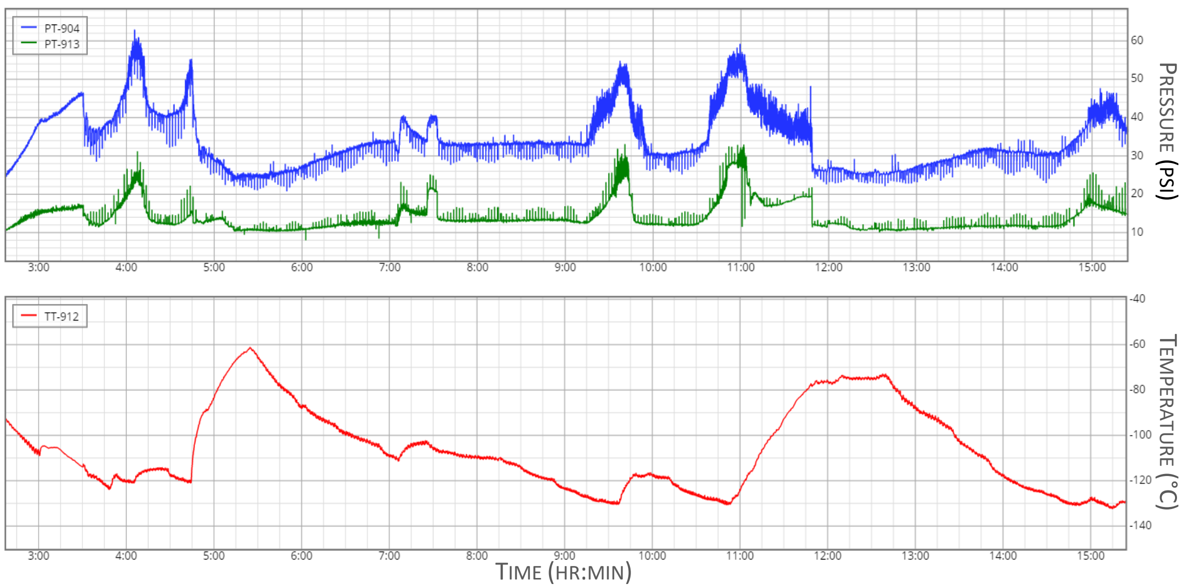


Figure 5. Pressure before (PT-913) and after (PT-904) the contact liquid heat exchanger compared with the contact liquid temperature (TT-912).

To mitigate fouling, SES removed the contact liquid and tested samples from various locations in the contact liquid cooling loop. When we would replace the contact liquid with new clean isopentane, we were often able to achieve longer test results until these contaminants accumulated again. Analytical results from samples of the contaminated liquid were somewhat inconclusive and are still being pursued. Several observations have been made about the contaminants found in the contact liquid despite not knowing the exact composition or source.

There appears to be two different observable contaminants found in the contact liquid cooling heat exchanger: An amber-colored substance (Figure 6) only appears when the liquid is cold (−40 °C) and dissolves back into the contact liquid when at room temperature. This is consistent with what we observed while operating with contaminated contact liquid because fouling was only an issue when the contact liquid temperature decreased. A second, perhaps unrelated, black pollutant appears to coat the surfaces of the entire contact liquid cooling loop. This is particularly noticeable inside the filter housing of the screw press and on the inserts for the shell and tube heat exchanger (Figure 7). Nuclear magnetic resonance (NMR) tests were conducted that indicate this liquid is likely related to contaminants in the feed isopentane. Future work will determine the exact composition of these contaminants to better understand how they behave in our system and how to contain or separate them.

Figure 6. Sample of contact liquid chilled in a freezer to −40 °C. The amber liquid is a separate liquid phase; its composition will be determined by future analytical tests.

Figure 7. (left) Dirty insert housing. (right) Dirty inserts that were cleaned with (left) acetone, (center) alcohol, and (right) water.

Figures of Merit for the ECL Process

Table 1 summarizes the figures of merit that quantify unit operation and CCC ECL™ process improvements. For several of the figures of merit, the objective of our testing is to determine the optimal operating conditions for that specific unit operation, thus the figure of merit is “to be determined” (TBD). These specific optimized operating conditions will allow for us to create better, updated designs of unit operations for designing the next iteration of the CCC ECL™ process for the next scale of demonstration and to better model these unit operations moving forward.

Table 1. Figures of merit for individual unit operations and the CCC process as a whole used to quantify the improvements achieved during this project.

Unit Operation	Figure of Merit	Projected Improvement
Desublimating Heat Exchanger	Optimal solid loading in slurry	TBD
	Capture efficiency	>90%
Solid–Liquid Separations	Optimal CO_2 content in melter	TBD
Vapor–Liquid Separations	CO_2 outlet purity	>99%
Non-fouling Heat Exchanger	Pressure drop across unit	TBD
CCC ECL™ Skid	Total hours capturing CO_2	500
	CO_2 capture efficiency	>90%
	Total tonnes of CO_2 captured	20.8

Demonstrate Figures of Merit

The CCC ECL™ skid was tested at Unit 3 of the Hunter Power Plant from December 2018 through August 2019. During this time, we were able to determine optimal operating conditions and parameters, while running for a total of over 600 hours capturing CO_2. Table 2 outlines the quantitative results from our tests and compares these values with those projected at the beginning of this phase of the project. SES did not meet the objective of 500 continuous hours of CO_2 capture from flue gas at the Hunter Power Plant. SES gained important information about how the process works and created an expansive operator handbook that includes the knowledge gained from the testing performed during this project.

Table 2. Quantitative results from operating the CCC ECL™ skid at the Hunter Power Plant for the figures of merit for individual unit operations and the CCC process as a whole.

Unit Operation	Figure of Merit	Projected Improvement	Test Results
Desublimating Heat Exchanger	Optimal solid loading in slurry	TBD	<10%
	Capture efficiency	>90%	91.4%
Solid–Liquid Separations	Optimal CO_2 content in melter	TBD	30–70%
Vapor–Liquid Separations	CO_2 outlet purity	>99%	99.99+%
Non-fouling Heat Exchanger	Pressure drop across unit	TBD	35 psi
CCC ECL™ Skid	Total hours capturing CO_2	500 (consecutive)	607 (non-consecutive)
	CO_2 capture efficiency	>90%	91.6%
	Total tonnes of CO_2 captured	20.8	6.13

These figures of merit show improvements in the process, including:

- Consistent CO_2 capture at rates higher than 91% for all the tests using flue gas (a total of over 100 tests).
- The heat integration recuperators for cooling and warming the incoming and outgoing flue gas, respectively, performed well and these designs can be utilized in future scales of the CCC ECL™ process.
- The spray tower performed well, consistently reaching high capture efficiencies. The spray cleaning nozzle performed very well, effectively eliminating the need for other methods to ensure that solid CO_2 did not accumulate on the sides of the spray tower.

- We gained invaluable insight into the cryogenic slurry pump performance, which we can utilize for the pilot- and full-scale CCC systems. We now have a scalable control scheme and geometry for skid- and pilot-scale pumping.
- We were able to operate for long periods of time with a consistent pressure drop through the shell and tube heat exchanger, which indicated no increase in fouling of the heat exchanger. However, we found that maintaining a pressure drop of 35 psi or less resulted in optimal performance of the shell and tube heat exchanger.
- The distillation column worked as designed for the duration of the field testing. We optimized and improved operational aspects of the distillation column, which resulted in improved performance of the column and other portions of the process.
- We have developed a robust and powerful Supervisory Control and Data Acquisition System that is easy for operators to use. We have compiled a database of test data that is easily accessed and analyzed.

Based in these figures of merit, future work includes:

- Determining the source of the contact liquid contamination that we began to see more and more towards the end of the field testing and eliminating this contamination.
- Improving the single screw press so it performs well at higher capacity and for longer tests.
- Further research into the performance of the pollutant removal settling tanks, including optimizing draining any pollutants and quantifying the pollutant capture of SO_x and NO_x.
- Testing the CCC ECL™ at higher CO_2 capture rates of 1 tonne CO_2/day for continuous tests up to and beyond 500 hr.

QUARTERLY REPORT AND MILESTONE SUBMISSION

October 15, 2019

Submitted by

SUSTAINABLE ENERGY SOLUTIONS

Submitted to

ROCKY MOUNTAIN POWER

Sustainable Transport and Energy Plan (STEP)

Overview

Sustainable Energy Solutions (SES) worked through several modifications to the existing Cryogenic Carbon Capture™ (CCC) process under Department of Energy (DOE) and Rocky Mountain Power (RMP) support over the last year. These modifications improve the reliability, and in some cases, decrease the energy and economic costs of the process.

As SES improved the reliability of these unit operations, SES also innovated technologies with improved reliability and energy efficiency that have the potential to replace existing unit operations. SES is also actively planning for the next scale of CCC operation and will explore the scalability of these and related unit operations as part of this investigation. These include:

1. Simultaneously drying and cooling the flue gas to the CO_2 frost point.
2. An alternative cooling and solid–liquid separation system for the contact liquid. This will also include the development of a pollutant removal system for SO_x and NO_x built into this separations system and the CO_2 purification system.
3. Investigating unit operation scalability.

Quarterly Milestones

As part of this project, SES reports quarterly on the progress made towards the above objectives. The exact wording of the milestones for this quarter are as follows:

Q11	SES will deliver a report containing the following: Task A1 – The receipt of the system and initial results of both assembly and dryer testing. Task A2 – Results of initial testing and subsequent iteration on solid-liquid or other separations system. Description of assembled pollutant removal system.	10/15/2019	$ 80,750

Task A1. Gas Drying and Cooling

Objective

The objective of this task is to mature the direct-contact cooling and drying systems to the point they can be tested in the skid. The quarterly objective is to have all the parts in house for the dryer, assemble the dryer, and have initial results from the dryer assembly.

Literature Review of Physical Characteristics of Methanol and Ethanol

A significant amount of research has gone into measuring the physical characteristics of methanol and ethanol (e.g., surface tension, density, viscosity). There are many good sets of measurement data going back more than a century. In 2010, Gonçalves et al. [1] thoroughly reviewed these data sets and used them to create equations to predict each characteristic for pure ethanol. This paper led us to earlier measurements for mixtures of ethanol/water and methanol/water [2, 3]. Unfortunately, none of the measurements were for temperatures lower than 0 °C. We could extrapolate down to the temperatures we aim to use in the direct-contact phase-change (DCPC) dryer, but extrapolation to temperatures that far from the last measured data point is rarely wise or even helpful. Thus, we decided to measure the viscosity of the ethanol/water and methanol/water solutions at SES. These measurements will be compared to the data in the literature and the fit of the equations will be reviewed to determine the next steps for possibly using known equations to predict other chemical characteristics for the ethanol and/or methanol.

Heat of Absorption of CO_2

This quarter, SES completed tests to measure heat of absorption (heat of mixing) of CO_2 dissolving in alcohol/water solutions. SES has recently investigated two liquid mixtures in the DCPC dryer. The first is a methanol/water mixture and the second is an ethanol/water mixture. A potential concern was raised during thermodynamic modeling that if CO_2 was absorbed into the alcohol/water mixture and if the heat of absorption was high, the efficiency could decrease, or the performance could degrade. Several experimental designs were discussed, and the experimental setup shown in Figure 1 was chosen.

The bench-scale system that was previously used for proof-of-concept dryer testing was modified to tightly control the gas temperature and flowrate of CO_2 and N_2 entering a bomb calorimeter. After searching for a bomb calorimeter to use for these tests, we decided to make one using a 1 gallon vacuum-walled flask with a 3D-printed top that holds an agitator, thermocouple, liquid nitrogen injection (for temperature control), and gas sampling port (Figure 2).

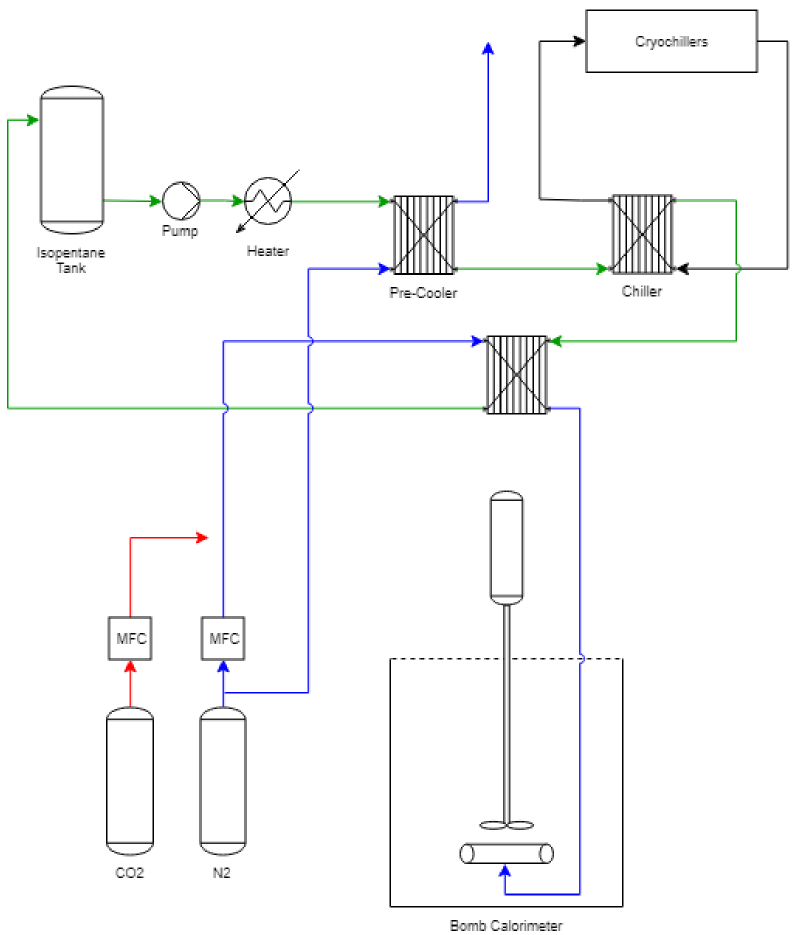


Figure 1. PFD of the Bomb Calorimeter Experiment.

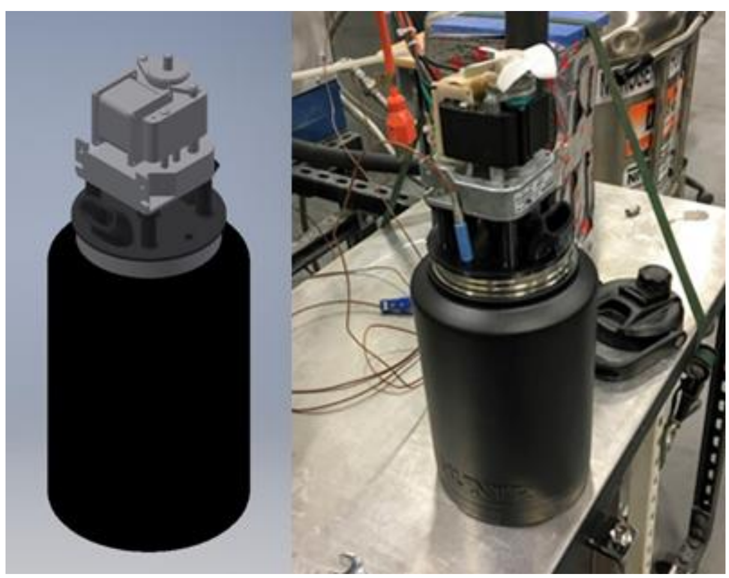


Figure 2. (left) CAD drawing of bomb calorimeter. (right) Fully assembled bomb calorimeter.

During our experiments, the bench-scale system cooled the gas heat exchanger while liquid nitrogen was slowly added to chill the alcohol/water mixture in the calorimeter. When the temperatures of the bath and heat exchanger were low, N_2 was fed through the heat exchanger into the alcohol mixture. After temperatures held steady at or near −100 °C, CO_2 was added to the N_2 stream, active cooling was stopped, and the temperature was recorded (Figure 3). In each experiment, the gas composition was controlled using two mass flow controllers and checked using an Enerac 700 nondispersive infrared (NDIR) portable gas analyzer (Figure 4). Preliminary results show that CO_2 is likely being absorbed to some degree and it looks like there is an associated heat of absorption. The preliminary estimate of this load is −25 to −33 kJ/mol CO_2, but this is a very early estimate with a large error bar.

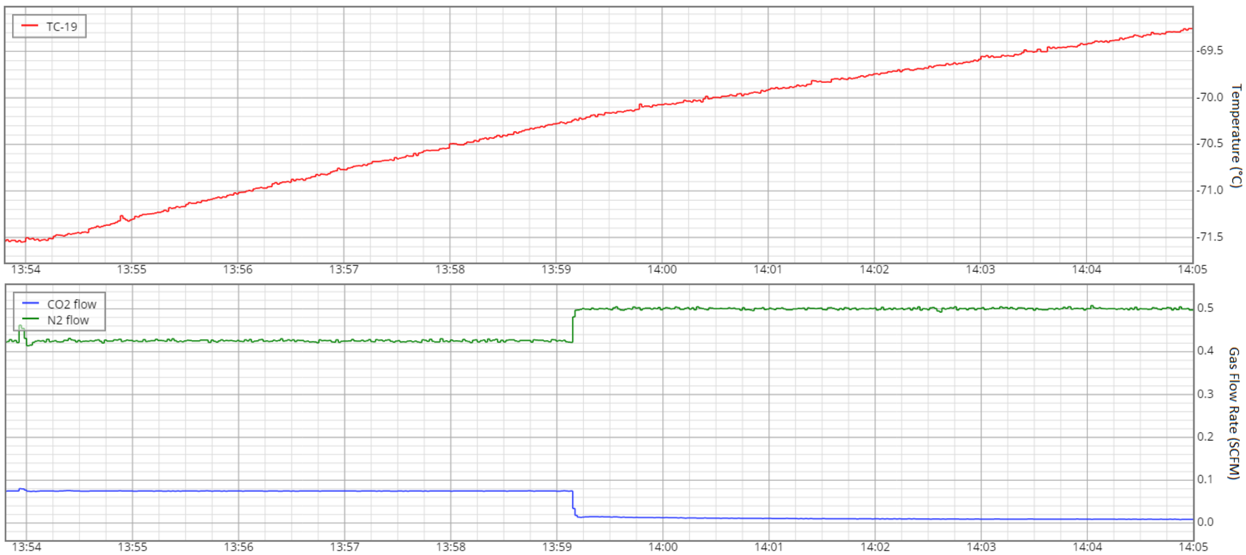


Figure 3. (top) Bomb calorimeter temperature during CO_2 injection into methanol on September 27, 2019. (bottom) CO_2 and N_2 flow rate during the experiment. Note: There is a slight knee in the temperature plot when the CO2 was stopped.

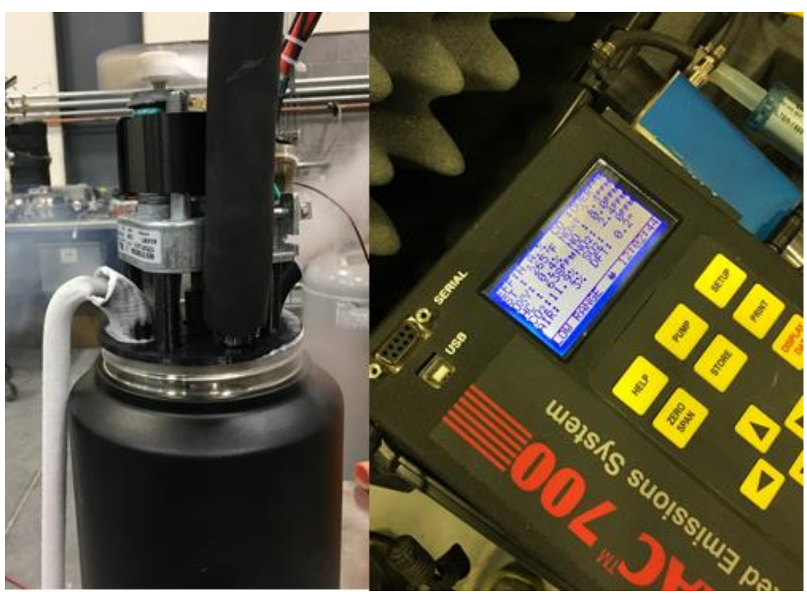


Figure 4. (left) Bomb calorimeter during an experiment. (right) Gas composition measured using an Enerac 700 portable gas analyzer.

While the experiment is informative and valuable, it has several limitations. One large shortcoming is that CO_2 injected into the calorimeter has a short residence time in the liquid before exiting through the top.

The alcohol/water solution is viscous enough that it is possible that the gas passes through large bubble channels in the liquid without coming into direct contact with the liquid. The experiment was changed to include a larger agitator and the sparger was changed to distribute the gas more evenly through the liquid. The most important improvement was the experimental method, which will be described in the next section.

Measurement of CO_2 Absorption in a Mixture of Water and Methanol

We used the bomb calorimeter to measure the rate of absorption of CO_2 as it bubbled through a bath of 73% methanol / 27% water near −93 °C. Using a combination of NDIR measurements and temperature, we estimate that approximately 20 to 40% of the CO_2 was absorbed as it bubbled through the bath.

On Oct 7, 2019, we filled the bomb calorimeter with 2 kg of a mixture of 73 wt% methanol and 27 wt% water. The mixture was cooled to −98 °C by pouring liquid nitrogen into the calorimeter while stirring continuously. We then began to bubble nitrogen at 1 SCFM through the mixture. Stirring was continued throughout the experiment. The nitrogen was dispersed into the liquid through about 15 small holes at the bottom of the calorimeter, directly underneath the mixing blades, to maximize the surface area available for heat and mass transfer. The nitrogen was precooled to about −85 °C. The calorimeter has several vents at the top to allow the bubbled nitrogen to escape.

While bubbling nitrogen, we measured the temperature of the mixture using a thermocouple placed in the bath near the mixing blades. The calorimeter walls, nitrogen, and mixer are all sources of heat, which we were able to quantify by observing the temperature increase over time.

We then began injecting CO_2 with the nitrogen. The concentration of CO_2 in the CO_2/nitrogen mixture was controlled with a thermal mass flow controller. We increased the CO_2 concentration over time to observe the effect on the calorimeter temperature. As we did so, the nitrogen flowrate was decreased so that the total gas flowrate remained at 1 SCFM. We monitored the CO_2 concentration of the gas exiting the vents at the top of the calorimeter using NDIR. After each step increase in the CO_2 concentration, we would wait approximately one minute for the gas analyzer to respond before recording that data point and moving to the next CO_2 concentration setpoint.

The temperature of the calorimeter and the CO_2 concentration are shown in Figure 5. Before beginning CO_2 injection, the temperature rise is the result of adding nitrogen that is slightly warmer than the bath, heat transfer through the calorimeter wall, and the mechanical action of mixing. Once we started injecting CO_2, the temperature increased more rapidly. The temperature of the calorimeter ranged between −98 and −88 °C throughout the experiment.

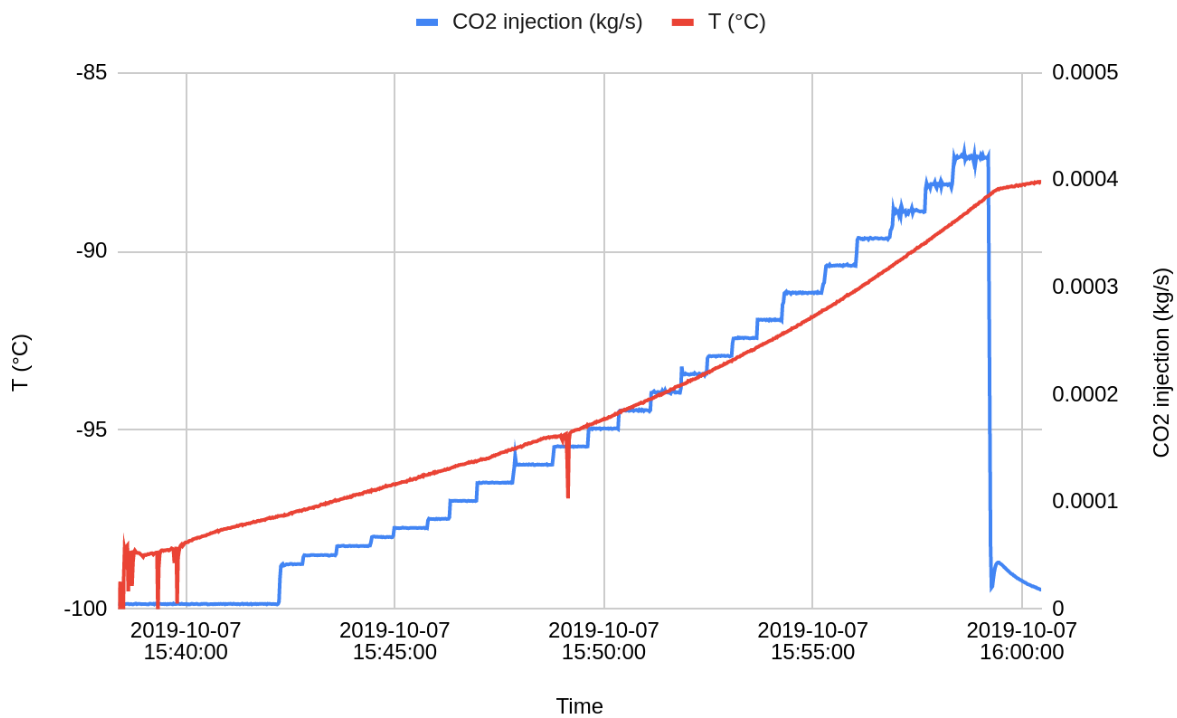


Figure 5. Plot of calorimeter temperature and CO_2 injection rate over time.

The measured outlet concentration of CO_2 also increased over time; these data were recorded manually throughout the experiment (Figure 6). The outlet concentration was slightly less than the concentration entering the calorimeter, which indicates that some CO_2 was being absorbed. However, the measurement error in the NDIR analyzer is large, so closing the CO_2 mass balance on the calorimeter using this data alone may not be accurate. This is especially true as the inlet and outlet data were measured using different technologies, a thermal mass flow controller in the former case and NDIR in the latter. If the data are to be trusted, this suggests that approximately 20% of the CO_2 being injected was being absorbed.

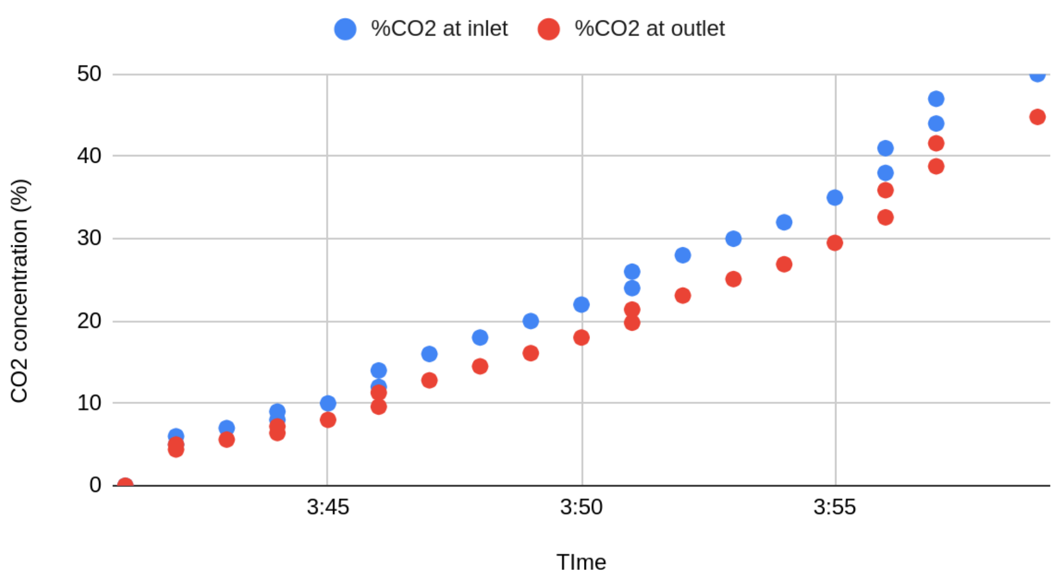


Figure 6. Concentration of CO_2 entering the calorimeter (as controlled by thermal mass flow controller) and exiting the calorimeter (as measured by NDIR)

We also estimated the absorption using the rate that the temperature increased. As CO_2 enters into solution, it releases heat, which warms the bath. Figure 7 shows how the rate of temperature rise (dT/dt) increased over time.

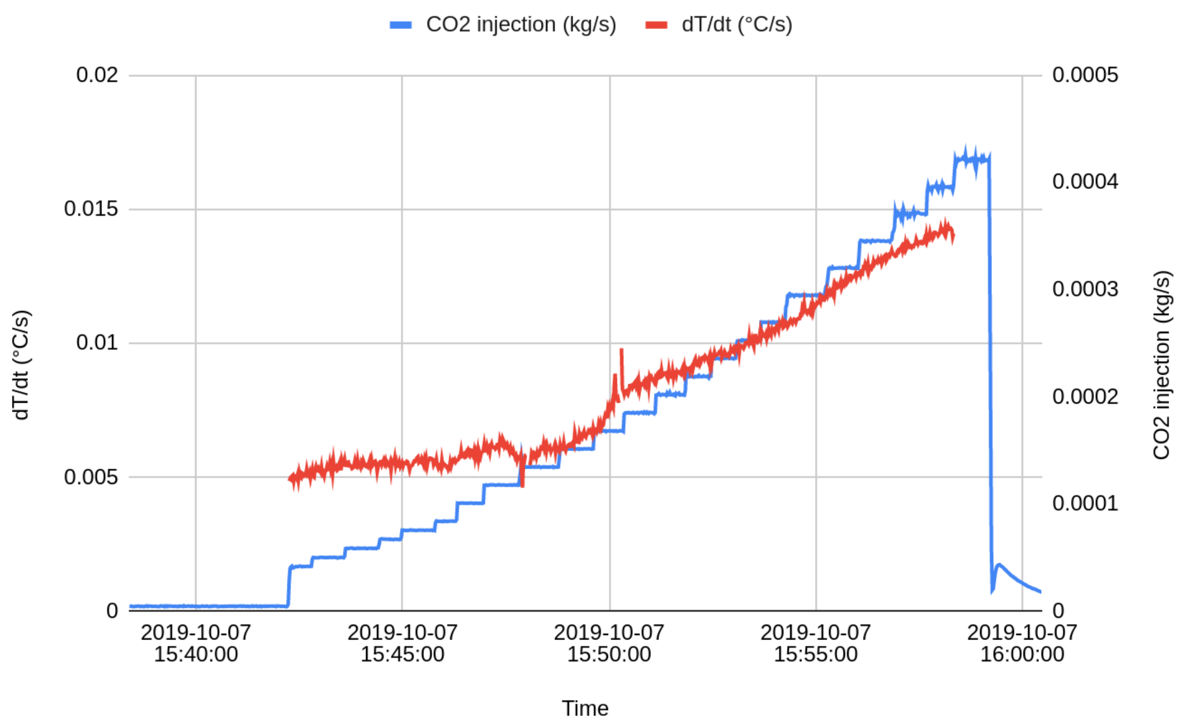


Figure 7. Rate of temperature increase over time

Figure 8 shows the dependence of dT/dt on the CO_2 injection rate. dT/dt was calculated using a windowed average width of ~135 s, so periods at the beginning and end of the experiment have been removed. The slope of the trendline (27.1 °C/kg) indicates how much the calorimeter temperature increases for every kg of CO_2 injected into the bath. The y-intercept of the trendline is the steady state rise in temperature due to external effects.

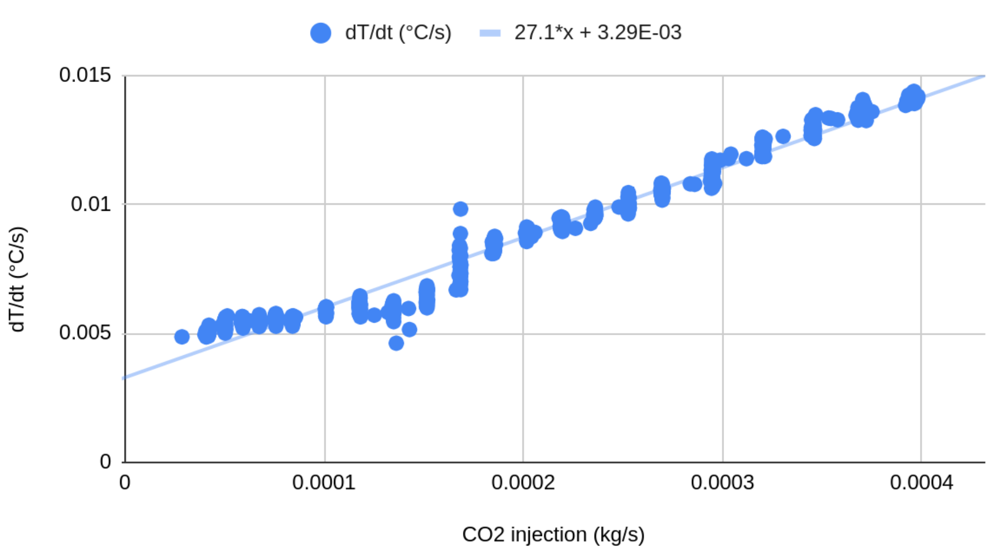


Figure 8. Correlation between dT/dt and the CO_2 injection rate

By correlating dT/dt with the CO_2 injection rate and knowing the heat of solution of CO_2 in the mixture, an absorption rate can be estimated. Because the availability of thermophysical data for water and methanol is limited at these temperatures, we had to choose representative values for some properties (Table 1).

Table 1. Thermophysical properties for the water/methanol solution, with extrapolated values noted.

Properties needed	Properties available	Value
Heat of solution of CO_2 in water/methanol solution	Heat of vaporization extrapolated to −93 °C	386 kJ/kg
Heat capacity of water/methanol solution	Heat capacity of methanol at −93 °C, heat capacity of water at 0 °C	2750 J/kg K

With these values, we calculated that the temperature rise at *complete* absorption of CO_2 should be 70 °C/kg CO_2. With our measured slope of 27.1 °C/kg, this suggests that approximately 40% of the CO_2 is being absorbed into solution.

The bath temperature ranged from −98 to −88 °C, so we are unable to say with certainty whether this change in temperature itself affected any of the experimental results. Thus, the best we can provide is a range of values that indicate that a significant portion of the CO_2, perhaps between 20 and 40%, is being absorbed. Further evidence of this was observed after the experiment, as CO_2 desorbed from solution: pure nitrogen was again bubbled through the bath, and CO_2 was observed in the gas exiting the calorimeter for as long as 30 minutes after the conclusion of the experiment.

Viscosity Experiments

The viscosities of the methanol/water and ethanol/water solutions were modeled previously; however, during the CO_2 absorption experiments, the viscosity appeared to be higher than expected. We measured the kinematic viscosity of the liquid using a bulb viscometer and a cold bath (Figure 9).

The bulb viscometer was placed a cold bath with a magnetic stirrer. The bath was insulated on three sides with a removable fourth side so we could see the viscometer during the test. The temperature was controlled at each measurement point within 1 °C and measurements were taken periodically from 0 °C down to –100 °C for the ethanol/water mixture and down to –90 °C for the methanol/water mixture (Figure 10). The large discrepancy between the model and measured viscosity is likely due to interactions between the alcohols and water. Some articles report excess viscosity like those seen in our tests.

Figure 9. Bulb viscometer in cold bath while testing ethanol and water.

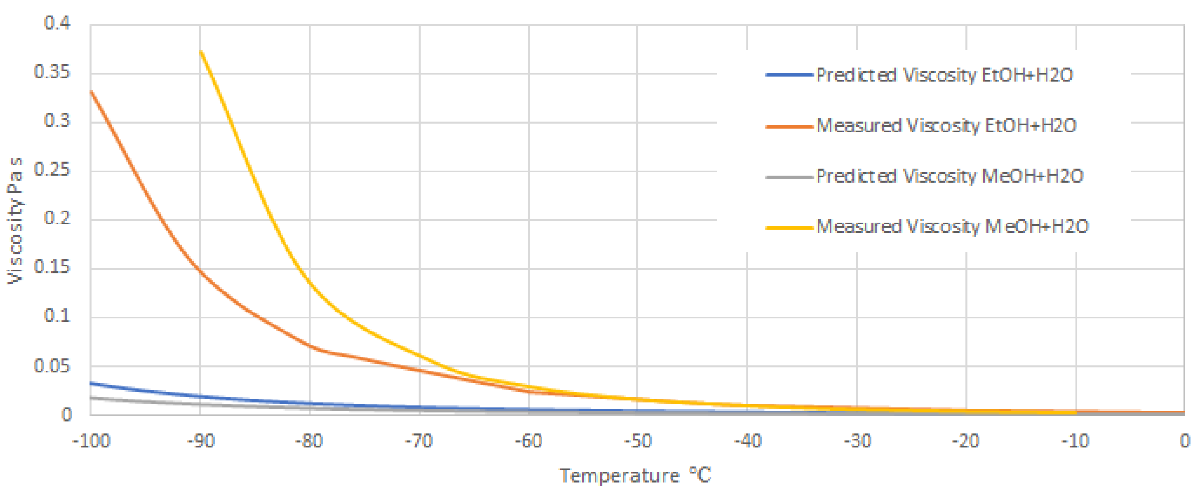


Figure 10. Predicted and measured viscosities for the ethanol/water and methanol/water mixtures.

DCPC Spray Tower Dryer Design

The measured viscosity was much higher than expected, thus we are using a spray tower or a packed bed rather than a bubbler. Some preliminary costing for a packed bed indicates that the cost to purchase the packing was high enough that it was desirable to test the less-expensive spray tower. In this configuration, the liquid exits the head in many small streams. A typical stream of liquid passing through a gas would break up into drops as it falls. The distance required to break the streams into droplets is governed by the Weber number which is the ratio of a fluid's inertia to its surface tension

$$We = \frac{D\rho v^2}{\sigma}$$

where D is the diameter of the stream, ρ is the density, v is the velocity of the stream, and σ is the surface tension. The diameter and velocity can be predicted from a model of the stream accelerating through a gravitational field. The density can be readily measured using the same cold bath that was used to measure viscosity. The surface tension is a thermodynamic property that is not readily available at the temperatures we are interested in. Further, models of stream breakup have been shown to overestimate breakup by as much as several orders of magnitude. Even if uncertainty surrounding the breakup of streams into droplets could be significantly mitigated, convective heat transfer is a strong function of the geometry and a separate heat transfer model would have to be developed for stream, breakup and droplets.

This has made modeling the spray tower a challenge. One could simplify the model by considering the spray tower as a shell and tube heat exchanger, at least in the continuous stream section, where the flowing gas forms the shell and the alcohol/water streams form a series of tubes. However, this is an imperfect analog to the spray tower because the gas and liquid are flowing counter-current, not cross-current, and the mass transfer is not included.

Advanced Experimental Spray Tower

As a result of the difficulty of measuring the surface tension, modeling the heat transfer, and the potential poor prediction of stream breakup, SES has developed a more advanced experimental spray tower that effectively replaces our bench-scale system, and can be used to verify our models and allow for additional measurements.

The scale of this spray tower could still be considered skid-scale, as it can be connected to the skid and operate as a more complete test platform than the bench-scale versions, but it is unlikely to accommodate the full flow rate of the 1 tonne/day CO_2 skid system.

Development of this intermediate experimental spray tower is occurring in parallel with the continued design of a larger skid scale version of the spray tower. In addition, the remaining equipment apart from the spray tower has been sized such that it can accommodate any scale of spray tower we attach to it. This unit and subsequent experiments will also inform us on the need to purchase packing to switch to a packed-bed column heat exchanger.

Spray Tower Physical Design

The intent of the advanced experimental version of the spray tower is to allow us to modify various parameters and measure the resulting performance. An image of the spray tower is shown in Figure 11. Cold alcohol (methanol or ethanol) and water enter at the top and leaves from the bottom after exchanging heat with the flue gas. The flue gas enters at the bottom and leaves at the top. Two sight glasses, one near the spray head and one near the bottom (Figure 12), will be used to observe the conditions of the spray and to determine if the streams will break into droplets. The large conical vessel at the top of the tower allows the flue gas to slow down and for any entrained alcohol/water to fall to the sides and join the liquid at the bottom.

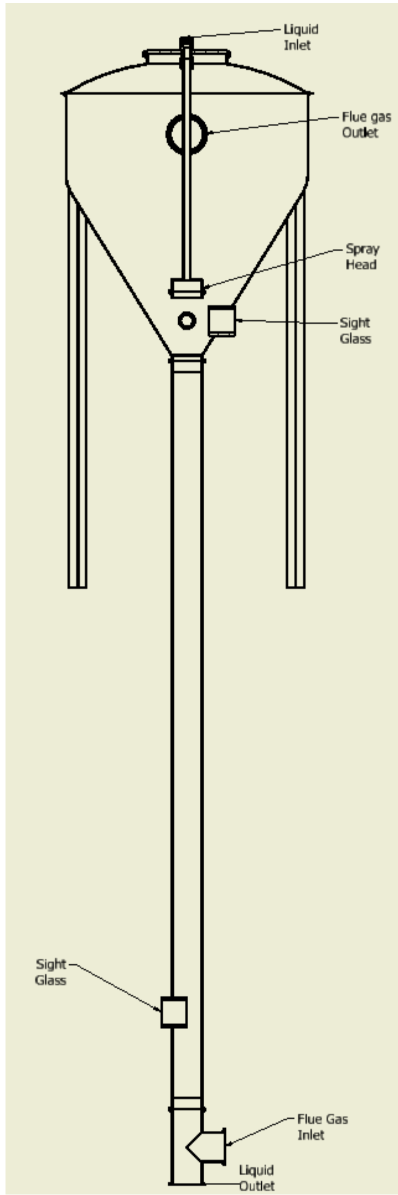


Figure 11. CAD Drawing of the spray tower.

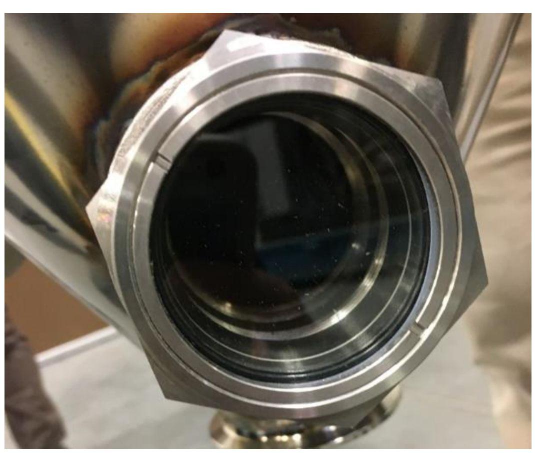


Figure 12. Sight glass used to observe the alcohol/water streams in the spray tower.

A basic P&ID of the alcohol loop for the dryer and the reverse bubbler is shown in Figure 13. When the alcohol/water mixture leaves the bottom of the spray tower, it will pass through a pump, and then it will enter a chamber (called the reverse bubbler), where it will come into contact with liquid nitrogen. The temperature of the mixture will be controlled by varying the liquid nitrogen flow.

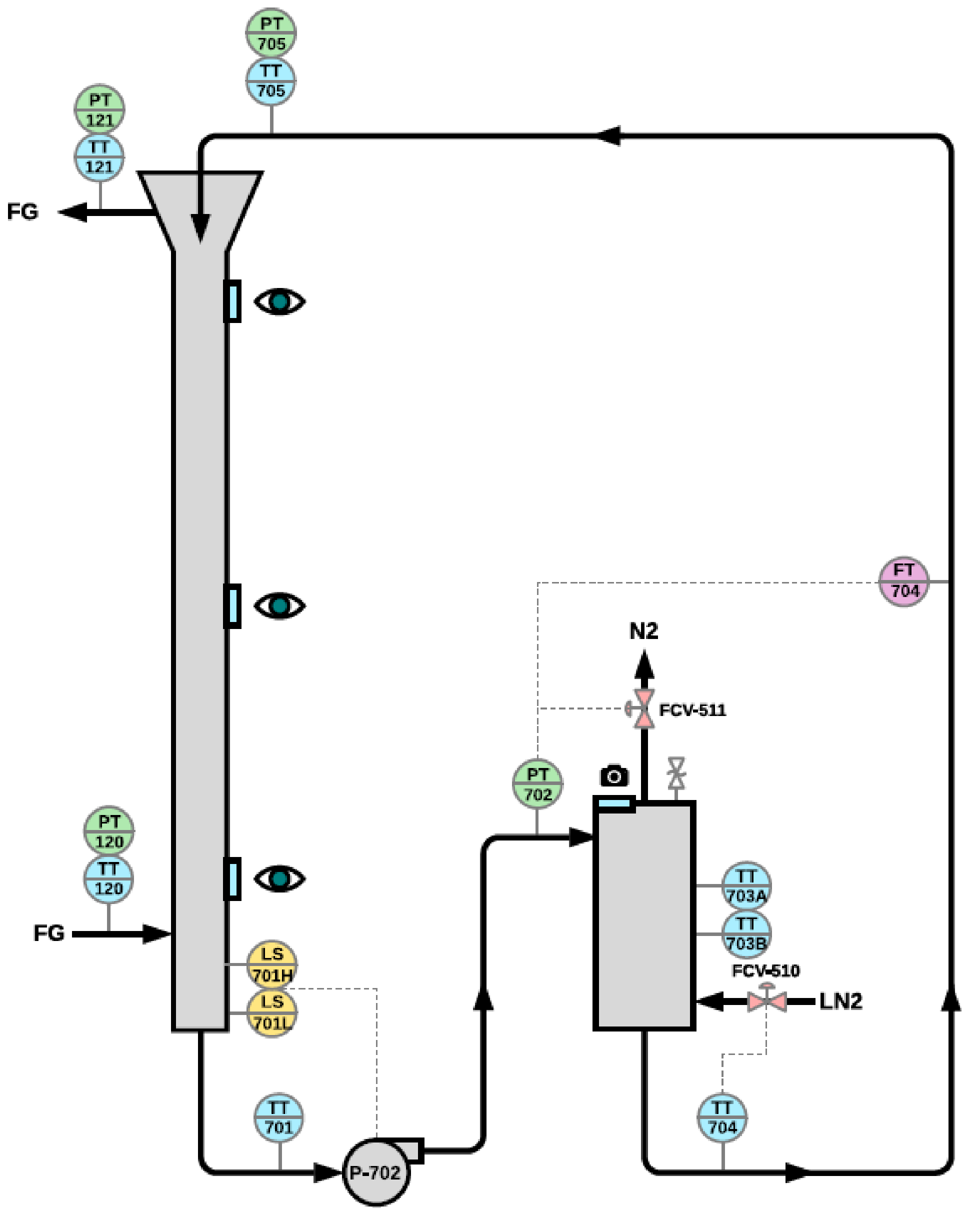


Figure 13. P&ID of the dryer and reverse bubbler.

The design of this system has been carefully reviewed and pressure reliefs have been added to ensure that the system remains safe while operating. One pressure relief is seen in the P&ID near FCV-511 (Figure 13). A second pressure relief will be added to the flue gas side of the system that is not shown here.

Building a test system in this way should allow us to learn everything we need to know for scale up while avoiding the pitfalls that could occur with modeling or prediction uncertainty.

Assembly and Testing

Figure 14 shows the vessel used to cool the alcohol/water mixture. The mixture flows continuously into and out of the vessel and forms a pool at the bottom of the vessel. A control valve injects liquid nitrogen into the bottom of the vessel, which vaporizes and bubbles upward through the pool. The nitrogen vents through a second control valve at the top of the vessel.

Figure 14. Cooling vessel for the alcohol/water mixture.

The reverse bubbler is shown mounted on the test stand. We have done some previous testing using a reverse bubbler system to chill the alcohol/water mixture, but this test will be the first time we are able to quantify the cooling in a meaningful way. The goals for this testing include continually removing solid water ice, maintaining cooling in the system, and verifying the estimated pressure drop through the reverse bubbler.

Figure 15 shows the assembled and installed reverse bubbler and the modified spray tower dryer. While we refer to it as an additional bench-scale test, we will be running gas from the ECL skid system, controlling from the skid system, and running tests that will directly inform a slight scale up to full flue gas flow of the skid. During testing, the streams from the spray head will be observed to see if they persist in columns or if they break up and disperse as they fall. Flue gas flowrates will be gradually increased to verify carryover as a function of column gas velocity. Finally, in an idealized system, gas and liquid streams will be roughly matched on a molar basis. As gas and liquid flowrates are varied, that model may change.

Figure 15. (left) Modified spray tower dryer and (right) reverse bubbler assembled and installed in the lab ready for testing.

Task A2. Solid-Liquid Separation and Contact Liquid Cleaning

Objective

This task is to develop a separation system or device for separating CO_2 from a contact liquid stream. Outputs of these potential systems include a low-CO_2 stream that can be reinjected into the desublimating heat exchanger without fouling.

Previous Solubility Testing Results

To better design the experiment that would determine whether it is possible to sinter the CO_2 and effectively separate from the liquid isopentane, SES reviewed previously conducted research into the separation of hydrocarbons from CO_2. This research included the measurement, previously conducted by SES, of the compositions of two liquid phases separated by a meniscus.

In those experiments, liquid CO_2 was added to a mix of methylcyclohexane and methylcyclopentane, which were being used as our primary contact liquid at the time. When enough CO_2 was added, two distinct phases were formed. One phase was rich in CO_2 and the other phase was rich in hydrocarbons. The CO_2 concentration in the hydrocarbon rich phase ranged from 40 to 50%. The CO_2 concentration in the CO_2-rich side varied from 79 to 93%. Temperature was varied from −50 to −54 °C. A CO_2-rich phase would not form until there was more than 40% CO_2 in the mixture. These results showed that liquid/liquid separations would not be a viable option with these hydrocarbons. Similar tests with isopentane have not been conducted.

The results of these experiments indicated that if the hydrocarbons were fully mixed, it would likely be difficult to separate them again based on density alone. We intend to repeat similar experiments using isopentane as the contact liquid; however, we expect similar results. Based on this input, the design of the experiments below were modified to reduce any agitation and mixing of the liquid and solid streams as much as possible until separation was complete.

Description of Selected Separations System

As SES further developed the design of the selected separations experiment, the scope became divided into two separate experiments: One set of experiments would be a simpler short-term test that would allow us to quickly experiment and iterate on the concepts we were developing, and the other set would be a more in-depth test that would be a more direct analogy to the state of the slurry inside the ECL skid system. The primary difference between these is the use of dry ice mixed with isopentane in the simple test versus a generated slurry in the more complex test. The simplified test diagram is shown in Figure 16 and the assembled test is shown in Figure 17.

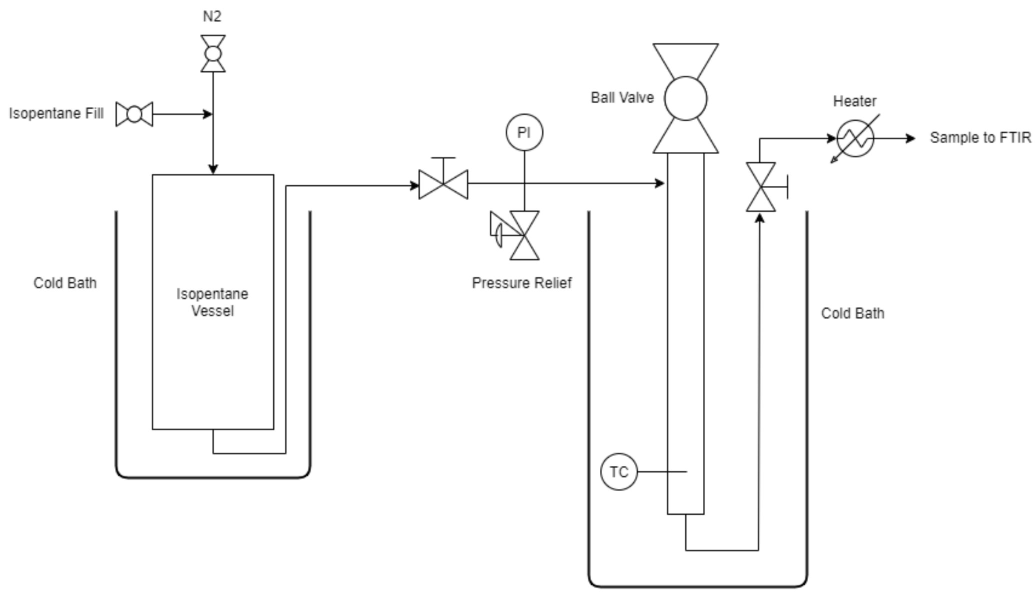


Figure 16. Experimental design for Solid CO_2 sintering separation from isopentane.

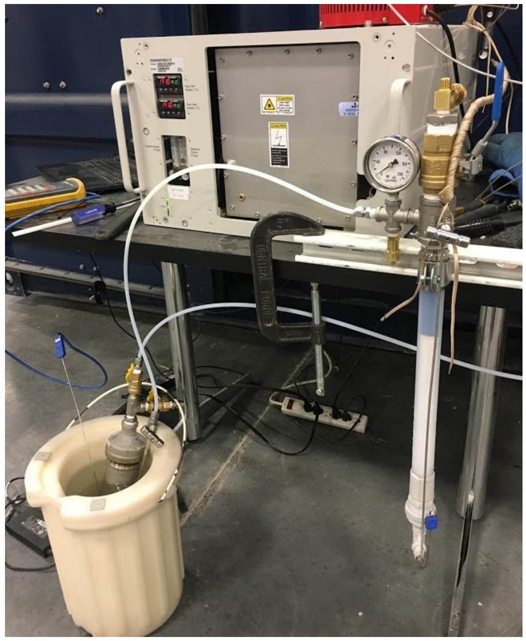


Figure 17. Experimental setup for testing CO_2 separation.

The simplified experiment followed these steps:

1. Both the FTIR and sample tube heater are turned on and warmed to the point at which it is certain no isopentane will remain liquid when sampled.
2. Isopentane is placed in the injection vessel and cooled in an alcohol bath with LN_2. The temperature is closely monitored to make sure that it remains at the proper value.
3. Crushed dry ice is loaded into the top of the test vessel. The vessel is left open to atmosphere until it is cooled and water ice forms on the exterior. At this point, the vessel is closed and allowed to build pressure.
4. The test vessel sits until liquid CO_2 begins to pool in the bottom.
5. The cooled isopentane is pressurized with N_2 and injected into the test vessel.
6. The mixture is sampled from the bottom of the vessel and passed through the FTIR where the amount of isopentane in the liquid CO_2 stream is measured.

Preliminary results show a meniscus forming to separate the CO_2 from the isopentane, and results from the FTIR show a high degree of CO_2 purity in the stream exiting at the bottom until the meniscus approaches the sample area. Further testing is required to determine the exact levels and characteristics of the separate liquids. The two liquids are both very clear and colorless, making photographing the meniscus difficult. The meniscus is easier to observe in person or in a video. Figure 18 shows the sample during a test. CO_2 gas bubbles were seen to form at the top of the CO_2 rich phase, at the meniscus.

The more in-depth experiment and equipment are also being developed. This involves the use of a bench-scale cold bath with a separate vessel for separating the liquids. The purpose of these experiments would be to see if we can generate a temperature gradient in the vessel such that the warmth introduced causes the solid particles to sinter together, after which they would become heavier than the bulk slurry and would sink to the bottom. This solid could then be melted and drawn off. SES has a bench-scale cold bath system that can be used to generate the temperatures needed to carry out such an experiment (Figure 19). We are evaluating the use of this cold bath with the simplified experiment shown above.

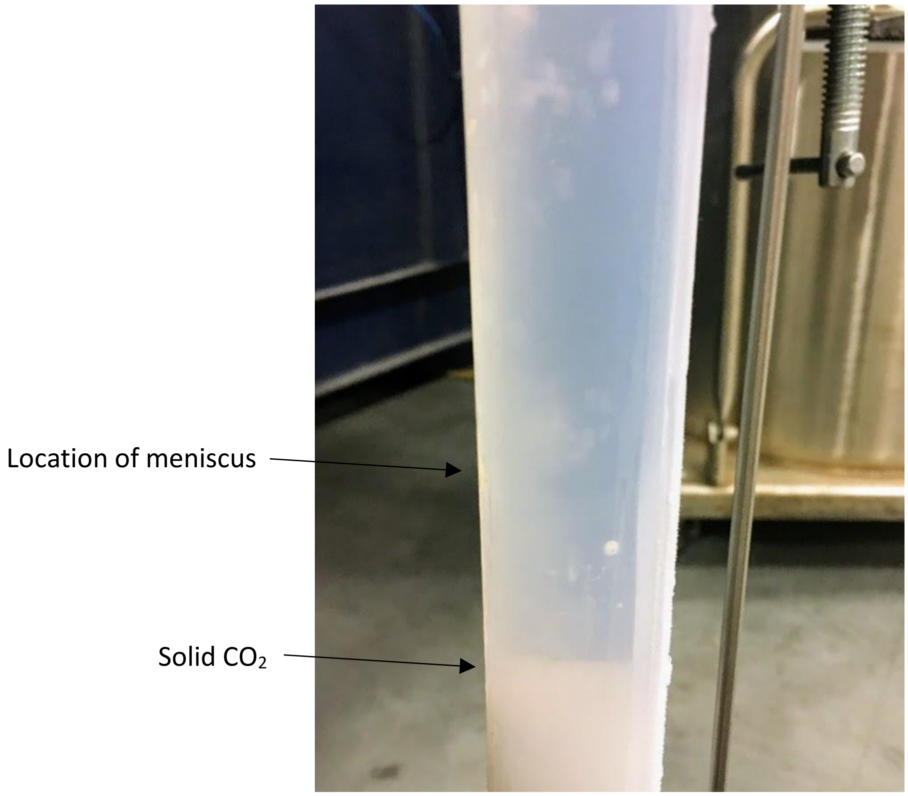


Figure 18. Solid CO_2 melting and the formation of the meniscus.

Figure 19. Cold bath vessel. A smaller vessel is confined within the larger vessel. A window on the outside of each vessel is aligned such that the conditions within can be observed.

Description of Assembled Pollutant Removal System

In the current system, we utilize settling tanks to remove the pollutants and keep them from building up over time. The NO_2 in the system remains a solid after the CO_2 has melted. Therefore, adding a settling tank directly after the melter unit allows these solids to settle into the bottom of the tank and they can be periodically removed from the system. The SO_2 melts at a lower temperature, so it will not be separated at this stage. However, any remaining SO_2 in the isopentane at the bottom of the distillation column will form a separate liquid phase. This liquid phase is significantly more dense than the isopentane phase and will settle in a similar manner to the solids. We computed the required settling velocities and designed two tanks to install in the system. An example of these tanks is included in Figure 20. The ports on the bottom of the settling tanks are connected to a series of hand valves to remove pollutants in a batch-wise manner without affecting system performance.

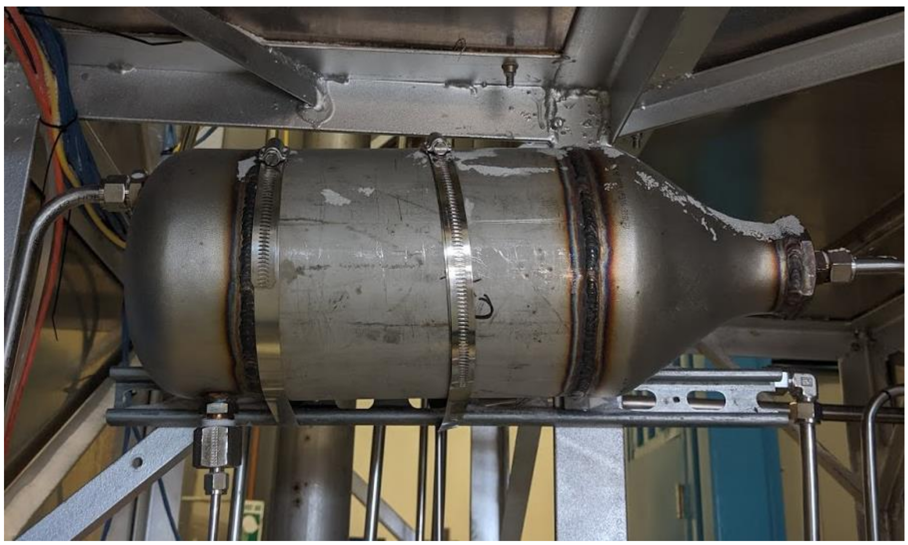


Figure 20. Pollutant settling tank

References

[1] F. Gonçalves, A. Trindade, C. Costa, J. Bernardo, I. Johnson, I. Fonseca and A. Ferreira, "PVT, viscosity, and surface tension of ethanol: New measurements and literature data evaluation," *J. Chem. Thermodynamics,* vol. 42, pp. 1039-1049, 2010.

[2] J. Livingston, R. Morgan and M. Neidle, "The Weight of a Falling Drop and the Laws of State, XVIII. The Drop Weights, Surface Tensions and Capillary Constants of Aqueous Solutions of Ethyl, Methyl and Amyl Alcohols, and of Acetic and Formic Acid.," *Journal of the American Chemical Society,* vol. 35, no. 12, pp. 1856-1865, 1913.

[3] J. Livingston, R. Morgan and A. J. Scarlett, Jr., "The Properties of Mixed Liquids. IV. The Law of Mixtures. II.," *Journal of the American Chemical Society,* vol. 39, no. 11, pp. 2275-2293, 1917.

QUARTERLY REPORT AND MILESTONE SUBMISSION

January 15, 2020

Submitted by

SUSTAINABLE ENERGY SOLUTIONS

Submitted to

ROCKY MOUNTAIN POWER

Sustainable Transport and Energy Plan (STEP)

Overview

Sustainable Energy Solutions (SES) worked through several modifications to the existing Cryogenic Carbon Capture™ (CCC) process under Department of Energy (DOE) and Rocky Mountain Power (RMP) support over the last year. These modifications improve the reliability, and in some cases, decrease the energy and economic costs of the process.

As SES improved the reliability of these unit operations, SES also innovated technologies with improved reliability and energy efficiency that have the potential to replace existing unit operations. SES is also actively planning for the next scale of CCC operation and will explore the scalability of these and related unit operations as part of this investigation. These include:

1. Simultaneously drying and cooling the flue gas to the CO_2 frost point.
2. An alternative cooling and solid–liquid separation system for the contact liquid. This will also include the development of a pollutant removal system for SO_x and NO_x built into this separations system and the CO_2 purification system.
3. Investigating unit operation scalability.

Quarterly Milestones

As part of this project, SES reports quarterly on the progress made towards the above objectives. The exact wording of the milestones for this quarter are as follows:

Q12	**SES will deliver a report containing the following:** Task A1 – Results of further test results including using real flue gas and initial integration with skid system. Final Reporting. Task A2 – Results of testing the finalized designs. Final Reporting. Task A3 – Assessment of scale-up potential of innovative unit ops including dryer and solid-liquid separations.	**1/15/2020**	**$ 113,000**

Task A1. Gas Drying and Cooling

Objective

The objective of this task is to mature the direct-contact cooling and drying systems to the point they can be tested in the skid.

DCPC Dryer Progress

At the start of this quarter, the Direct-Contact Phase-Change (DCPC) dryer prototype was installed next to the skid-scale CCC process. The dryer instrumentation and controls were added to the skid-scale CCC unit control system. A queue of tests were run on the DCPC dryer with variations in gas flow rate, water and CO_2 content, liquid distributor type, liquid droplet size, liquid flow rate and others. These tests culminated in testing the DCPC dryer to remove water from flue gas in a combustion process using SES's multifuel reactor (MFR). Some of the test results have validated models and came out as expected, but other results were unexpected and surprising. Results from each of these tests help inform the scale-up design, but research is ongoing.

Q12 was tremendously productive for the DCPC dryer. The testing was extensive and varied; the results and actions are summarized in this order:

- Development and testing of gas-wetting techniques
- Mist characterization and elimination
- Skid integration and testing with flue gas
- Current status and future work

Development and Testing of Gas-Wetting Techniques

Gas wetting is a primary success criterion for the DCPC dryer. Virtually every gas molecule needs to contact the cold alcohol stream for heat transfer from the gas and mass transfer of the water into the liquid stream. The target water content of the outlet gas is 9.8 parts per billion (ppb_v). Ethanol-water and methanol-water viscosities and heat of absorption measurements during Q11 prompted a significant design shift for the DCPC dryer. Work on a column using structured packing was abandoned for the near future in favor of a single-stage or multiple-stage spray tower. Since heat transfer and water/CO_2 absorption have different limiting factors, it is possible that an optimal condition exists where the gas is cooled to a temperature above the desublimation temperature of CO_2 at a rate that is faster than the absorption rate of the CO_2 into the alcohol-water solution, which would minimize heat loss from heat of absorption or heat of mixing of the CO_2 into solution. There is a hypothesis that the spray tower could operate in this regime, particularly at the coldest point near the top where the liquid is coldest and most viscous.

While testing was completed using multiple spray nozzle types, a significant portion of the testing focused on showerhead designs that produce long columns of the cold alcohol-water mixture that chill the gas and absorb the water as they fall. This design has been modeled since Q11, and the modeling continues, but Q12 has focused extensively at testing these designs and comparing them empirically.

Showerhead design is not trivial: if the holes are too close together, the liquid streams merge together and leave large gaps for the gas to pass through uncontacted; if the streams start too far apart, gas can also pass through without contacting the liquid. We selected nine hole/size pattern combinations and had them fabricated on a laser cutting machine (Figure 1).

Figure 1. Showerhead designs

A view port was installed just below the shower head to observe the spray pattern as gas flowed through it. During the first shakedown test with ethanol, we were surprised to measure a dew point near −60 °C.

The showerheads were designed to emit long spaghetti-like tendrils that would ideally persist most of the way down the dryer. Because of this, the DCPC dryer earned the nickname “spaghetti dryer” among engineers at SES this quarter. Below are examples of two similar showerheads during cooldown (Figure 2).

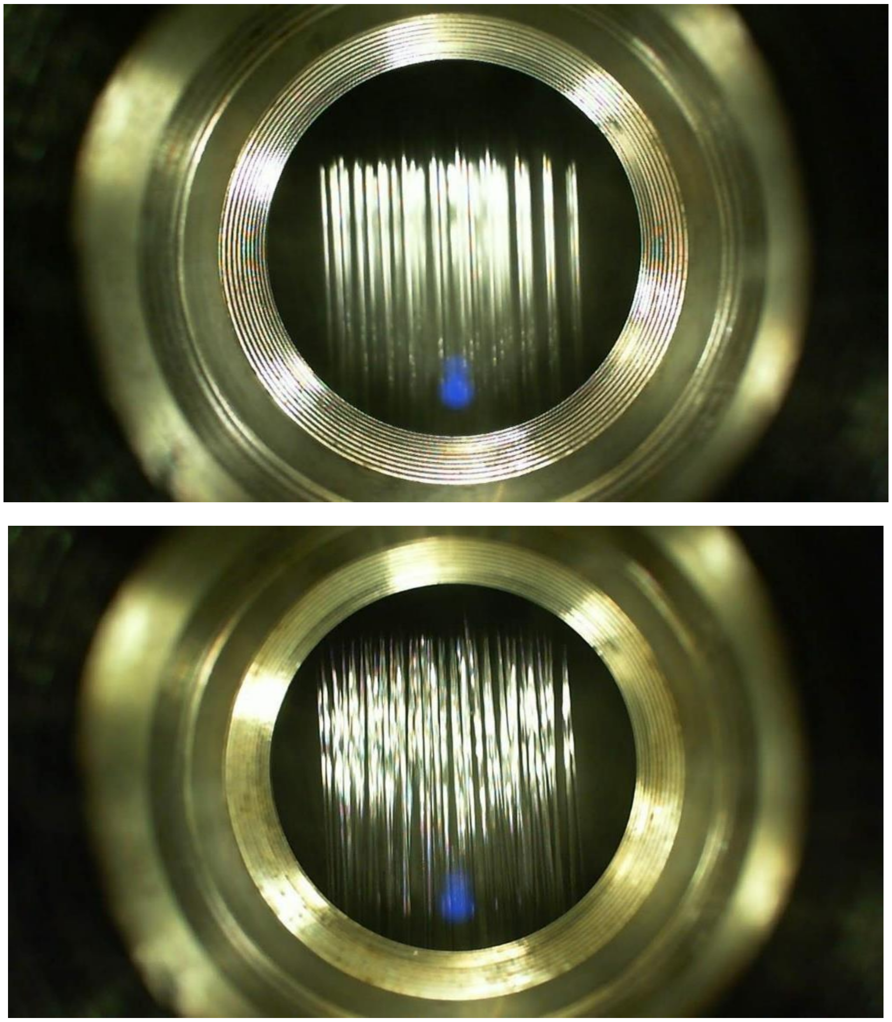
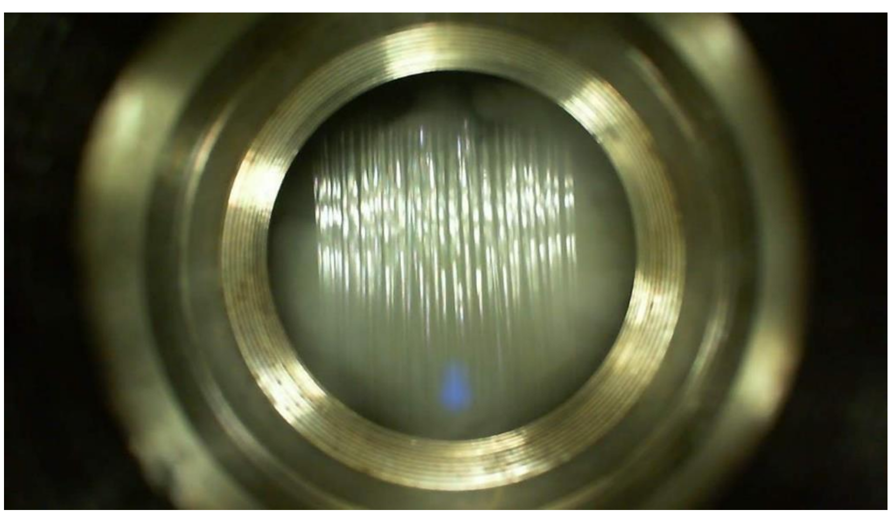


Figure 2. Showerheads spraying ethanol

A reoccurring observation during experiments is the formation of a mist that forms consistently at alcohol temperatures at or below about −50 °C (Figure 3).



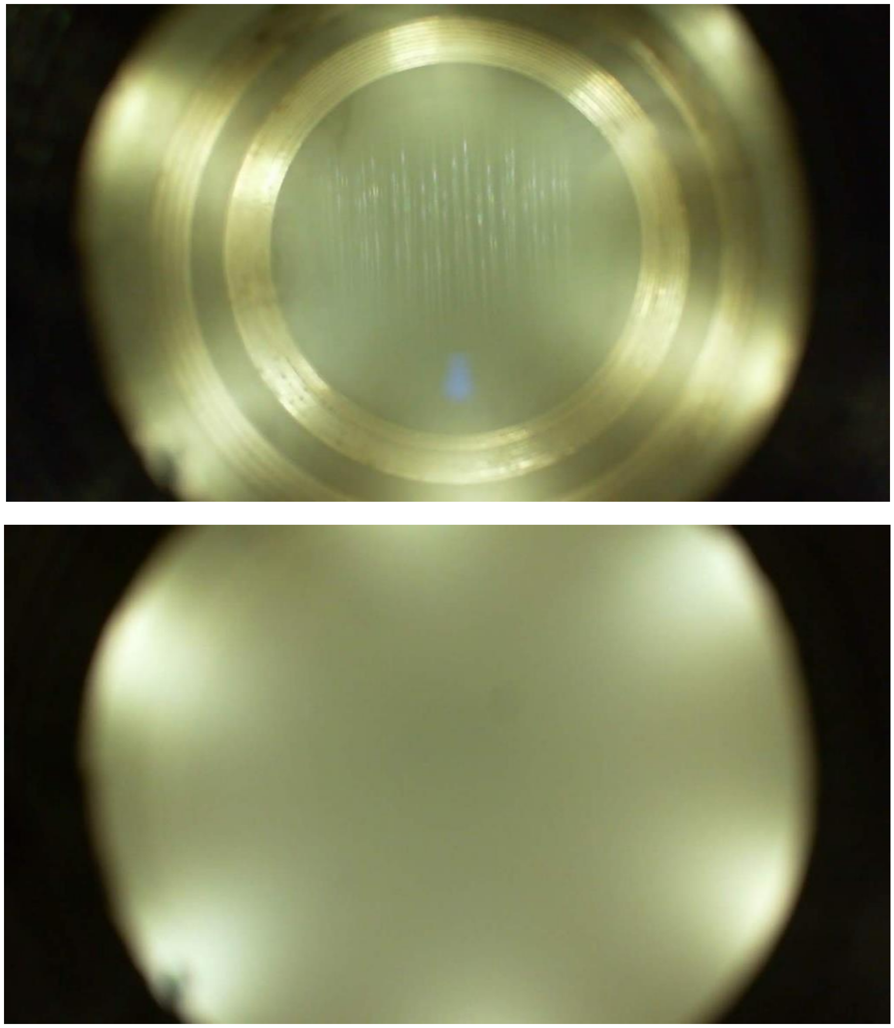
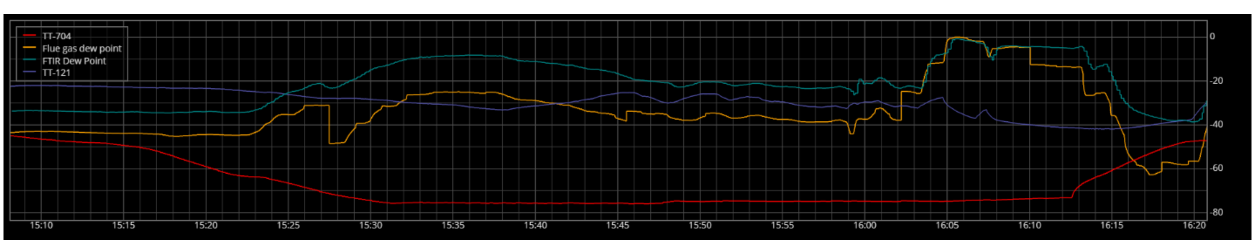


Figure 3. Mist in dryer

As the mist forms, the dew point measurement gets higher (worse). This is a condition where the measured dew point of the gas is higher than the temperature of the gas. During test runs, the system occasionally warms up and the alcohol stream temperature rises; when this happens, the dew point typically drops (better) until the streams cool back down. The picture below shows an example where the dew point gets worse as the liquid and gas temperatures get lower and then gets better as the temperatures go up.



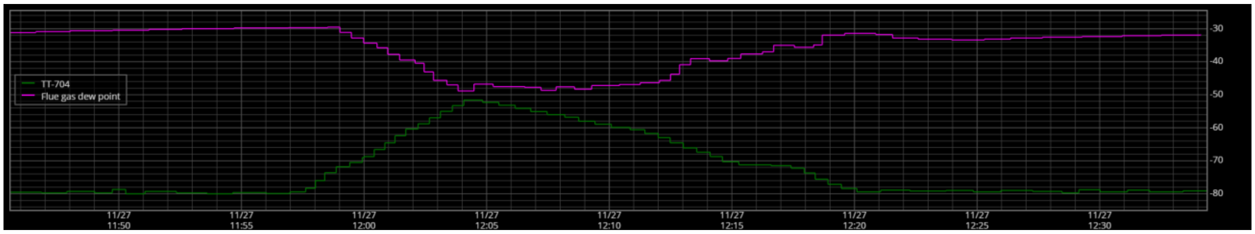


Figure 4. Dew point drops as liquid temperature rises. TT-704 is the liquid temperature in the DCPC dryer, TT-121 is the gas outlet temperature, Flue gas dew point is the dew point as measured by a Vaisala DMT-152 polymer film dew point transmitter, and FTIR Dew Point is the dew point as measured by an FTIR.

One early hypothesis for the mist was that the gas was not getting adequately wetted in the column, so we tested two spray head designs. Figure 5 shows one of these spray heads at two different temperatures.

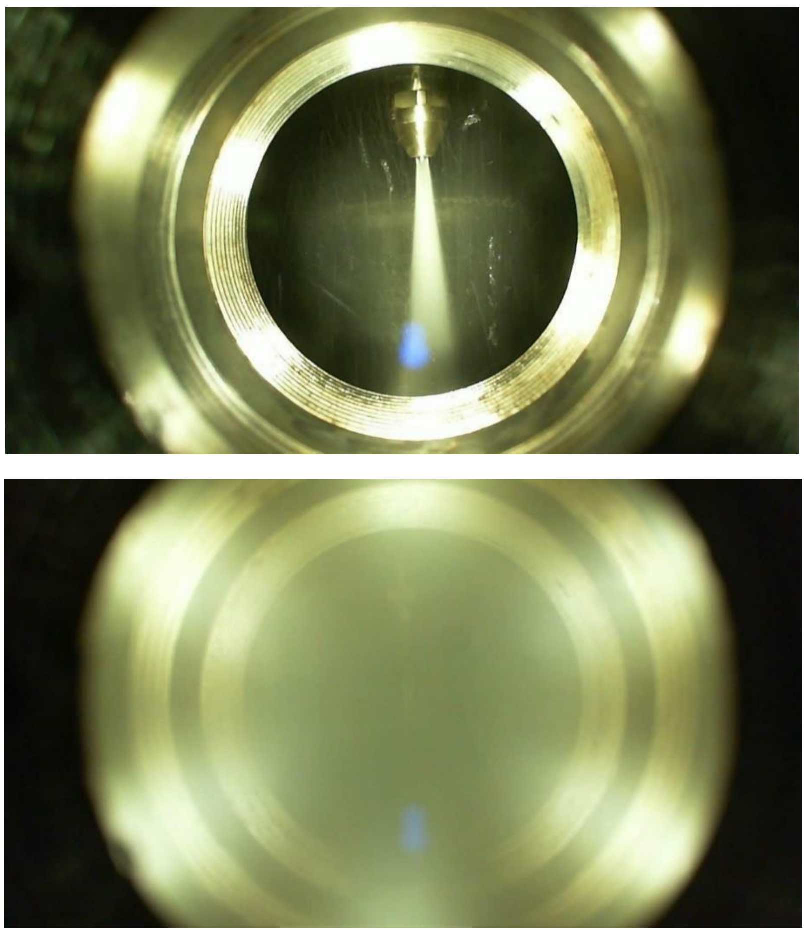


Figure 5. Spray head testing. About -45 °C (top) and about -60 °C (bottom), the temperature at which mist would begin to form.

After testing various showerheads and spray heads, the showerheads with the densest hole patterns worked the best amongst the showerheads tested. A spray head with a small orifice appears to have wetted the gas better than the best showerhead we tested, but its results were only slightly better.

Neither style eliminated the mist seen during most tests, but there were some exceptions that will be discussed later.

Mist Characterization and Elimination

The mist may form in for several reasons. When we first observed the mist, we thought it might be caused by incomplete gas wetting or temperature gradients between the liquid and gas streams or between a stream and the walls of the DCPC dryer. It was also thought to be caused by thermal heating as CO_2 absorbed into the liquid near the top of the tower because CO_2 absorption into alcohol is slightly exothermic. The following actions were taken to identify the source of the mist and mitigate it:

- Additional insulation was added to and around the DCPC dryer to minimize thermal gradients in the system between the gas and tower walls.
- The gas was precooled in a brazed-plate heat exchanger prior to entering the dryer to minimize temperature gradients between the gas and contact liquid.
- The gas was precooled in an ice column prior to entering the dryer to remove water from the gas and maintain an inlet temperature of 0 °C.
- CO_2 was injected into the simulated flue gas at different concentrations to see if mist generation correlated with the CO_2 content.
- Cold dry nitrogen was blown through the dryer to see if water vapor on the inlet gas was creating the mist.
- Warm dry nitrogen was blown through the dryer to see if more mist was produced at a higher gas temperature.
- A warm water-saturated gas stream was injected into the dryer to see how high water loading affects the mist.
- Anhydrous ethanol was used in place of the ethanol-water mixture to see if the mist forms when only alcohol is used.
- Extended tests were completed to see if the mist was a transient condition.
- The geometry of the gas outlet was modified from a large open top to a smaller restricted outlet to increase gas velocity and reduce cooldown time.
- A copper gauze mist eliminator was designed and installed to catch mist particles.
- A mist eliminator from a previous project was installed to catch the mist particles.
- A blanking plate was added to the mist eliminator to increase mist particle speed and impaction.
- The spray tower was extended and a second section was added with a second spray head.

Each of the tests and changes listed above contributed to the observation that at almost every condition, an alcohol-water mist is reliably created in the process as the liquid temperature approaches and drops below about −50 °C. A big effort has been made to better understand the mist and to reduce it. It is important to note that the inlet condition of the gas seems to have very little effect on the DCPC dryer outlet. In tests with very wet gas, the dryer was just as effective as in tests with drier gas. It is also worth noting that the partial pressure of water and alcohol above the liquid is always suppressed because of interactions in the mixture so when the mist is not present, the dew point of the gas is lower than the temperature of the alcohol-water spray that cools the gas. Consequently, many of the lowest measured dew points with the DCPC dryer have occurred when the liquid temperature in the dryer is just above the mist point. In these cases, the liquid may be close to −50 °C while the dew point is −60 °C or lower.

AMACS produces industrial mist eliminators and has literature on how some particles are formed (Figure 6).

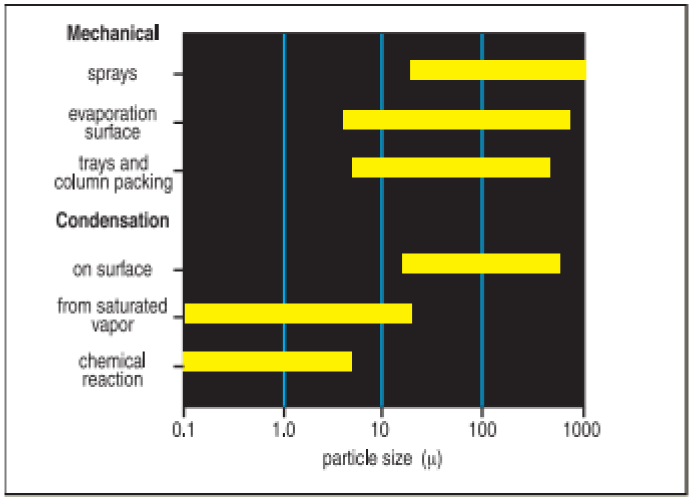


Figure 6. Mist particle generation from AMACS brochure

It is likely that some of the mist is formed mechanically as the flue gas blows through the spray. It is also possible that particles are formed chemically in the mixture. One intriguing possibility is that our attempt to minimize CO_2 absorption into the liquid by favoring heat transfer into the liquid over mass transfer from the gas to the liquid is working on the water as well. In this scenario, a large constituent of the observed mist would be water that chills and condenses but fails to absorb into the liquid stream. We ran tests blowing dry nitrogen through the alcohol spray that still produced mist, which suggests that at least some of the mist is formed mechanically in the spray.

Borrowing again from AMACS, most mist eliminators have a wire or mesh in the gas stream that helps mist particles to come in contact with each other and then as the mist droplets get big enough, they drop back into the liquid (Figure 7).

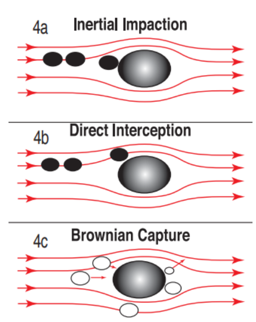


Figure 7. Mist particle capture diagram from AMACS brochure

Our first attempt to make a mist eliminator used copper gauze as the particle impaction medium. Our thought was that the copper gauze wouldn't rust and that it would be easy to install in the top of the existing dryer (Figure 8).

Figure 8. Copper gauze mist eliminator. (left) collapsible tray for holding copper gauze. (center) copper gauze on the tray. (right) copper gauze installation in the DCPC dryer.

The copper gauze mist eliminator failed to reduce the gas dew point. We think that the thermal mass of the mist eliminator prevented it from getting cold enough to condense the mist during the course of each experiment. It also may have cooled enough to condense the mist and then reevaporated it into the stream during changes in temperature. Ultimately, the measured dew point remained high throughout the duration of the run (Figure 9). This led to several changes to the upper portion of the dryer. A smaller upper section was designed, fabricated, and installed. A smaller, more developed mist eliminator from a previous experiment was installed. Better instrumentation and insulation was also installed on the dryer.

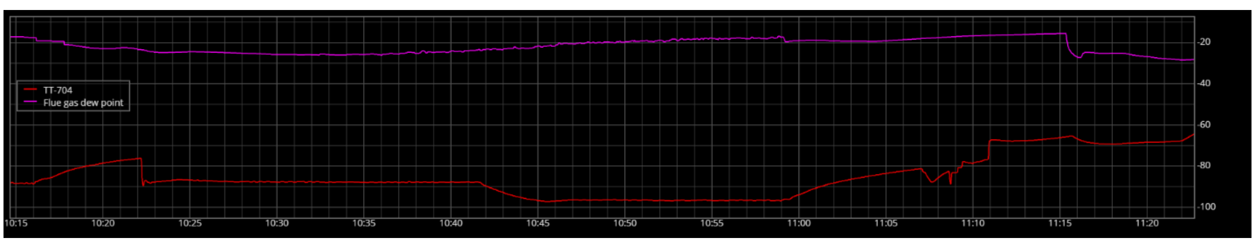


Figure 9. Copper gauze mist eliminator run data. TT-704 is the liquid temperature in the DCPC dryer and Flue gas dew point is the dew point as measured by a Vaisala DMT-152 polymer film dew point transmitter.

This mist eliminator also failed initially to reduce the measured dew point of the gas. During these tests, we reached out to mist eliminator companies, including AMACS. They suggested that we install a blanking plate with the mist eliminator. A blanking plate is a plate has a small opening where the gas passes through at a higher velocity. This higher velocity increases mist particle impaction on the mist eliminator and helps increase mist eliminator efficiency.

We fabricated a blanking plate set with two indexable disks (one side is shown in Figure 10). Every 90 degrees opens a different aperture size that corresponds to a different flow regime. Some of the lowest measured dew points during Q12 were measured during recent tests with the blanking plate. These tests are discussed in the “Current Status and Future Work” section.

Figure 10. Blanking plate designed to be used with the mist eliminator.

Skid Integration

Integrating the dryer with the skid-scale CCC system and testing it on real flue gas was a big milestone for this quarter. After completing appropriate safety and hazard reviews, we started SES's multifuel reactor (MFR) and directed the flue gas stream through the DCPC dryer. Figure 11 shows the MFR burning natural gas; the exhaust is cooled by direct contact with water as it exits through the probe and goes to the DCPC dryer.

Figure 11. MFR burner combusting natural gas.

The DCPC dryer performed as well with the MFR flue gas as it did with simulated flue gas. No difference in performance was observed. Additional test runs were completed with simulated flue gas at flow rates as high at 20 SCFM with no negative effect.

Current Status and Future Work

Our primary goal through this project has been to see if the DCPC dryer could be feasible for pilot-scale and full-scale CCC processes. Testing this quarter has required many iterations, but our understanding of how the dryer works has grown tremendously. In the last few weeks, we have seen very positive results from the dryer. The liquid pump on the dryer had to be replaced and the replacement delivered more flow than the original pump. Increasing the liquid flowrate from 400 kg/hr to 600 kg/hr seemed to significantly reduce the mist (Figure 12).

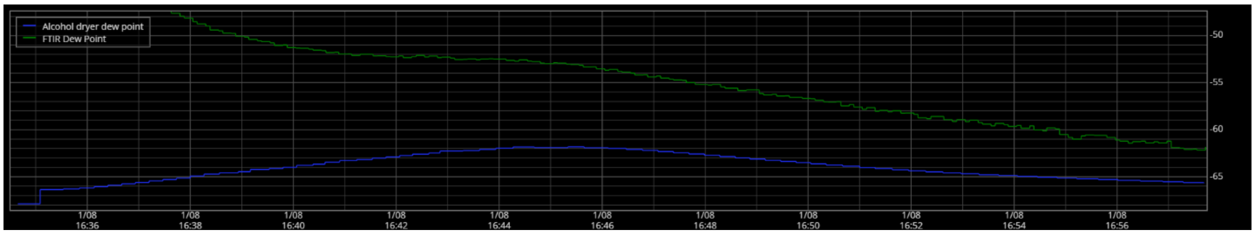


Figure 12. FTIR/polymer film dew point transmitter agreement during spray head tests

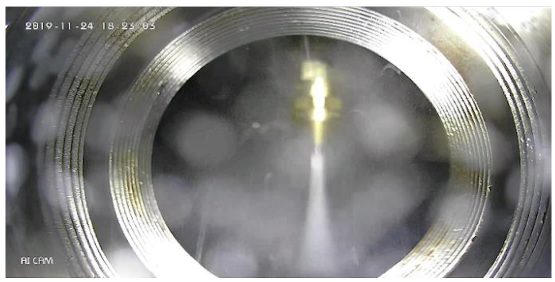


Figure 13. Spray head at 600 kg/hr

Instrumentation disagreement has steadily decreased through the experiments that have been run, which increases our confidence in our experimental method. More testing is needed, but we feel confident that the DCPC dryer could work on a pilot-scale or full-scale CCC process.

Moving forward there are at least three major areas of research that need to be addressed for the DCPC dryer: First, gas outlet composition data has been gathered through each of the tests this quarter but we don't know how much water or alcohol can actually be tolerated by the CCC process desublimator. Continuing research will focus on what those limits are. Second, more testing needs to be done cooling the DCPC dryer through heat recovery from the cold light gas outlet on the CCC process desublimator. Some heat recovery testing was done this quarter and it worked but more testing is needed. Finally, future testing needs to focus on continuously running the DCPC dryer with water alcohol separation by distillation.

Task A2. Solid-Liquid Separation and Contact Liquid Cleaning

Objective

This task is to develop a separation system or device for separating CO_2 from a contact liquid stream. Outputs of these potential systems include a low-CO_2 stream that can be reinjected into the desublimating heat exchanger without fouling.

Overview of Previous Analysis

As SES further developed the potential separations system, we developed a set of experiments that would be useful as a simple, short-term test that would allow us to quickly experiment and iterate on the concepts we were developing. A more complex, integrated system could then be developed based off the results of the initial experiments. The simplified test diagram is shown in Figure 14 and the assembled test is shown in Figure 15.

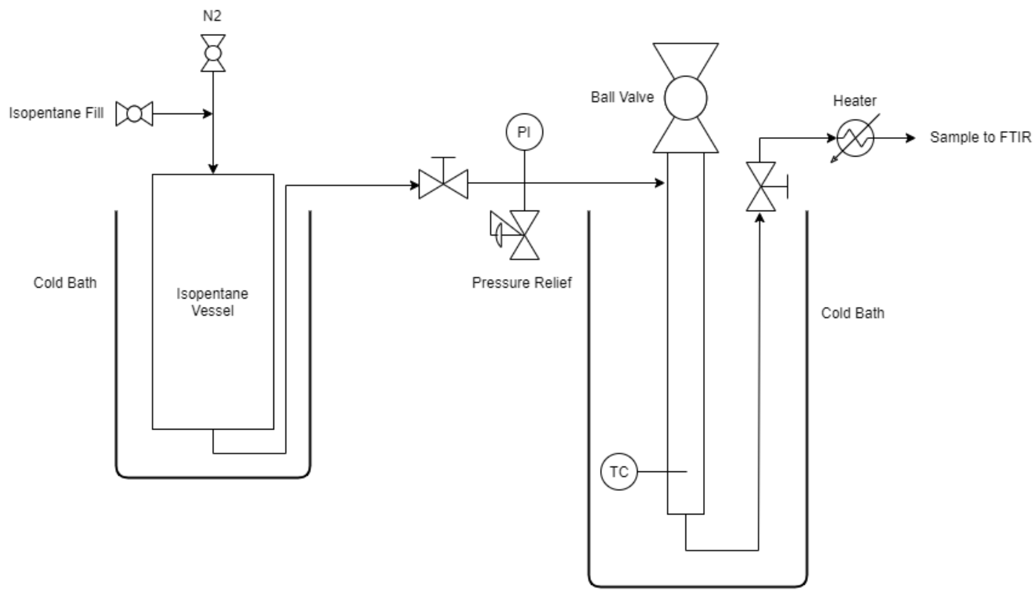


Figure 14. Experimental design for solid CO_2 sintering separation from isopentane.

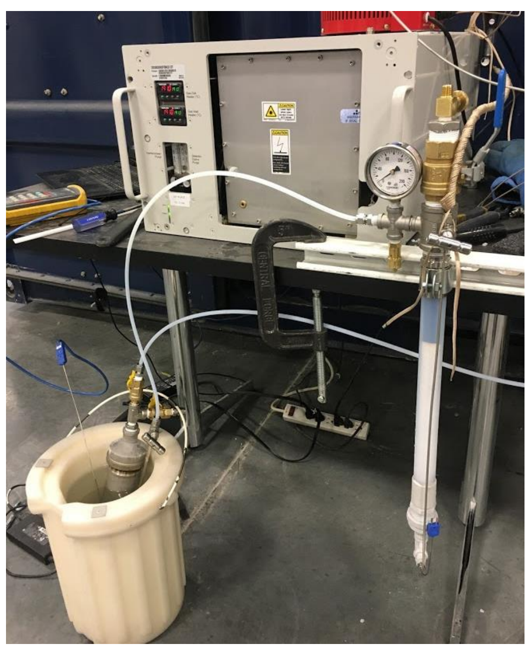


Figure 15. Experimental setup for testing CO_2 separation.

Results of this experiment showed a meniscus forming to separate the CO_2 from the isopentane, and results from the FTIR showed a high degree of CO_2 purity in the stream exiting at the bottom until the meniscus approaches the sample area. The two liquids are both very clear and colorless, making photographing the meniscus difficult. Figure 16 shows the sample during a test. CO_2 gas bubbles were seen to form at the top of the CO_2-rich phase (i.e., at the meniscus).

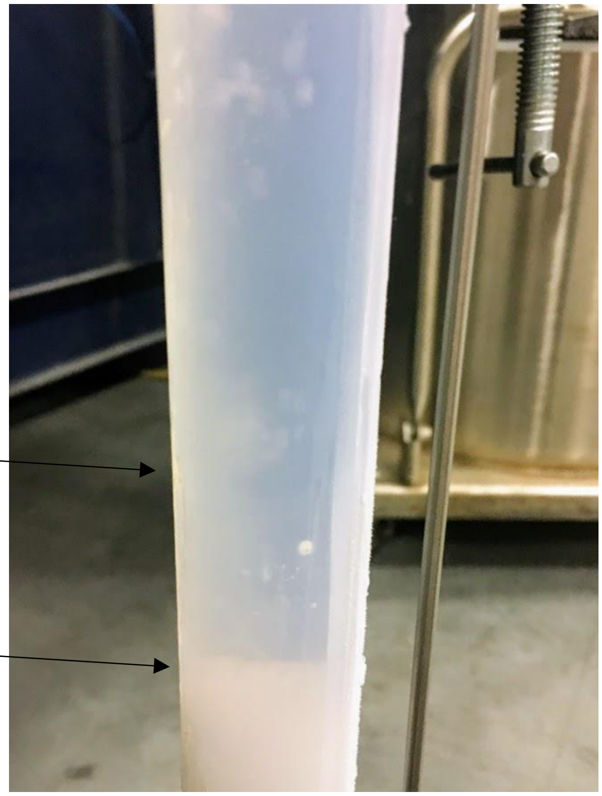


Figure 16. Solid CO_2 melting and the formation of the meniscus.

Isopentane and Carbon Dioxide Solubility Testing

To determine whether the results of the above experiment could be translated into a viable unit operation, we ran additional experiments to see if the separation could occur in non-ideal conditions. These conditions included a more complete mixing of the isopentane and CO_2, which would better represent conditions in a process. These experiments were based on previous solubility experiments, which are discussed below.

Previous Solubility Testing Results

To better design the experiment that would determine whether it is possible to sinter the CO_2 and effectively separate it from the liquid isopentane, SES reviewed previously conducted research into the separation of hydrocarbons from CO_2. This research included the measurement, previously conducted by SES, of the compositions of two liquid phases separated by a meniscus.

In those experiments, liquid CO_2 was added to a mixture of methylcyclohexane and methylcyclopentane, which were being used as our primary contact liquid at the time. When enough CO_2 was added, two distinct phases were formed. One phase was rich in CO_2 and the other phase was rich in hydrocarbons. The CO_2 concentration in the hydrocarbon-rich phase ranged from 40 to 50%. The CO_2 concentration in the CO_2-rich side varied from 79 to 93%. Temperature was varied from −50 to −54 °C. A CO_2-rich phase would not form until there was more than 40% CO_2 in the mixture. These results showed that liquid/liquid separations would not be a viable option with these hydrocarbons.

The results of these experiments indicated that if the hydrocarbons were fully mixed, it would likely be difficult to separate them again, based on density alone. We intend to repeat similar experiments using isopentane as the contact liquid; however, we expect similar results. Based on this input, the design of the experiments below were modified to reduce any agitation and mixing of the liquid and solid streams as much as possible until separation was complete.

Test Procedure

Previously, multiple tests were run where isopentane was mixed with CO_2 at a cold temperature under pressure to see if they would separate into two different phases. The test apparatus is shown in the photo below in Figure 17. The bottom of the test tube was filled with metal balls to take up space where the sample will not be visible. After the balls were in place, the remaining volume of the bottom of the test tube was measured by draining the remaining liquid into a graduated cylinder.

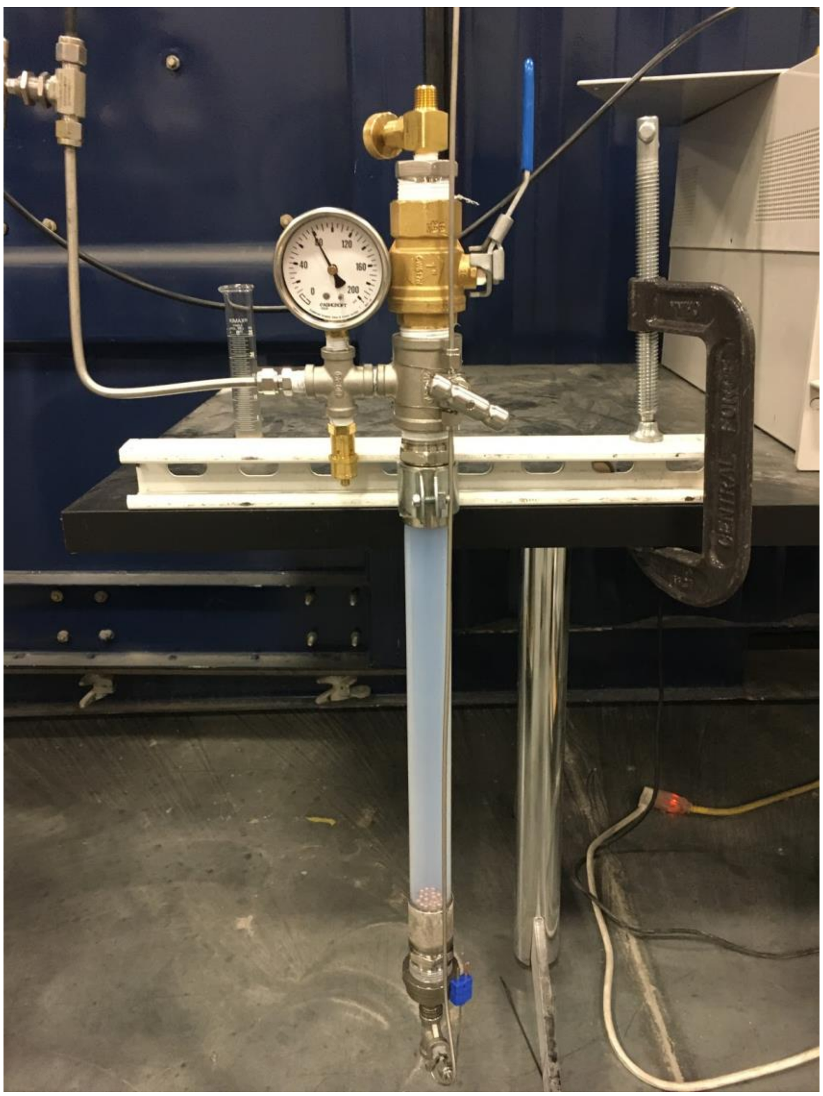


Figure 17. Solubility experiment test setup.

To begin the experiment, isopentane was injected into the test tube while the tube was warm. The height of the isopentane in the tube was used to measure the amount of isopentane added based on earlier calibration measurements. The tube was purged with CO_2 and placed in an alcohol bath cooled to −56 °C with liquid nitrogen. Pressurized gaseous CO_2 was condensed in the cold sample tube until the desired sample height in the tube was reached. The condensing CO_2 is visible when looking at the tube with a light behind it, and it appears to travel to the bottom of the tube, which helped to thoroughly mix the sample. The final sample height and the initial isopentane volume were used to estimate the concentration of the sample. This estimate did not account for excess volume of mixing.

After the CO_2 condensed, the high-pressure CO_2 gas was valved off. The samples were allowed to sit for at least 30 minutes to allow the sample to separate, and some samples were allowed to sit for over an hour while the temperature was maintained. It was necessary to add a small amount of N_2 gas to prevent the CO_2 from forming gas bubbles that would disturb the sample.

Results

The following concentrations and temperatures were tested, and no meniscus formation was observed for any of the tests. The sample in the tube was carefully examined with a backlight to look for a meniscus.

Isopentane (%)	Temperature (°C)
25	−56
38	−56 to −45
55	−56
64	−56

Task A3. Unit operation scalability

Objective

This task will investigate unit operation scalability to both pilot and commercial scale operation.

DCPC Dryer

The direct contact dryer has shown considerable promise. While there are still remaining issues with CO_2 solubility and demisting, we feel confident that they can be solved moving forward. The low pressure drop coupled with the high efficiency of heat exchange represent a significant improvement in performance over other drying systems. Additionally, even though there are still some obstacles that must be overcome, significant progress has been made towards implementation in our current and future demonstration systems.

The knowledge gained during this project has led to multiple redesigns and key discoveries that have moved this portion of the technology forward. Our current demonstration system has an adequate drying system installed, but it would be impractically expensive and energy intensive to use on the next scale of our process. We now see a much clearer path to implementing the DCPC dryer on our current demonstration unit. The knowledge we have gained will be invaluable as we move to larger scales. The DCPC dryer remains the most promising path forward for drying flue gas to be processed by the CCC system.

Solubility Separation

The solubility testing results were inconclusive and we never saw a defined meniscus in our liquid-liquid experiments when using isopentane mixed with CO_2. Our prior experimentation with methylcyclohexane and methylcyclopentane had given us hope that this would be a viable solution. However, the lack of a defined meniscus in the controlled isopentane experiments leads us to believe that this will not be a viable solution at larger scales.

Pollutant Removal System

We were unable to have sufficiently long runtimes on real flue gas to fully test the ability of the traps to control pollutant build up. However, we are confident in their performance and will continue to monitor the outlet concentrations of the traps in future tests. It is also possible that at the small scale of the current system, the accumulation of pollutants will be so slow that they will be undetectable at the intervals we currently use to drain the pollutant removal tanks. We still consider these settling tanks as the preferred technology moving forward and will continue to test them at the current scale and at larger scales in the future.

PacifiCorp
Hunter Unit 3

SES Phase 2 CO_2 Capture Scalability Report

Report SL-015967

Revision A

October 28, 2020

Project No.: A11801.022

☐ Safety-Related
☒ Non-Safety-Related

55 East Monroe Street
Chicago, IL 60603-5780 USA
312-269-2000
www.sargentlundy.com

LEGAL NOTICE

This deliverable was prepared by Sargent & Lundy, L.L.C. (S&L) expressly for the sole use of PacifiCorp (Client) in accordance with the contract agreement between S&L and Client. This deliverable was prepared using the degree of skill and care ordinarily exercised by engineers practicing under similar circumstances. Client acknowledges: (1) S&L prepared this deliverable subject to the particular scope limitations, budgetary and time constraints, and business objectives of Client; (2) information and data provided by others, including Client, may not have been independently verified by S&L; and (3) the information and data contained in this deliverable are time-sensitive and changes in the data, applicable codes, standards, and acceptable engineering practices may invalidate the findings of this deliverable. Any use or reliance upon this deliverable by third parties shall be at their sole risk.

ISSUE SUMMARY AND APPROVAL PAGE

This is to certify that this Report has been prepared, reviewed and approved in accordance with Sargent & Lundy's Standard Operating Procedure SOP-0405, which is based on ANSI/ISO/ASSQC Q9001 Quality Management Systems.

Contributors

Prepared by:

Emily Kunkel
Environmental Lead

Reviewed by:

Wayshalee Pate — Date
Project Manager

Approved by:

Wayshalee Patel — Date
Project Manager

TABLE OF CONTENTS

1. INTRODUCTION AND PURPOSE

1.1 PROJECT INTRODUCTION

PacifiCorp is evaluating the technical and commercial feasibility of Sustainable Energy Solutions' (SES) Cryogenic Carbon Capture (CCC) technology for PacifiCorp's Hunter Plant ~~as part of their integrated resource plan (IRP)~~. As part of a Department of Energy (DOE) funded project (DE-FE0028697), SES completed on-site skid operation ("Phase 1 Pilot Project") at the Hunter Plant Unit 3 as input to the Scalability Study for the CCC technology ("Phase 2 Scalability").

PacifiCorp has engaged Sargent & Lundy LLC (S&L) to evaluate the applicability of the SES CO_2 capture technology on a full-scale application based on the results of the pilot project results. This Scalability Study focuses on the requirements to scale up the technology and develops a conceptual "full-scale" CCC system including conceptual design and arrangement, capital cost estimate, and O&M cost estimate.

The purpose of this report is to provide direction to SES on scalability of process equipment sizes and arrangement, and to provide input to Pacificorp and SES as to the overall estimated cost of capture for a full-scale 550 MWn nominal application.

1.2 STATION BACKGROUND

While Hunter Station Unit 3 was initially selected as the applicable facility for implementing full-scale CO_2 capture, a similar sized green-field facility was ultimately selected for the basis of the scalability study. SES had initially set up their process model based on results from the pilot tests and developed material balances and equipment information for the full-scale application. A design basis was developed to modify the process results with Hunter Unit 3 specific information; however, the model was misplaced and no longer available to use for scaling for Hunter-specific information.

After discussion with PacifiCorp and the team, it was determined that the unit sizes between the green-field facility and Hunter Unit 3 were reasonably similar and there would be used as the basis. Therefore, SES did not redevelop the process model for Hunter Unit 3 specifics. As such, this scalability report is based on the unit sizing for a green-field power plant with a power output of approximately 550 MWnet. Data from a techno-economic assessment (TEA) prepared from a previous DOE study was used as the input. The previous DOE study was conducted in the Midwest and includes modern backend controls, including wet flue gas desulfurization (WFGD). For comparison, Hunter is in the process of upgrading their existing WFGD systems.

2. PROCESS OVERVIEW

SES's CO_2 capture technology called the Cryogenic Carbon Capture™ (CCC) process is a post-combustion technology that separates CO_2 from flue gas to produce a compressed CO_2 stream. The high-level process, as shown in Figure 1, consists of a number of steps including; cooling CO_2-laden flue gas to desublimation temperatures (−100 to −135 °C), separating solid CO_2 from the light gases, using a recuperative heat exchanger to separate the CO_2 stream, recovery of the contact liquid, and compressing the solid/liquid CO_2 to final pressures (100–200 bar) to produce a compressed CO_2 stream. A more detailed version of the process flow diagram is included in Attachment A.

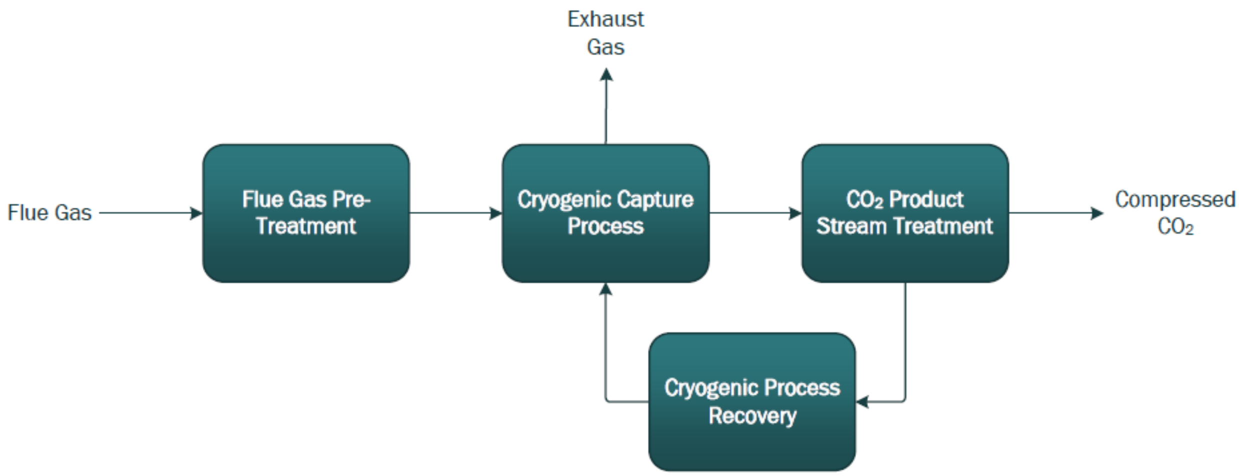


Figure 1: CCC Block Flow Diagram

3. DESIGN INPUTS

Table 1 summarizes the approximate flue gas properties downstream of the WFGD at Hunter Unit 3 compared to the new green-field facility. The properties are based on mass balance calculations that were prepared previously by S&L for the Hunter Unit 3 FGD and supplemented by inputs from additional data as necessary. The greenfield unit information is provided by the DOE/NETL report for Case 12B, adjusted by SES for unit sizing to maintain 550 MWnet.

Note that there is only approximately a 10% difference in fuel heat input; however, based on fuel characteristics and unit operating characteristics (e.g. excess air, in-leakage, etc.) there is a significant differential in overall volumetric flow leading to the CCC island. However, based on a previous review of the flue gas oxygen concentration, flue gas at Hunter Unit 3 could be lower than shown in Table 1, on the order of 1,575,000 acfm which is closer to the DOE Case 12B but still slightly higher. As such, it is expected that the capital and operating costs of the SES scaled system for application at Hunter Unit 3 could be nominally to moderately higher than what is reported herein depending on the volumetric flow.

Table 1: Summary of Design Inputs and Assumptions

Variable	Unit	Hunter Unit 3	DOE / NETL Case 12B
Boiler Type	--	Subcritical	Supercritical
Fuel	--	Western Bituminous	High Sulfur Eastern Bituminous
Plant Elevation	ft above MSL	5,640	0
Heat Input	MMBtu/hr	Full – 4,992	Full – 5,506
CCC Application	--	Retrofit	Green-field
WFGD Outlet Conditions			
Flue Gas Concentration	vol %	N_2 – 70.18 O_2 – 7.69 H_2O – 12.69 CO_2 – 9.16 Ar – 0	N_2 – 68.54 O_2 – 3.25 H_2O – 14.51 CO_2 – 12.88 Ar – 0.82
Total Volumetric Flow	acfm	2,164,000	1,436,539
Total Flue Gas Mass Flow	lb/hr	7,142,300	5,774,482

Variable	Unit	Hunter Unit 3	DOE / NETL Case 12B
Temperature	°F	123	133
Pressure	psia / in.w.c.	12.063 / +1	14.7 / 0

4. CCC SYSTEM COMPONENTS

4.1 PROCESS EQUIPMENT

SES's process for desublimating CO_2 is novel in both its application for CO_2 capture and size. As such, scaling equipment based on process model results is imperative to understand application of the equipment in real world applications. An initial equipment list was provided to S&L to review and as a basis to seek budgetary information as necessary. Based on discussions with original equipment manufacturers, vendors, and previously completed work, the equipment size and number of components was adjusted to fit the process requirements. During the budgetary information and quote request phase, it was determined that certain critical process components will in fact have to be broken down into either various stages in series or parallel trains to handle the entire capacity of the system. Where possible, a 1x100% configuration was used; this is predominantly applied to vessels rather than rotating equipment (e.g. pumps, compressors, etc.). One rare case where the sparing basis was more than a 2x50% or 2x100% configuration was the screw press. When S&L discussed the screw press with Vincent Corporation, their quote based on the flow requirement was for 216 parallel components. This is one critical piece of the process that would benefit additional discussion with the manufacturer to develop larger components for the SES process itself as the company continues to scale up applications in the field.

It is also prudent to mention S&L's concerns with scalability on certain heat exchangers. When reviewing the individual heat exchanger performance and sizing requirements, there was hesitation from certain vendors. Because the process model was no longer available, many details that equipment vendors were requesting regarding fluid properties such as specific heat, thermal conductivity, viscosity, particle size, and others for certain components of the project were not available. In many instances, after much communication, information requests, and clarifications the requested equipment quotations were still far too complicated for vendors to provide without prompting the need to enter into a monetary agreement for additional internal engineering and R&D. In other instances, vendors simply chose to deny providing a quotation due to the unknowns and level of complexity.

The equipment list is included in Attachment B, including component sparing. Note that based on information provided by vendors, various parallel components are required in certain areas for pricing; however, as the process continues to scale up, it is expected that these components can be scaled up to much larger sizes for a typical sparing philosophy as denoted.

4.2 UTILITY USAGE

SES also provided an initial utility rate summary for the major components within the capture island. S&L updated the list based on information provided by vendors and incorporated additional information as required. The major difference in overall power consumption is due to two major power users, the electric reboiler and the screw presses that are included in the list that S&L developed. The reboiler power consumption was provided separately by SES and the screw press consumption was provided by a vendor.

Table 2: Equipment Utility List (MW)

Energy User	SES's TEA	S&L's Estimate
CCC Process Island		
Refrigerant Compression	101.7	93.8
Separations Compression	0.7	
Condensed Phase Pumping	3.1	3.6
Steam Redirection	2.6	--
Electric Reboiler	Not included	27.3
Screw Presses	Not included	16.1
CCC BOP		
Flue Gas Booster Fan	8.8	9.4
CCC Circulating Water Pump	Not included	2.1
CCC Cooling Tower	Not included	1.2
Total	**116.9**	**153.4**

4.3 EQUIPMENT ARRANGEMENT

S&L was tasked with developing a general arrangement for the CO_2 capture island. Based on the process flow diagram and discussions with SES, a configuration was developed with the understanding that it was based on a green-field facility with no spatial constraints or difficult tie-in considerations. The general arrangement is included in Attachment C.

5. COST ESTIMATES

The overall scaled-up conceptual design was used to develop operating and maintenance (O&M) costs as well as overnight capital costs. Due to the limited detailed information from suppliers and the level of the project development completed, this estimate is categorized under Class 5 Estimates per the AACE Guideline.

5.1 CAPITAL COSTS

The SES equipment list provided as part of the CCC island was the input for the cost estimate. However, various additional balance of plant components were added. The following provides background of the estimate components. Additional detail is included in the Basis of Estimate document in Attachment D along with the summary capital cost.

- SES CCC island equipment, including all heat exchangers, vessels, compression equipment, blowers, and pumps
- An in-duct heat exchanger to reheat flue gas
- New circulating water system, including pumps, piping, and cooling tower
- All civil work, foundations, and structural steel
- Ductwork from WFGD outlet to CCC island and CCC island to new stack
- Cold process equipment building
- Electrical equipment (including cable, motor control centers, transformers, etc.)
- Electrical and controls building
- Zero liquid discharge wastewater treatment system
- Other utility supply (instrument air, fire protection, sewer, potable water, etc.)

5.2 O&M COSTS

Operating and maintenance (O&M) costs were developed for the system, including the balance of plant impacts. The following components were estimated:

- Auxiliary power derate/purchase cost
- Wastewater treatment chemicals
- Process island refrigerants makeup
- Operator costs (based on 23 employees dedicated to CO_2 system)
- Maintenance material and labor (based on capital cost)
- Transportation, storage and maintenance (TS&M) costs are also included, using the DOE standard $10/tonne.

The detailed O&M costs are provided in Attachment E.

5.3 COST EFFECTIVENESS

Based on the information provided from the material balances with regard to achieving 90% capture through the system, along with an assumed capacity factor for future operations, S&L estimated the annual metric tons (tonnes) of CO_2 captured and compressed. This was used to develop an overall cost effectiveness for the CO_2 system, represented in $/tonne, which can be compared to the IRS' 45Q tax credits of $35/tonne for beneficial reuse or $50/tonne for permanent sequestration in a storage well.

To determine an overall annual cost of the CO_2 capture system, both from operating and capital cost expenses, the capital cost was annualized using an interest rate and a payment period. For the purposes of this evaluation, an interest rate of 7% and an equipment life of 20 years was used, resulting in an annualization factor of 0.0944.

Table 3: Cost Effectiveness Evaluation

	Units	Value
Total Capital Cost	$	579,539,298
Annualization Factor	--	0.0944
Annualized Capital Cost	$/yr	54,708,510
Annual O&M Costs	$/yr	93,077,778
Total Annual Costs	$/yr	147,786,288
Total CO_2 Captured	tonnes/yr	3,436,560
Cost Effectiveness	$/tonne	43

For comparison, the DOE has estimated between $45-60/tonne, with costs continuing to be reduced on a commercial scale.

6. RECOMMENDATIONS

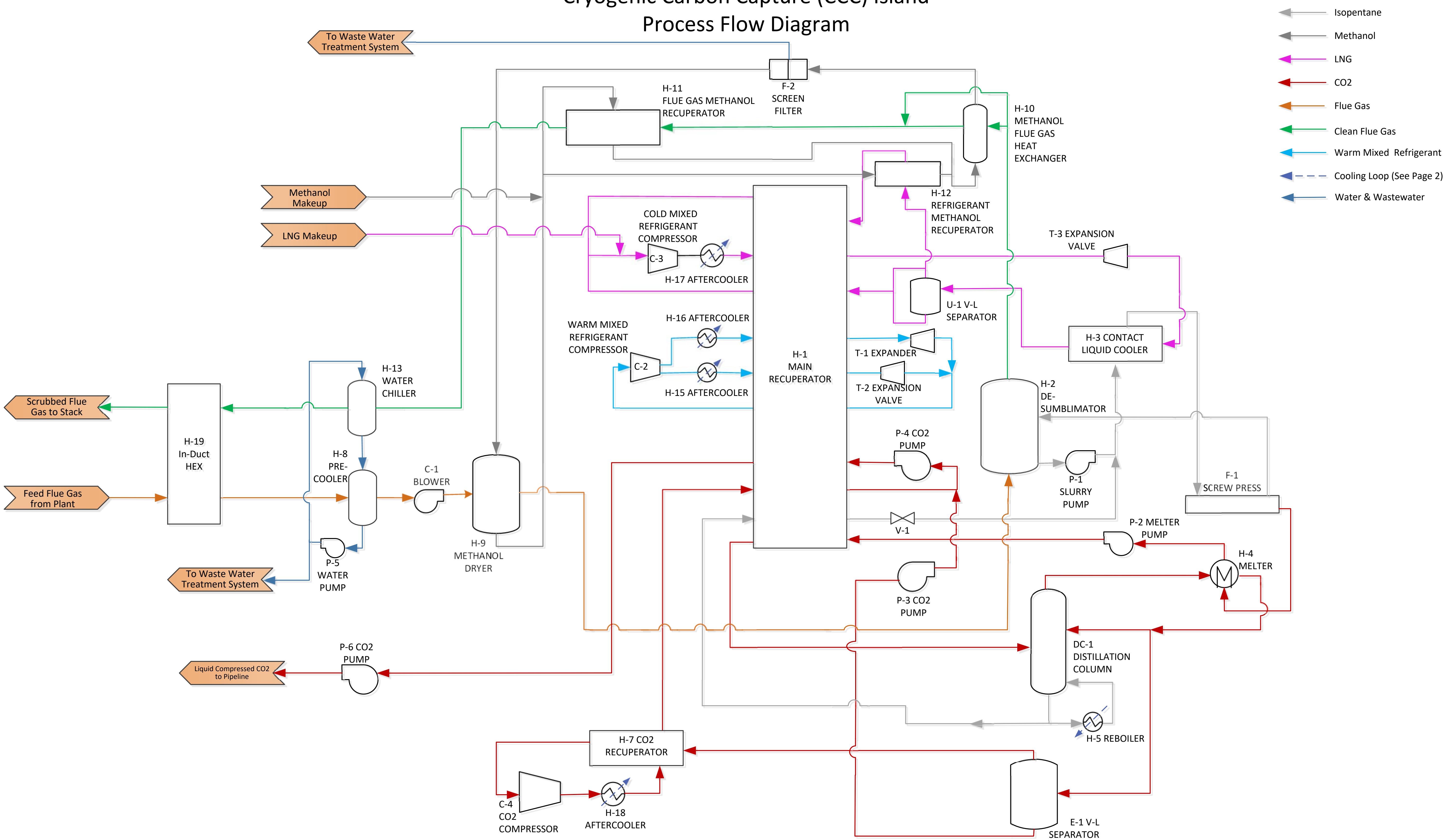
The SES process is in the early stages of scale up based on their recent pilot projects, one of which was completed at Hunter Unit 3. Due to the complexity and size of specific vessels and heat exchangers that would be required for a 550 MWnet site, it is recommended that SES partner with a process design company to apply the technology and develop a true scale-up of equipment associated with critical CCC-specific components (i.e. screw press, heat exchangers, main recuperator).

Due to the lack of available vendor information on many integral components within the CCC island, the accuracy range of this estimate is very wide. As more information is developed by vendors, individual subsystems of the components may not be as costly if vendors are able to find a more applicable component; one example would be for the screw-press system that is currently 216 components in parallel. Alternatively, as more details are available there may be even more components that will need to use special materials of construction or design requirements, which may drive up the costs; one example is the Main Recuperator which may have even more support components to provide the expected performance on all integrated streams.

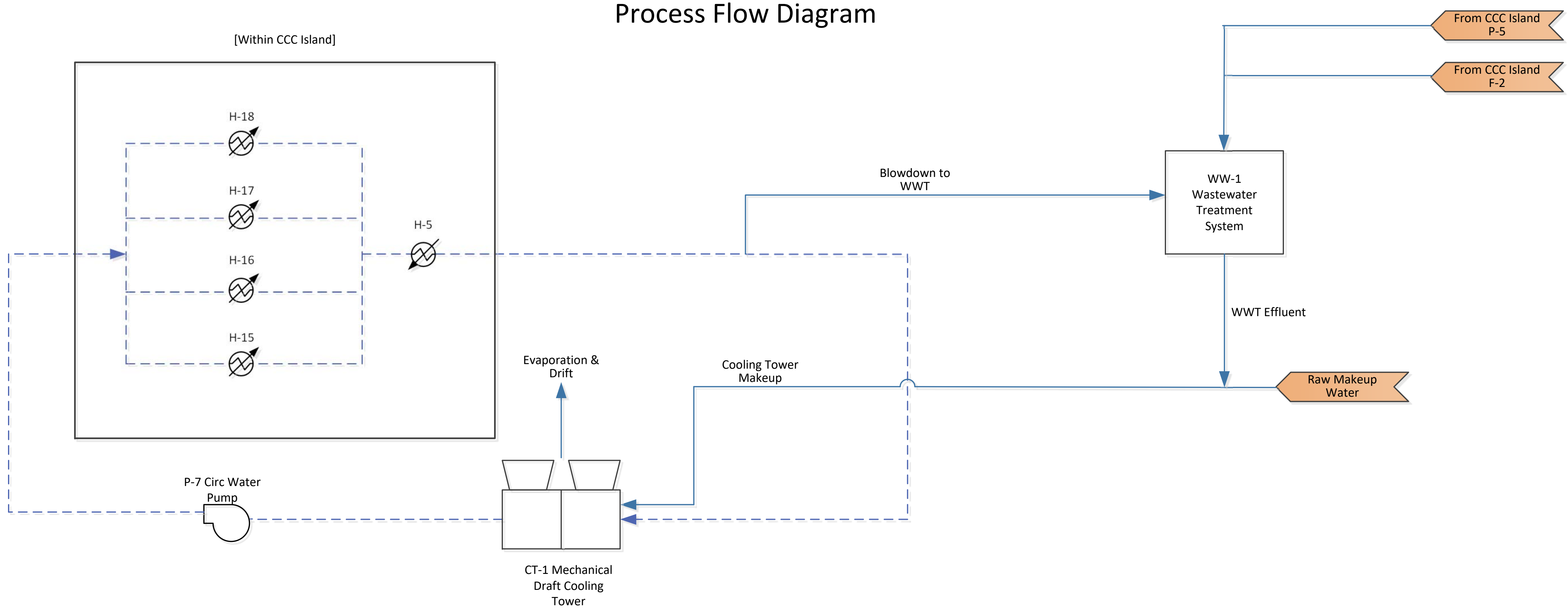
Nonetheless, a significant level of progress has been made on the application of the SES technology. As SES continues to do internal R&D, pilot testing, process model development, and research with equipment manufacturers, many of the current unknowns will become known. One of the most difficult aspects of scaling up a system is figuring out what is unknown. This study has been conducted to determine balance of plant impacts, availability of commercial or off-the-shelf components, arrangement of the equipment, and overall costs. It is recommended that this type of study be conducted again after further testing is conducted, additional R&D is conducted on critical components, and the process model is redeveloped.

ATTACHMENT A — PROCESS FLOW DIAGRAM

Cryogenic Carbon Capture (CCC) Island
Process Flow Diagram



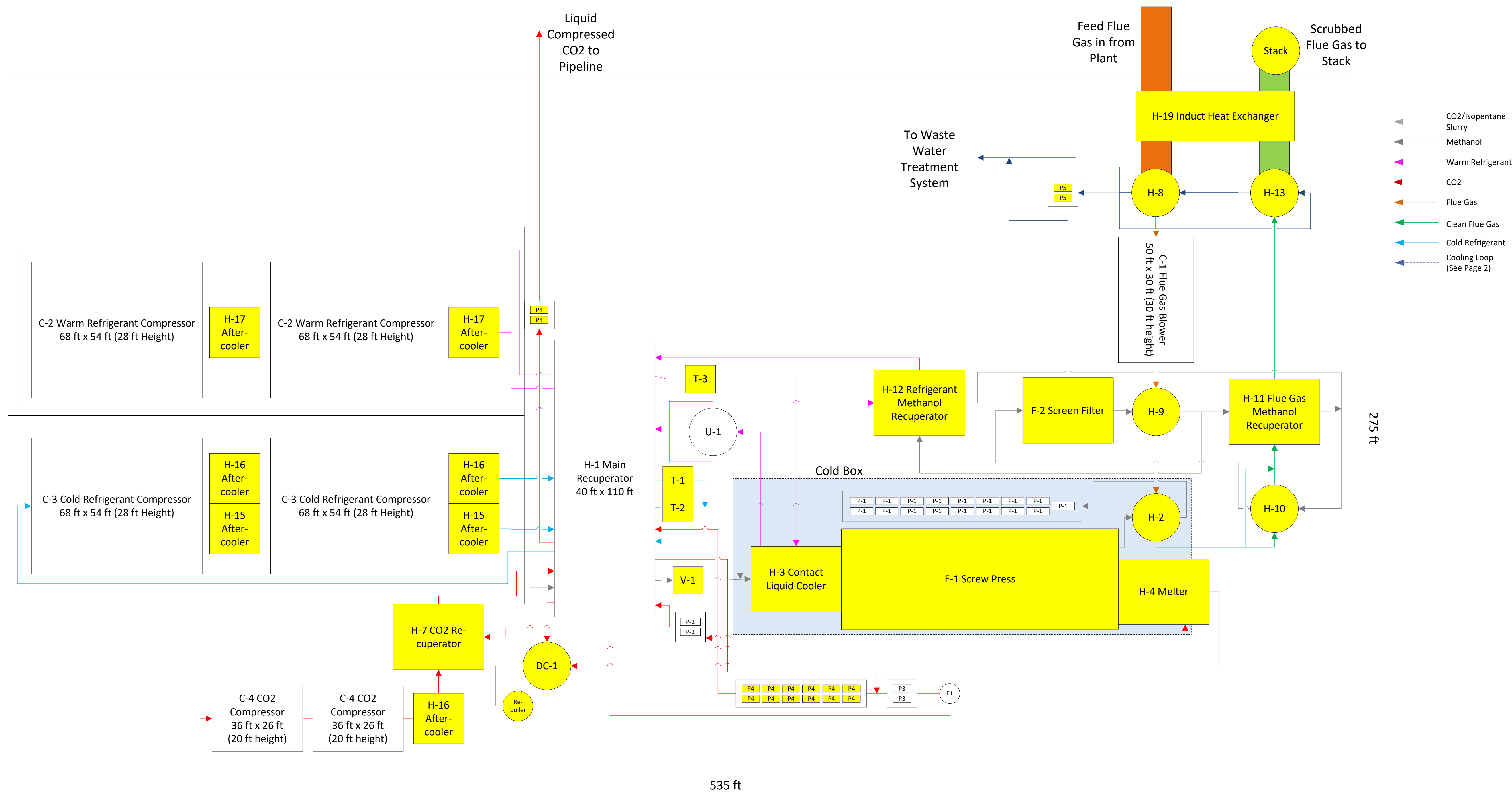
Cooling Water & Wastewater Process Flow Diagram



ATTACHMENT B — EQUIPMENT LIST

Tag	Component	Sparing Basis
	Heat Exchangers	
H-1	Main Recuperator	1 x 100%
H-2	Desublimator	1 x 100%
H-3	Contact Liquid Cooler	1 x 100%
H-4	Melter	1 x 100%
H-5	Reboiler	1 x 100%
H-7	CO2 Recuperator	1 x 100%
H-8	Direct Contact Precooler	1 x 100%
H-9	Methanol Dehydrator	1 x 100%
H-10	Methanol Flue Gas Direct Contact Heat Exchanger	1 x 100%
H-11	Flue Gas Methanol Recuperator	1 x 100%
H-12	Refrigerant Methanol Recuperator	1 x 100%
H-13	Water Chiller	1 x 100%
H-19	Induct Heat Exchanger	1 x 100%
	Compression	
C-1	Flue Gas Blower	2 x 50%
C-2	Warm Refrigerant Compressor	2 x 50%
H-15	C-2 Warm Mixed Aftercooler	1 x 100%
H-16	C-2 Warm Mixed Aftercooler	1 x 100%
C-3	Cold Refrigerant Compressor	3 x 50%
H-17	C-3 Cold Mixed Aftercooler	1 x 100%
C-4	CO2 Compressor	2 x 100%
H-18	C-4 CO2 Aftercooler	1 x 100%
	Pumps	
P-1	Slurry Pump	2 x 100% 17 x 12% basis used for pricing
P-2	Melter Pump	2 x 100%
P-3	CO2 Pump 1	2 x 100%
P-4	CO2 Pump 2	2 x 100% 6 x 33% basis used for pricing
P-5	Water Pump	2 x 100%
P-6	CO2 Product Pump	2 x 50%
P-7	Circ Water Pump	1 x 100%
	Other	
F-1	Screw Press	1 x 100% 216 x 0.5% basis used for pricing
F-2	Screen Filter	1 x 100%
E-1	V-L Separator	1 x 100%
U-1	V-L Separator	1 x 100%
DC-1	Distillation Column	1 x 100%
T-1	Expander	1 x 100%
T-2	Cryogenic Turboexpander	1 x 100%
T-3	Cryogenic Turboexpander	2 x 50%
V-1	Valve	1 x 100%
CT-1	Mechanical Draft Cooling Tower	1x100%
WW-1	Wastewater Treatment System	1x100%

ATTACHMENT C — GENERAL ARRANGEMENT


Liquid Compressed CO2 to Pipeline
Feed Flue Gas in from Plant
Stack
Scrubbed Flue Gas to Stack
H-19 Induct Heat Exchanger
To Waste Water Treatment System
P5
P5
H-8
H-13
C-1 Flue Gas Blower 50 ft x 30 ft (30 ft height)
C-2 Warm Refrigerant Compressor 68 ft x 54 ft (28 ft Height)
H-17 After-cooler
C-2 Warm Refrigerant Compressor 68 ft x 54 ft (28 ft Height)
H-17 After-cooler
P4
P4
H-1 Main Recuperator 40 ft x 110 ft
T-3
H-12 Refrigerant Methanol Recuperator
F-2 Screen Filter
H-9
H-11 Flue Gas Methanol Recuperator
275 ft
U-1
C-3 Cold Refrigerant Compressor 68 ft x 54 ft (28 ft Height)
H-16 After-cooler
H-15 After-cooler
C-3 Cold Refrigerant Compressor 68 ft x 54 ft (28 ft Height)
H-16 After-cooler
H-15 After-cooler
T-1
T-2
Cold Box
P-1
H-2
H-10
H-3 Contact Liquid Cooler
F-1 Screw Press
H-4 Melter
V-1
P-2
P-2
H-7 CO2 Re-cuperator
DC-1
Re-boiler
P4
P3
P3
E1
C-4 CO2 Compressor 36 ft x 26 ft (20 ft height)
C-4 CO2 Compressor 36 ft x 26 ft (20 ft height)
H-16 After-cooler
535 ft
CO2/Isopentane Slurry
Methanol
Warm Refrigerant
CO2
Flue Gas
Clean Flue Gas
Cold Refrigerant
Cooling Loop (See Page 2)

ATTACHMENT D — CAPTIAL COSTS & BASIS OF ESTIMATE

Basis of Estimate

Estimate No.: 35192A – Cryogenic Carbon Capture Study

General Information

Project Type – Cryogenic Carbon Capture Facility
Project location – Castle Dale, UT
New or Existing Facility – Existing
Unique site issues – None
Contracting strategy – EPC
Unit of Measurement – United States customary units

Based on the level of the project development this estimate is categorized under Class 5 Estimates per the AACE Guideline.

Estimate Development

The cost estimate is based largely on Sargent & Lundy LLC experience on similar projects. Detailed engineering has not been performed to firm up the project details, and specific site characteristics have not been fully analyzed. We have attempted to assign allowances where necessary to cover issues that are likely to arise but are not clearly quantified at this time.

Listed below is a summary level scope (not all inclusive) of facilities included in the CO_2 island estimate:

- All vessels, pumps, tanks, and heat exchangers associated with CO_2 process system
- CO_2 compressor, including dehydration
- All process piping, including valves, supports, and insulation
- All support steel for large vessels, platforms, and pipe rack
- Booster fans
- Electrical building
- Electrical equipment and components, including transformers, MCCS, cable/wiring
- Instrumentation and controls associated with CO_2 capture system, including DCS integration and CEMS
- Heavy lifting crane rental

Listed below is a summary level scope (not all inclusive) of facilities included in the BOP estimate:

- Steam piping supply to CO_2 island
- Cooling tower and all appurtenances
- Circulating water piping to CO_2 island
- Ductwork to CO_2 island
- All civil, site work, and foundations
- BOP support systems (fire protection, eyewash stations, instrument/compressed air, etc.)
- Electrical equipment for BOP systems and switchyard tie-in
- Instrumentation and Controls associated with BOP systems
- Wastewater Treatment

Pricing and Quantities

Scope of work details and quantities were provided by the engineering team.

In most cases, the costs for bulk materials and equipment were derived from S&L database and recent vendor or manufacturer's quotes for same or similar items on other projects.
Equipment and material costs included in the cost estimates do not take into account any impact (cost or lead time) from the current COVID-19 pandemic.

Budgetary quotes to furnish the following equipment were obtained from vendors:

Item	Equipment Description	Quantity Required	Unit Price	Total Price
1	Main Recuperator	1	$25,000,000	$25,000,000
2	Flue Gas Blower	2	$919,116	$1,838,232
3	Warm Refrigerant Compressor	2	$11,500,000	$23,000,000
4	Warm Mixed Aftercooler (Liquid)	1	$2,960,454	$2,960,454
5	Warm Mixed Aftercooler (Vapor)			
6	Cold Mixed Aftercooler			
7	CO2 Aftercooler			
8	Cold Refrigerant Compressor	3	$10,000,000	$30,000,000
9	CO2 Compressor	2	$1,380,000	$2,760,000
10	Slurry Pump	17	$160,000	$2,720,000
11	Melter Pump	2	$150,000	$300,000
12	CO2 Pump 1	2	$100,000	$200,000
13	CO2 Pump 2	12	$300,000	$3,600,000
14	Screw Press	1	$84,000,000	$84,000,000
15	V-L Separator (Sulzer KnitMeshTM wire mesh mist eliminator)	1	$11,838	$11,838
16	V-L Separator (Combination of Sulzer KnitMesh preconditioner and Sulzer Mellachevron vane-type mist eliminator)	1	$103,162	$103,162

Labor Wage Rates

Labor profile: Prevailing wages for Provo, UT.

Labor wage rate selected for the estimate are based on 2020 rates as published in RS Means Labor Rates for the Construction Industry, 2020 Edition. Costs have been added to cover social security, workmen's compensation, federal and state unemployment insurance. The resulting burdened craft rates were then used to develop typical crew rates applicable to the task being performed.

A regional labor productivity multiplier 1.1 is included based on Compass International Global Construction Yearbook.

Labor Work Schedule and Incentives - Assumed 5x10's work week. Per-diem is included at $10/hr.

Labor man-hours to perform activities do not take into account any impact (inefficiency) from the current COVID-19 pandemic.

Construction Equipment

Construction equipment cost is included on each estimate line as needed based on the type of activity and construction equipment requirements to perform the work.

Excluded from this cost are heavy lifting cranes which, if required, are included as a separate line item. For this project, no heavy lift cranes are believed to be necessary.

Construction Direct and Indirect Costs (General Expense Costs)

The estimate is constructed in such a manner where most of the direct construction costs are determined directly and some direct construction cost accounts are determined indirectly by taking a percentage of the directly determined costs and are identified as "Variable Accounts". These percentages are based on our experience with similar type and size projects. Listed below are the variable accounts.

- Additional Labor "Variable Account" Costs:
  - Labor Supervision (Foreman)
  - Show-up time
  - Cost of overtime
  - Subsistence (per diem)
  - General Liability Insurance

- Construction Site Overheads:
  - Construction Management
  - Field Office Expenses
  - Materials and Quality Control QA/QC
  - Site Services (includes site security, service trucks and supplies)
  - Safety (includes occupational health and safety specialists who design and implement safety regulations to minimize injuries and accidents. Also included are detours/barricades/flags.)
  - Temporary Facilities
  - Temporary Utilities
  - Mobilization/Demobilization
  - Legal Expenses/Claims (Contractor's expense)

- Other Construction "Variable Account" Costs:
  - Small Tools and Consumables
  - Scaffolding
  - Construction Equipment Mob/Demob
  - Freight on Equipment – included with equipment cost
  - Freight on Material
  - Sales tax – not included
  - Contractors G&A Expense – included at 7% of the construction cost (material, labor, and construction equipment)

Project Indirect Costs

- EPC Engineering Services, CM and Start-up – included at 10% of the project cost
- Start-Up Spare Parts – 0.3% of the process equipment cost
- Initial Fills – included with the Owner's costs
- Process Licensing Fee – not included
- Spare Parts – 0.5% of the total project cost
- EPC Risk Fee and Profit – included at 10% of the total project cost
- Owner's Costs – included at 7% of the total project cost

- Construction Management (Third Party) – included in the Owner's Costs
- Start-up and Commissioning support (Third Party) – included in the Owner's Costs
- Owner's Engineer – included in the Owner's Costs
- AFUDC (Interest During Construction) – not included

Escalation

Escalation is not included.

Contingency

Contingency is included at 20% on all cost categories.

The contingency relates to pricing and quantity variation in the specific scope estimated. The contingency does not cover new scope outside of what has been estimated, only the variation in the defined scope. The rate does not represent the high range of all costs, nor is it expected that the project will experience all actual costs at the maximum value of their range of variation.

Items Excluded

All known scope of required physical facilities as provided by the project team to encompass a complete project has been included in the estimate. Any known intentional omissions are documented in the assumptions and clarifications.
The cost estimate represents only the costs listed in the estimate. The estimate does not include allowances for any other costs not listed and incurred by the owner.

There may be additional costs that the Owner should consider such as (the list below is not all inclusive):

- Permitting (considered to be a project development cost)
- CO_2 pipeline
- Sales Tax
- Property tax
- Payment and Performance Bonds
- Insurance (example Builder's Risk)
- AFUDC
- Project financing
- Right of way
- Land Acquisition
- Community Relations (if applicable, costs associated with any special provisions or facilities required by the local community, such as support for schools, fire department, police due to increased temporary population, etc.)

Assumptions/Clarifications

- Assumed no demolition/relocation required
- Assumed area is flat and the elevation is adequate. No mass excavation/fill is required.
- CO_2 pipeline is not included.
- Electrical feeds from the plant to the island are not included in the cost estimate.
- New stack not included in the cost estimate. Assumed ductwork will be connected to the existing stack.

Estimator	A. KOCI
Labor rate table	20UTPRO
Project No.	11801.019
Estimate Date	08/11/2020
Reviewed By	EK
Approved By	BA/WP
Estimate No.	35192A
Estimate Class	Class 5
Cost index	UTPRO

Group	Description	Subcontract Cost	Process Equipment Cost	Material Cost	Man Hours	Labor Cost	Equip Amount	Total Cost
11.00.00	DEMOLITION							
	STEEL				502	31,972	2,251	34,224
	INSULATION				21	1,206	155	1,361
	DEMOLITION				523	33,178	2,407	35,585
21.00.00	CIVIL WORK							
	CLEARING & GRUBBING				1,158	62,647	66,381	129,028
	STRIP & STOCKPILE TOPSOIL				673	36,410	57,871	94,281
	EXCAVATION				9,385	487,344	140,266	627,610
	DISPOSAL				1,216	63,068	16,030	79,098
	BACKFILL			224,346	4,103	213,003	57,322	494,671
	MASS FILL							
	EQUIPMENT		85,000		220	10,854	2,334	98,188
	EROSION AND SEDIMENTATION CONTROL			529,608	2,574	124,666	80,474	734,749
	FENCEWORK			164,780	878	32,157	3,320	200,257
	LANDSCAPING			3,600	53	2,856	4,539	10,995
	PILING	470,000						470,000
	ROAD, PARKING AREA, & SURFACED AREA	378,000		287,000	1,870	70,573	10,784	746,357
	SURVEY	50,000						50,000
	CIVIL WORK,TESTING	180,000						180,000
	CIVIL WORK, MISCELLANEOUS		30,000	4,200	2,464	125,879	15,889	175,968
	CIVIL WORK	1,078,000	115,000	1,213,534	24,596	1,229,457	455,210	4,091,201
22.00.00	CONCRETE							
	CONCRETE	337,500		2,276,950	35,990	1,441,236	189,979	4,245,665
	EMBEDMENT			196,500	3,603	153,878	5,961	356,339
	FORMWORK			533,100	14,616	647,345	106,288	1,286,733
	PRECAST			111,800	862	35,396	9,910	157,106
	REINFORCING			1,029,100	19,881	1,164,839	198,792	2,392,731
	CONCRETE, MISCELLANEOUS			147,500	8,883	378,675	19,025	545,199
	CONCRETE	337,500		4,294,950	83,836	3,821,369	529,954	8,983,773
23.00.00	STEEL							
	DUCTWORK			2,696,000	15,908	1,061,514	318,436	4,075,949
	GALLERY			1,144,930	10,237	704,942	72,581	1,922,453
	ROLLED SHAPE			4,419,676	29,509	1,947,327	717,091	7,084,094
	STEEL			8,260,606	55,654	3,713,782	1,108,108	13,082,497
24.00.00	ARCHITECTURAL							
	DOOR (INCL. FRAME & HARDWARE)			46,950	264	11,277	437	58,663
	PLUMBING FIXTURE			70,000	343	19,043	1,329	90,372
	PRE-ENGINEERED BUILDING	4,300,400						4,300,400
	ROOFING	382,800						382,800
	SIDING	773,500						773,500
	ARCHITECTURAL	5,456,700		116,950	607	30,319	1,766	5,605,735
27.00.00	PAINTING & COATING							
	PAINTING			41,768	2,635	108,052	14,750	164,570
	PAINTING & COATING			41,768	2,635	108,052	14,750	164,570
31.00.00	MECHANICAL EQUIPMENT							
	COMPRESSOR & ACCESSORIES		463,500		638	31,476	6,769	501,744
	COOLING TOWER	4,200,000						4,200,000
	CRANES & HOISTS		480,000		488	24,095	5,181	509,277
	DAMPERS & ACCESSORIES		882,000		1,683	112,318	35,771	1,030,089
	EXPANSION JOINT		212,500		2,338	155,997	49,683	418,179
	FIRE PROTECTION EQUIPMENT & SYSTEM	735,000						735,000
	CO2 CAPTURE EQUIPMENT	500,000	163,787,777	90,000	162,525	9,671,141	2,735,762	176,784,680
	HEAT EXCHANGER	4,500,000	29,039,000		12,506	666,824	184,905	34,390,729
	PUMP		12,047,450		11,736	578,936	124,496	12,750,881
	TANK	475,000	30,000		35	1,737	373	507,110
	WATER TREATING	3,700,000						3,700,000
	MECHANICAL EQUIPMENT, MISCELLANEOUS		251,900		312	15,412	3,314	270,627
	MECHANICAL EQUIPMENT	14,110,000	207,194,127	90,000	192,262	11,257,936	3,146,254	235,798,317
34.00.00	HVAC							
	AIR HANDLING UNIT			330,000	616	33,532	4,155	367,687
	DUCTWORK			2,128	364	19,796	2,453	24,377
	DUCTWORK ACCESSORIES			252,000	1,109	60,358	7,479	319,837

Group	Description	Subcontract Cost	Process Equipment Cost	Material Cost	Man Hours	Labor Cost	Equip Amount	Total Cost
	FAN			302,400	418	22,754	2,820	327,974
	UNIT HEATER			148,600	1,001	54,490	6,752	209,842
	HVAC			1,035,128	3,508	190,930	23,659	1,249,718
35.00.00	PIPING							
	SS 304, ABOVE GROUND, PROCESS AREA			1,886,564	30,401	1,672,072	503,592	4,062,228
	SS 316, ABOVE GROUND, PROCESS AREA			36,963	617	33,916	10,244	81,123
	CARBON STEEL, ABOVE GROUND, PROCESS AREA			915,612	15,143	828,874	202,783	1,947,268
	COPPER, ABOVE GROUND, PROCESS AREA			1,484	19	1,021	307	2,812
	FRP, ABOVE GROUND, PROCESS AREA			27,344	541	29,752	8,949	66,045
	CS LINED, ABOVE GROUND, PROCESS AREA			291,631	4,061	223,345	67,181	582,157
	PVC, ABOVE GROUND, PROCESS AREA			11,402	84	4,617	1,389	17,407
	CARBON STEEL, STRAIGHT RUN			382,306	6,575	361,606	107,301	851,214
	CS LINED, STRAIGHT RUN			957,434	12,354	679,486	204,387	1,841,307
	SS 304, BURIED			10,894	334	18,382	5,169	34,445
	HDPE, BURIED			139,020	4,703	258,663	77,805	475,488
	CHDPE, BURIED			44,790	263	14,108	3,590	62,488
	DUCTILE IRON, BURIED			3,722	24	1,310	394	5,426
	CAST IRON, BURIED			33,206	271	14,925	4,489	52,621
	CS LINED, BURIED			749,793	10,850	596,768	179,506	1,526,067
	PVC, BURIED			30,515	767	42,173	12,685	85,373
	PIPE SUPPORTS, HANGERS			282,047	9,865	542,590	163,209	987,846
	PIPE SUPPORTS, RACK			24,441	2,535	139,421	41,937	205,800
	CARBON STEEL VALVES			663,108	1,405	76,760	17,126	756,994
	STAINLESS STEEL VALVES			1,115,769	6,015	330,851	99,519	1,546,139
	MISCELLANEOUS VALVES			21,000	123	6,777	2,038	29,815
	MISCELLANEOUS			625,135	1,200	65,739	16,793	707,667
	PIPING			8,254,178	108,150	5,943,156	1,730,395	15,927,730
36.00.00	INSULATION							
	DUCT			224,250	11,262	638,014	78,955	941,219
	PIPE, MINERAL WOOL W/ALUMINUM JACKETING			198,950	3,990	226,037	29,124	454,111
	INSULATION			423,200	15,252	864,050	108,079	1,395,330
41.00.00	ELECTRICAL EQUIPMENT							
	BUS DUCT		2,563,556		21,249	1,144,173	74,203	3,781,932
	CATHODIC PROTECTION	150,000						150,000
	COMMUNICATION SYSTEM	710,000						710,000
	CONTROL & BACKUP POWER			460,000	213	12,043	3,028	475,072
	CONTROL STATION			11,500	62	3,284	76	14,859
	ELECTRICAL EQUIPMENT, GROUNDING			372,207	4,572	247,549	60,561	680,317
	HEAT TRACING	35,000	75,000	104,062	4,245	231,218	60,944	506,224
	LIGHTNING PROTECTION			11,800	1,268	71,424	17,424	100,648
	LIGHTING ACCESSORY (FIXTURE)	382,800		268,600	1,677	91,918	17,421	760,739
	EXTERIOR LIGHTING			104,000	477	25,944	2,639	132,583
	MOTOR CONTROL CENTER (MCC), COMPLETE		535,500		742	38,377	648	574,525
	MOTOR CONTROL CENTER (MCC), COMPONENT			14,800	110	5,864	135	20,799
	PANEL: CONTROL, DISTRIBUTION, & RELAY	95,000	50,000	25,800	282	15,011	346	186,156
	POWER TRANSFORMER		6,942,100	26,350	5,753	321,427	74,514	7,364,391
	SECURITY SYSTEM	250,000						250,000
	SWITCHGEAR, COMPLETE		3,738,900		3,091	174,443	43,864	3,957,207
	SWITCHGEAR, COMPONENT		13,500	3,375	172	8,783		25,658
	WIRING DEVICE			26,115	351	18,683	2,353	47,151
	ELECTRICAL EQUIPMENT	1,622,800	13,918,556	1,428,608	44,264	2,410,140	358,156	19,738,260
42.00.00	RACEWAY, CABLE TRAY & CONDUIT							
	CABLE TRAY COVER, ALUMINUM			3,914	68	3,611	83	7,608
	CABLE TRAY, ALUMINUM			234,530	16,022	853,995	19,662	1,108,188
	CONDUIT, FLEXIBLE SEALTIGHT ASSEMBLY			27,620	698	36,985	729	65,334
	CONDUIT, PVC	27,000		16,754	521	26,656		70,409
	CONDUIT, RGS			625,838	26,556	1,410,854	30,014	2,066,706
	CONDUIT BOX			44,443	314	16,695	356	61,494
	RACEWAY, CABLE TRAY & CONDUIT	27,000		953,098	44,180	2,348,795	50,845	3,379,739
43.00.00	CABLE							
	CONTROL/INSTRUMENTATION/COMMUNICATION CABLE & TERMINATION			340,513	10,513	571,887	150,985	1,063,384
	600V CABLE & TERMINATION			966,493	9,886	531,471	119,019	1,616,983
	5/8KV CABLE & TERMINATION			104,543	666	36,217	9,562	150,322

PACIFICORP - SES
HUNTER UNIT 3
CRYOGENIC CARBON CAPTURE STUDY

Group	Description	Subcontract Cost	Process Equipment Cost	Material Cost	Man Hours	Labor Cost	Equip Amount	Total Cost
	15KV CABLE & TERMINATION			1,215,831	5,745	310,643	75,694	1,602,167
	CABLE			2,627,379	26,809	1,450,219	355,259	4,432,857
44.00.00	CONTROL & INSTRUMENTATION							
	CONTROL SYSTEM	2,000,000			282	15,011	346	2,015,356
	INSTRUMENT PANEL AND RACK			74,000	504	26,855	618	101,474
	INSTRUMENT		559,294	319,895	3,561	194,307	30,007	1,103,503
	MONITORING EQUIPMENT		400,000		561	29,977	903	430,880
	CONTROL & INSTRUMENTATION, TESTING				3,355	182,530	48,190	230,720
	CONTROL & INSTRUMENTATION, MISCELLANEOUS				198	10,772	887	11,660
	CONTROL & INSTRUMENTATION	2,000,000	959,294	393,895	8,461	459,452	80,952	3,893,593
61.00.00	CONSTRUCTION INDIRECT							
	CONSTRUCTION EQUIPMENT	2,000,000						2,000,000
	CRAFT PERSONNEL				38,504	1,899,395		1,899,395
	CONSTRUCTION INDIRECT	2,000,000			38,504	1,899,395		3,899,395
71.00.00	PROJECT INDIRECT							
	CONSULTANT, THIRD PARTY	100,000						100,000
	FREIGHT	1,000,000						1,000,000
	PROJECT INDIRECT	1,100,000						1,100,000
	TOTAL DIRECT	27,732,000	222,186,977	29,133,294	649,241	35,760,232	7,965,795	322,778,298

Estimate Totals

Description	Amount	Totals	Hours
Labor	35,760,232		649,241
Material	29,133,294		
Subcontract	27,732,000		
Construction Equipment	7,965,795		
Process Equipment	222,186,977		
	322,778,298	322,778,298	
General Conditions			
Additional Labor Costs			
90-1 Labor Supervision	2,146,000		
90-2 Show-up Time	715,000		
90-3 Cost Due To OT 5-10's	7,562,000		
90-4 Cost Due To OT 6-10's			
90-5 Per Diem	6,492,000		
Site Overheads			
91-1 Construction Management	7,741,000		
91-2 Field Office Expenses	4,759,000		
91-3 Material&Quality Control	1,206,000		
91-4 Site Services	991,000		
91-5 Safety	763,000		
91-6 Temporary Facilities	580,000		
91-7 Temporary Utilities	636,000		
91-8 Mobilization/Demob.	612,000		
91-9 Legal Expenses/Claims	90,000		
Other Construction Indirects			
92-1 Small Tools & Consumables	1,159,000		
92-2 Scaffolding	2,703,000		
92-3 General Liability Insur.	386,000		
92-4 Constr. Equip. Mob/Demob	80,000		
92-5 Freight on Material	1,457,000		
92-6 Freight on Process Equip			
92-7 Sales Tax			
92-8 Contractors G&A	7,873,000		
	47,951,000	370,729,298	
Project Indirect Costs			
93-1 EPC Engineering Services	37,073,000		
93-2 Start-Up/Spare Parts	667,000		
93-3 Spare Parts	1,854,000		
93-4 Initial Fills			
93-5 Process Licensing Fee			
93-6 EPC Fee Risk & Fee	41,032,000		
93-7 Owner's Costs	31,595,000		
	112,221,000	482,950,298	
Contingency			
94-1 Contingency on Const Eq	1,721,000		
94-3 Contingency on Material	6,546,000		
94-4 Contingency on Labor	15,895,000		
94-5 Contingency on Subcontr.	5,546,000		
94-6 Contingency on Process Eq	44,437,000		
94-7 Contingency on Indirect	22,444,000		
	96,589,000	579,539,298	
Escalation			
96-1 Escalation on Const Equip			
96-3 Escalation on Material			
96-4 Escalation on Labor			
96-5 Escalation on Subcontract			
96-6 Escalation on Process Eqp			
96-7 Escalation on Indirects			
		579,539,298	
98 Interest During Constr			
		579,539,298	
Total		**579,539,298**	

ATTACHMENT E — DETAILED O&M COSTS

.

SUMMARY SES CO2 CAPTURE FIRST YEAR O&M COSTS ($2020) - GREENFIELD POWER PLANT TEA

Input Data		**SES Technology**	**Notes:**
Plant Gross Capacity (Full Load)	MW	698	Provided by SES
Base Plant Aux Power Consumption	MW	36	from TEA document (2015 edition. Case 12A input = 30 MW of 580 MWg total)
Baseline Net Capacity @ Full Load	MW	662	calculated
Capacity Factor	%	85%	from TEA document
CO_2 Capture Design			
CO_2 Capture Island Aux Power Consumption	MW	140.8	from S&L equipment list
CO_2 Capture BOP Aux Power Consumption	MW	12.7	from equipment list (circ water pump and cooling tower only)
Net Plant Capacity @ Full Load w/ CO_2 Capture	MW	509	Adjusted for revised aux power load
CO_2 Capture Efficiency	%	90%	from SES mass balances
CO_2 Production Rate	lb CO_2/hr	1,017,492	from SES mass balances (2915 mol/s)
CO_2 Production Rate	tonne CO_2/year	3,436,560	calculated
O&M Consumables			
CO_2 Island & CO_2 BOP Auxiliary Power Consumption	MW	153	
Wastewater to Treatment	gpm	983	from cooling tower blowdown
CO_2 Capture Island Methanol Makeup	lb/hr	114	0.01% makeup for methanol. Assumed loss in flue gas.
CO_2 Capture Island Refrigerant (LNG) Makeup	lb/hr	67,150	<5% blowdown and makeup for LNG.
O&M Unit Pricing			
Auxiliary Power Cost	$/MWh	40.00	Provided by Hunter
Methanol Refrigerant	$/lb	1.52	Methanol cost = ($2500/250 gallons, $1.52/lb)
LNG Refrigerant	$/1000lb	0.20	LNG cost = ($5.20/1000cuft, $0.20/1000lb,)
CO_2 Transportation, Storage, Monitoring Cost	$/tonne	10.00	Assumption from the DOE
Operator Wage Rate	$/hr	66.00	Provided by Hunter
Variable O&M Summary			
Wastewater Treatment O&M	$/yr	600,000	Denitrification, filtration, and pH control chemicals
CO_2 Capture Refrigerants (Methanol)	$/yr	1,287,946	calculated
CO_2 Capture Refrigerants (LNG)	$/yr	100,000	allowance
Aux Power Cost	$/yr	45,694,000	calculated
Total Variable O&M Cost (First Year)	**$/yr**	**47,681,946**	
Fixed O&M Cost:			
New CO_2 Island Operators	#	23	S&L assumption: 3 operators per shift, 1 mechanical/maintenance technician per shift, 1 chemist/process lead per shift, 1 ops manager, 1 I&C specialist, 1 electrical specialist
Annual Operator Labor Cost	$/yr	3,157,440	calculated
Maintenance Material & Labor	$/yr	7,872,392	Based on 3% of total material and equipment capital cost
Fixed O&M Cost	**$/yr**	**11,029,832**	
CO_2 Transportation, Storage, Monitoring O&M Cost	**$/yr**	**34,366,000**	
Total O&M	**$/yr**	**93,077,778**	