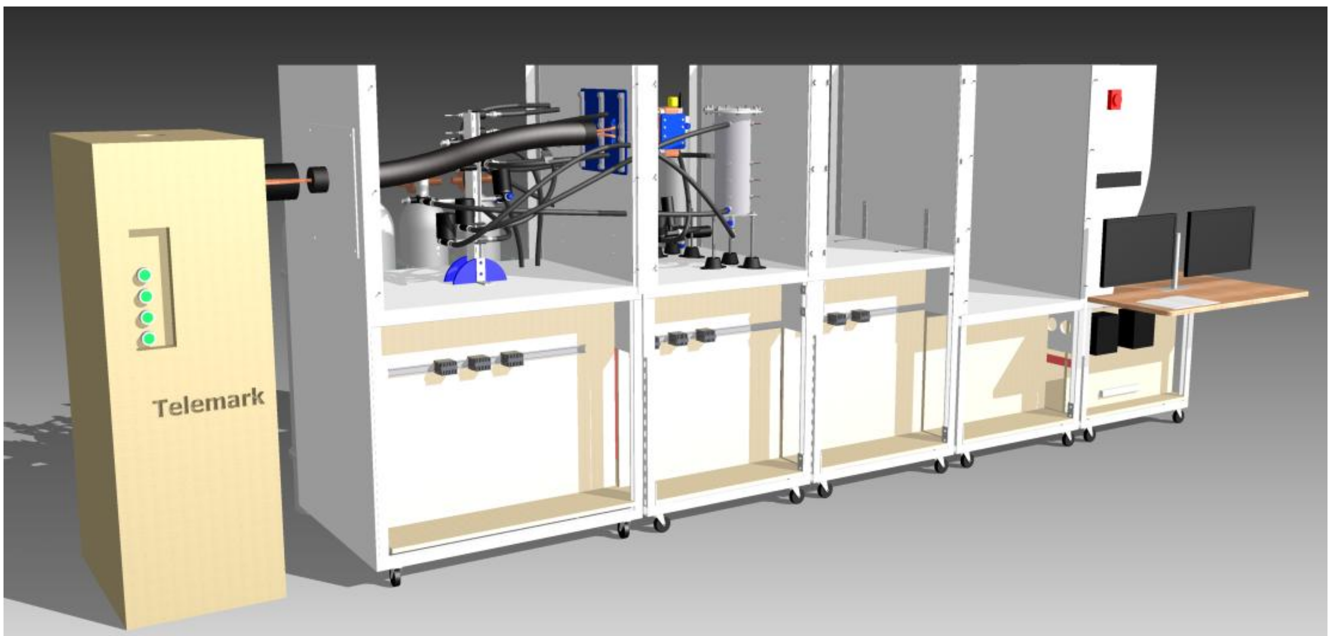
SUSTAINABLE ENERGY SOLUTIONS



Cryogenic Carbon Capture University of Wyoming Bench Scale Project

Final Executive Summary Report

-Sponsor-

Wyoming Department of Environmental Quality

Sustainable Energy Solutions

Wyoming Bench-Scale Cryogenic Carbon Capture Project

This grant from the Legislature of the State of Wyoming's Clean Coal Technologies Research Program enabled Sustainable Energy Solutions to further develop Cryogenic Carbon Capture (CCC) in the following four areas: (1) process flow analysis, (2) heat exchanger analysis and design, (3) bench scale design, and (4) completion of a fully integrated bench scale demonstration unit. Completing these four tasks produced the first fully integrated CCC process unit, while making significant improvements to the design of the CCC process by solving specific challenges associated with efficient heat exchange.

Sustainable Energy Solutions (SES) was founded in 2008 in response to a growing need for solutions to sustainability problems within the energy industry. SES is primarily focused on the development and commercialization of Cryogenic Carbon Capture, a patented carbon capture technology. Since its founding, SES has filed several additional patents on multiple technologies to help realize SES's mission: Create practical solutions to help solve energy problems on a regional and global scale.

Cryogenic Carbon Capture

The Cryogenic Carbon Capture Technology (CCC) is a patent pending process designed to separate a nearly pure stream of CO_2 from power plant gases. This technology adds a process to the plant after normal energy production where CO_2 is separated from the other gases.

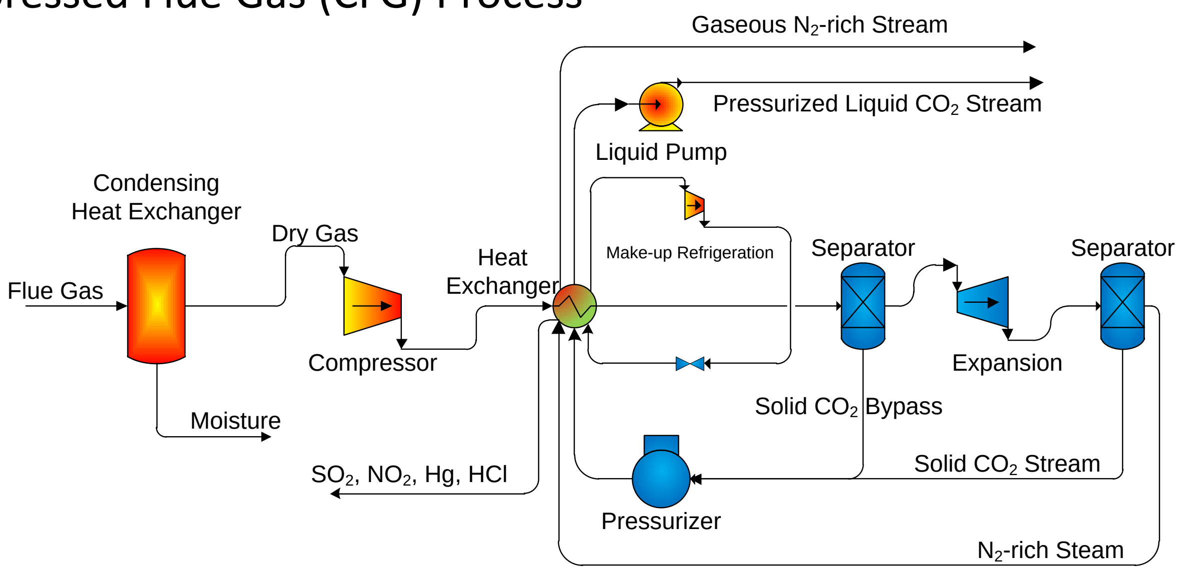
Energy storage is also possible using the CCC process. This allows for increased use of renewable energy resources and helps to balance the power grid when incorporating intermittent energy sources (e.g., wind, solar) that produce power at non-peak demand times.

The Cryogenic Carbon Capture technology offers the most cost effective and practical solution to carbon capture, compared to amine and oxy-fuel combustion, in today's market.

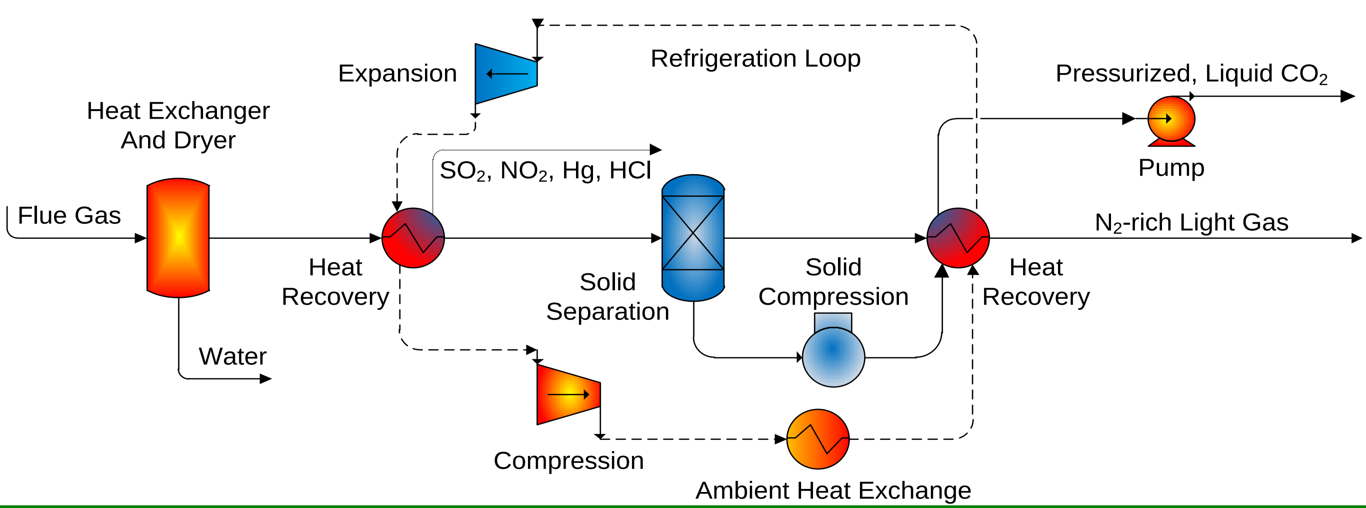
Cryogenic Carbon Capture Process

The Cryogenic Carbon Capture (CCC) process is being developed in 2 variations: the Compressed Flue Gas (CFG) and External Cooling Loop (ECL) processes, where each variation includes flue gas conditioning (e.g. removes particulates & water, pre-cools), desublimating heat exchange, recuperative heat exchange, solid separation, and CO_2 pressurization steps. In the CFG process, the flue gas is modestly compressed and cooled to slightly above the frost point of CO_2. The gas is then expanded, further cooling the stream. In the ECL process, a refrigeration loop is used in lieu of the expansion step for the final required cooling. The final result is liquid CO_2 and a clean gaseous nitrogen stream.

Compressed Flue Gas (CFG) Process

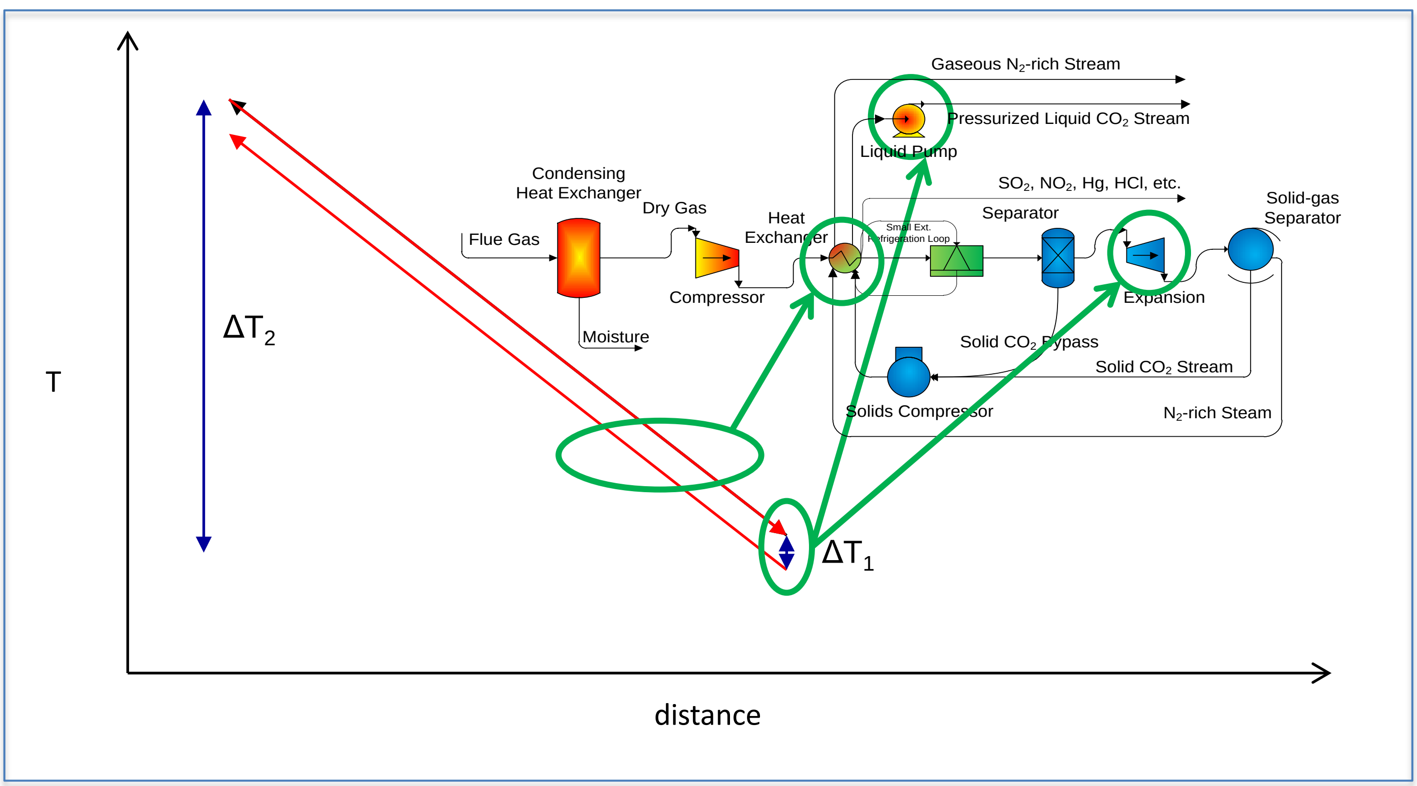


External Cooling Loop (ECL) Process

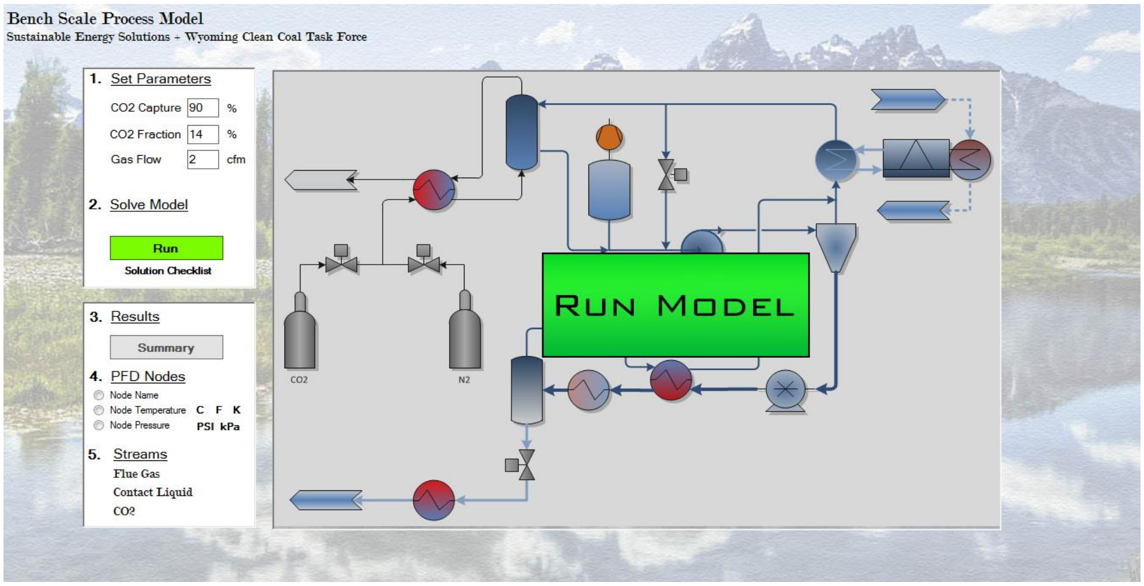


Basic Principles

Cryogenic Carbon Capture is not a refrigeration loop. The inlet and outlet streams in the process are at approximately the same temperature. The minimal cooling required to drive the process, indicated by ΔT_1, is significantly less than the cooling required for traditional refrigeration, indicated by ΔT_2, where the outlet product is significantly colder than the inlet stream. This diagram shows that the sensible energy for a simple system is very low, but it does not address the other energy demands.

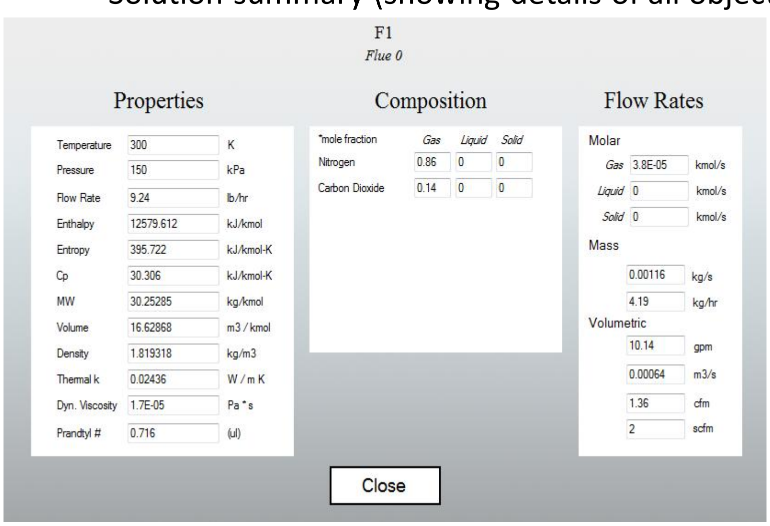


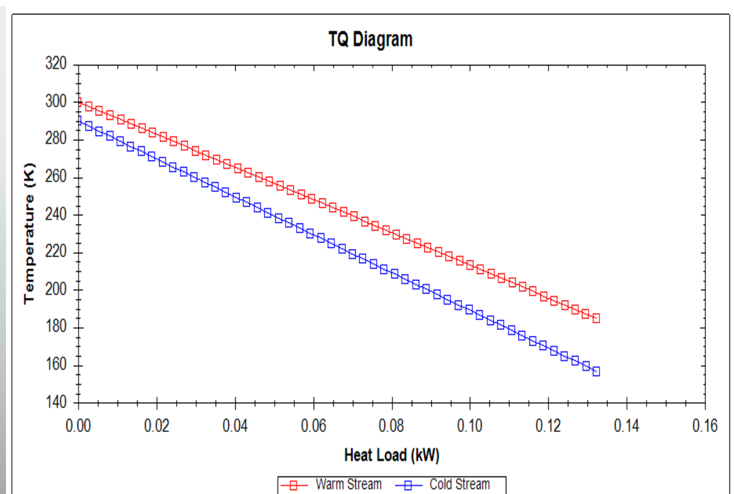
Process Modeling



SES has developed custom-built process modeling software that provide quantitative and accurate mass, energy, and species balances for (a) process options involving external cooling and no compression/expansion of flue gases, and (b) process options that explicitly deal with latent heats, specifically heats of fusion of CO_2. SES has developed a framework to model every detail of the CCC process. This framework is a collection of C# classes that power the model:

- Process equipment definitions
- Data access (thermodynamic & materials data; conversion factors)
- Thermodynamic state
- Equation library (heat transfer, thermodynamic, geometric, etc.)
- Graphic user interface (GUI)
- Solution summary (showing details of all objects used in model)

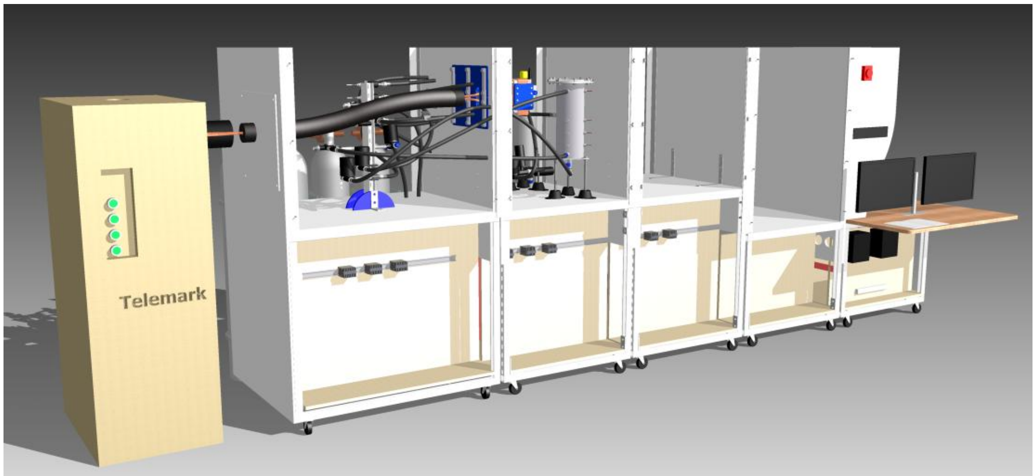




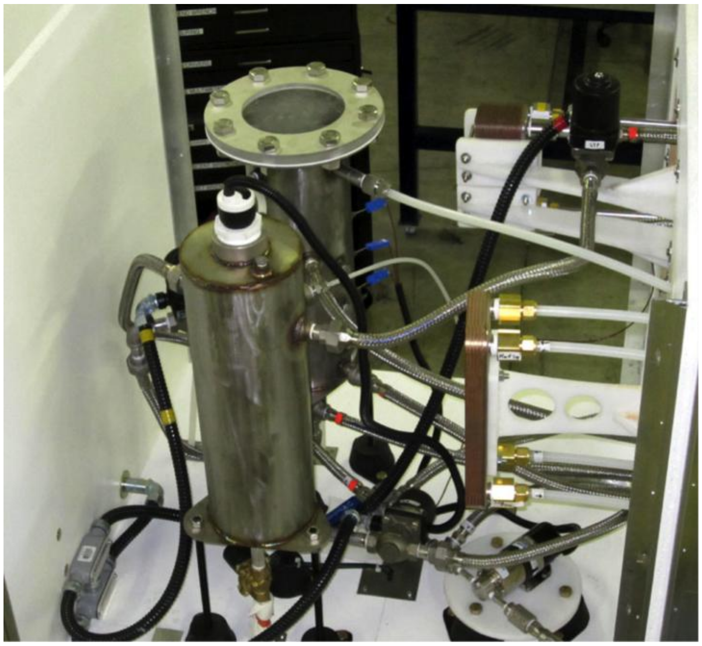
Model output screens showing the thermodynamic state for a single node (left) and a heat exchanger temperature profile

Bench-scale Process

A bench-scale process has been completed to demonstrate the CCC process, in its entirety, on a small scale. This process accommodates heat exchanger testing and further optimization of the process for design and construction of larger-scale demonstrations.

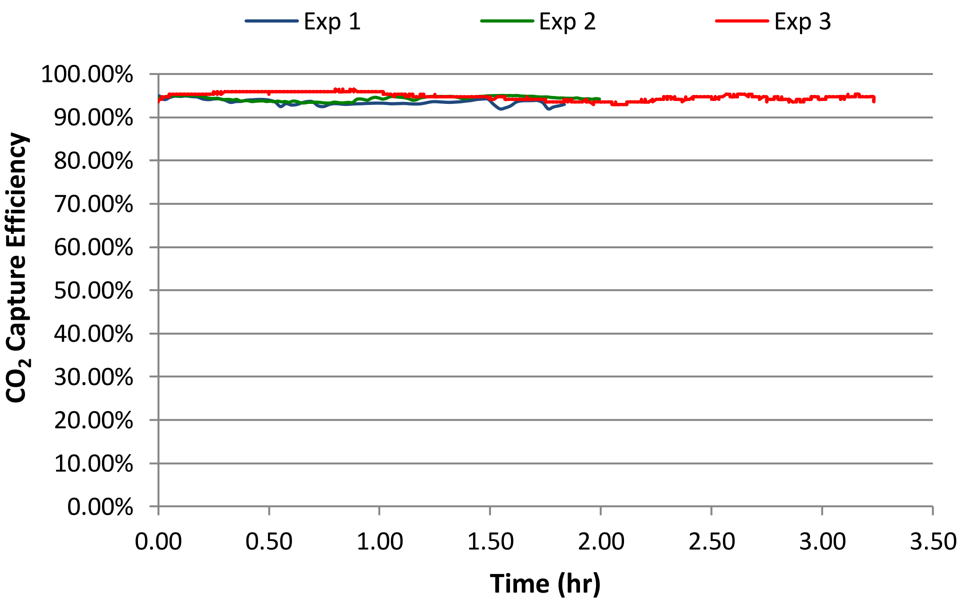


Labview Bench Scale Control System.

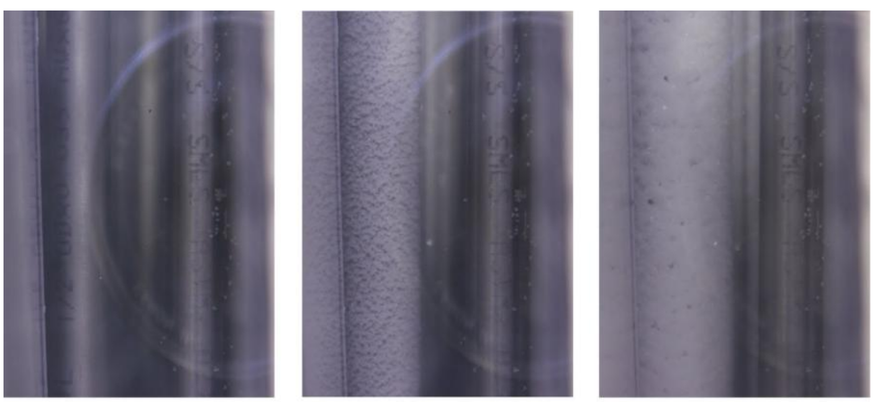


Primary coldbox containing (clockwise, from top left) the desublimating heat exchanger, liquid cooler, gas recuperator, contact liquid pump, and contact liquid reservoir.

CO_2 Capture



The bench-scale CCC process was run for 2 hours to demonstrate the CO_2 and SO_2 capture efficiencies. The CO_2 capture efficiency was between 93 and 94% for runs 1 and 2 (left). A bench-scale CCC process was run for 3 hours to further demonstration the CO_2 capture efficiency with an average CO_2 capture efficiency of 95%. During these experiments, there was no indication of process degradation.



0 min 30 min 150 min

CO_2 Capture on Fluid Bed Tubes

Fluidization

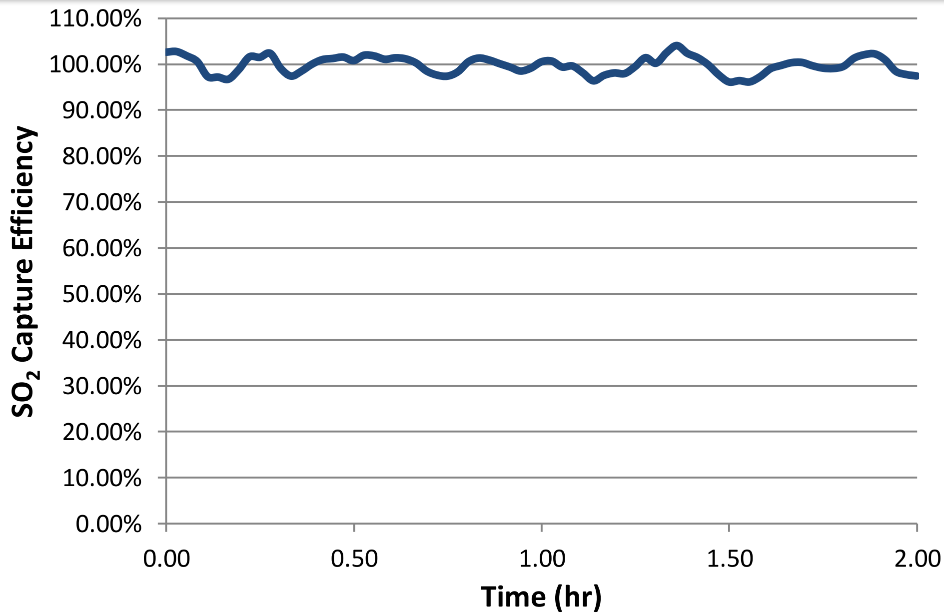
CO2 Removal

Captured CO_2

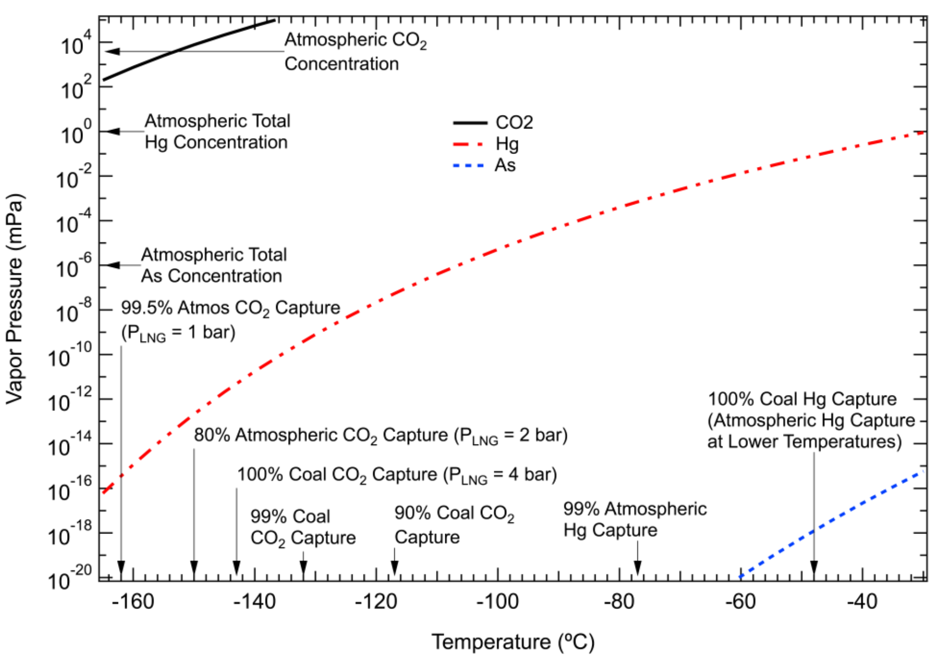
Pollutant Removal

The SO_2 capture efficiency measured during a 2-hour experiment was 99.8%, from an inlet concentration of 400 ppm . The SO_2 concentration in the outlet stream was so low that it approached the measurable limit of the gas analyzer.

CCC also has the capability to remove NO_2.



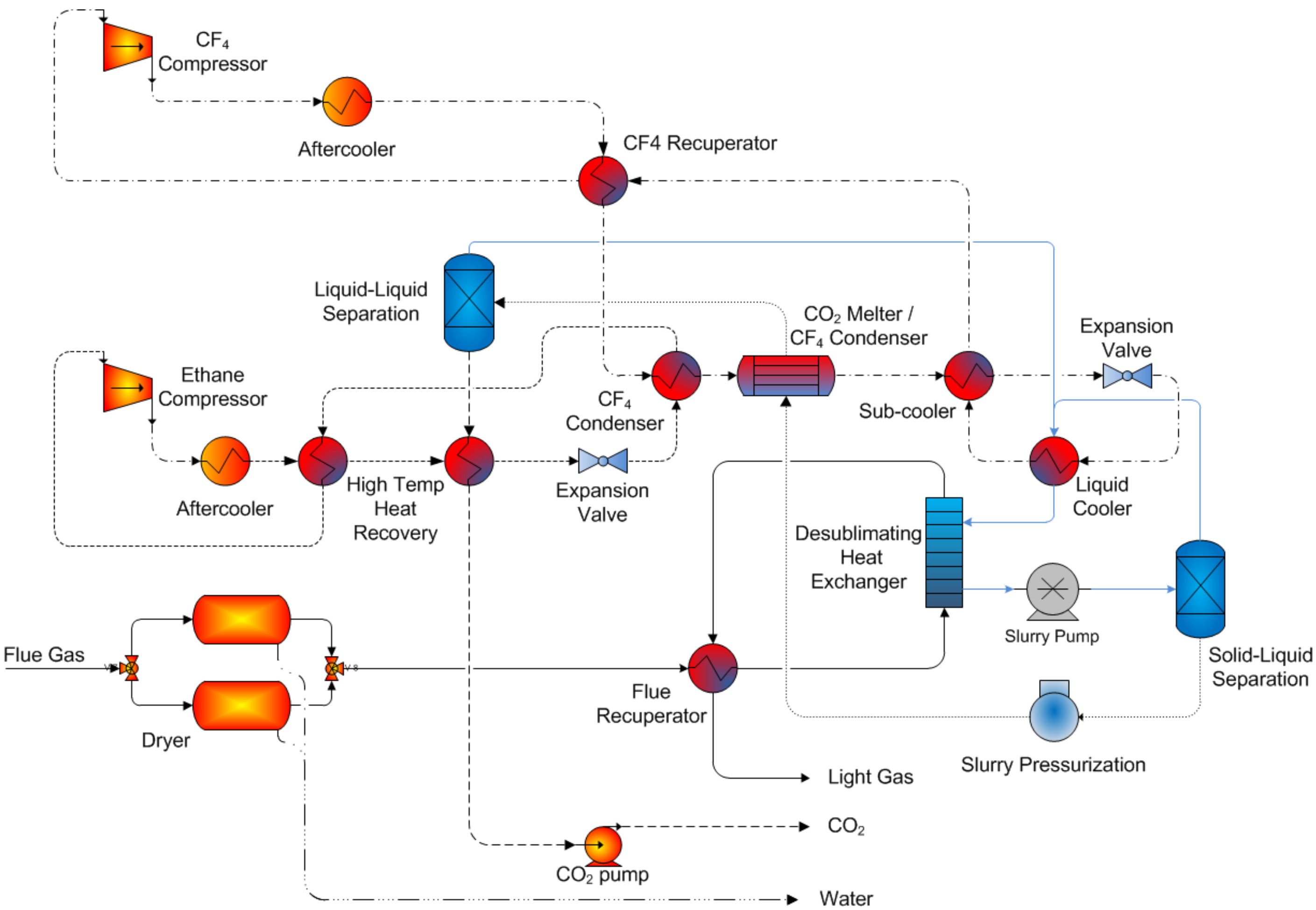
The theoretical capture for some common pollutants (CO_2, arsenic -As, and mercury - Hg) at CCC temperatures is shown below. This shows that CCC has the potential to not only remove the pollutants associated with coal combustion, but also pollutants found in the atmosphere.



Hyperion

A second revision of the bench scale system was designed and constructed to improve upon the original. Hyperion was designed to be an intermediary between the bench- and skid-scale systems. Much was learned in the design and construction to improve the design process of the bench-scale system. Hyperion is much more compact and transportable; everything is mounted inside an aluminum frame. There is a single coldbox to house all of the components, rather than the 3 separate coldboxes in the original bench-scale system.

Steps to Skid-scale Process



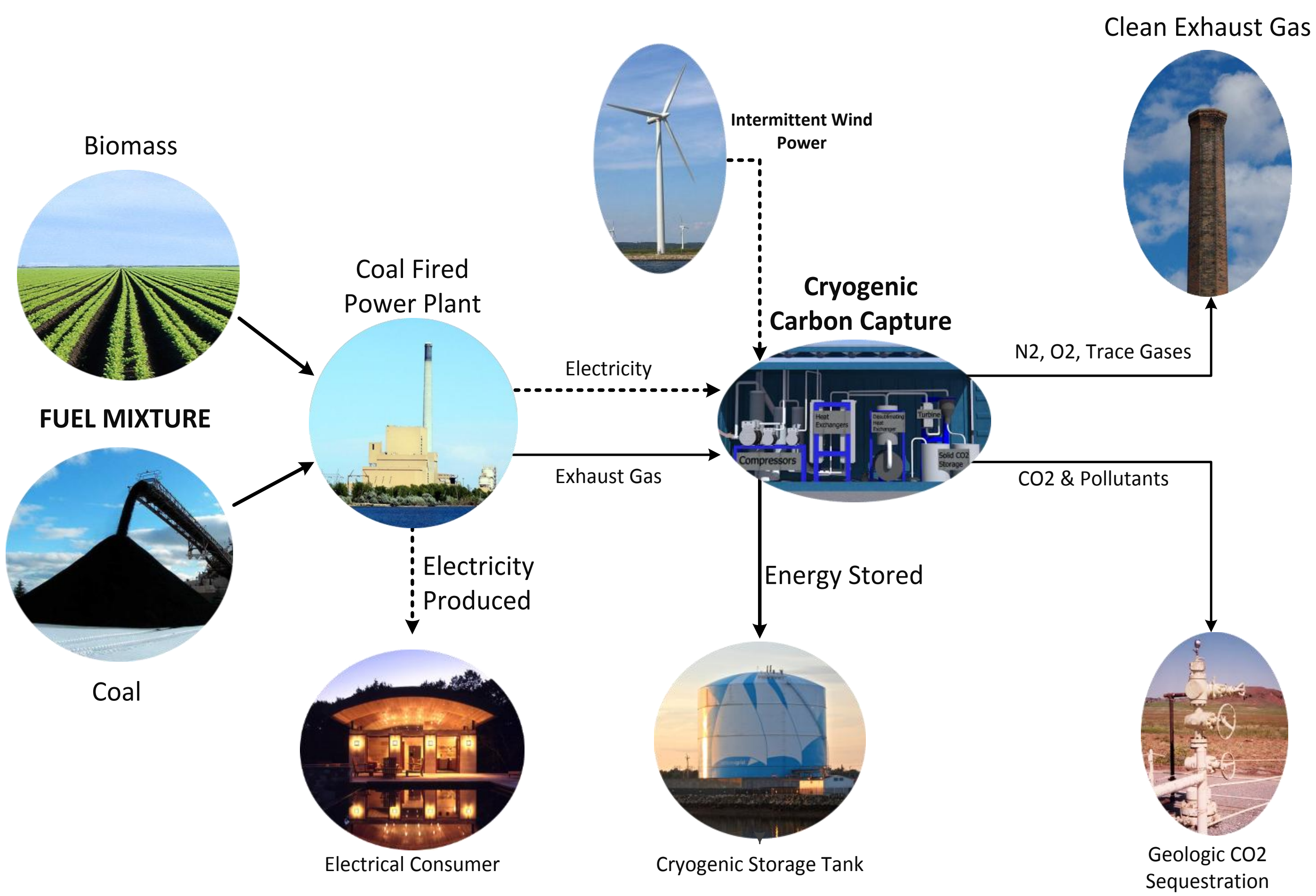
The bench and Hyperion systems have helped prove various systems that will be incorporated into the skid-scale, pilot-scale, and full-scale processes. Many parts of the electrical and control systems were first prototyped on the bench-scale process and are now being incorporated into the skid-scale process (PFD shown above).

CCC Integration

The Cryogenic Carbon Capture process offers more than just removing CO_2 from flue gas. When combined with SES's patent-pending energy storage option, CCC facilitates the use of solar and wind energy by storing excess energy during low energy demand periods and using that stored energy during peak demand times. In addition to helping balance the grid, this energy storage also effectively reduces the parasitic energy required for CCC, lessening the impact on the cost of electricity due to carbon capture.

Integration advantages include:

1. Energy efficient and cost effective CO_2 capture
2. Bolt-on technology with broad application
3. Multi-pollutant removal capabilities (captures SO_2, SO_3, NO_2, Hg, HCl and recovers some H_2O)
4. Energy storage and grid management
5. Safety, compatibility and simplicity (uses unit operations common to power plants with no toxic materials or other unusual hazards)



For Further Information

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