Direct Air Capture Recovery of Energy for CCUS Partnership (DAC RECO$_2$UP)

Project Number: DE-FE0031961

Joshua Miles, Aircapture

Kenneth Nemeth, PI – SSEB

Matthew Atwood , PI - Aircapture

U.S. Department of Energy
National Energy Technology Laboratory
Carbon Management Project Review Meeting
August 2024

Project Overview

Period of Performance:

10/1/2020 – 07/31/2024

Project Funding:

Federal Share: $2,500,000

DOD: $1,000,000

DOE: $1,500,000

Non-Federal Share: $635,805

Total: $3,135,805

Project Team Members:

Southern States Energy Board

Aircapture LLC

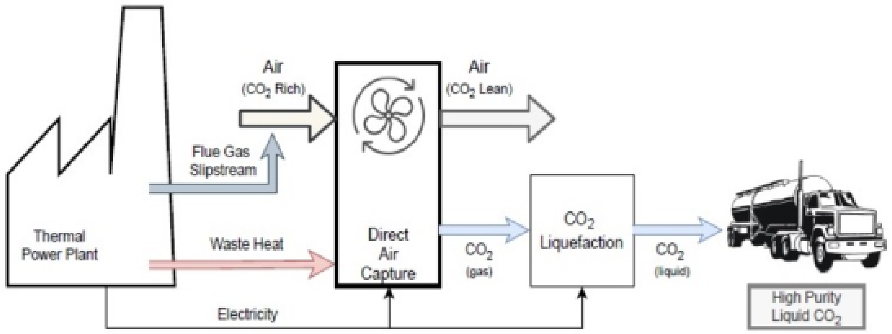
Synapse Product Development

Crescent Resource Innovation

National Carbon Capture Center

Southern Company

Global Thermostat LLC



Project Goal:

Decrease the cost of capture through testing of existing DAC materials in integrated field units that produce concentrated CO_2 stream of at least 95% purity.

Project Objectives and Program Alignment

Stated Program Goals (FOA 2188 AOI-2):

Decrease the cost of capture through testing of existing DAC materials in integrated field units that produce concentrated CO_2 stream of at least 95% purity.

Conduct in-field testing of integrated systems allowing for continued development of the process and opportunities to identify optimization options.

Fully develop the techno-economics of these DAC configurations and their overall CO_2 impact through life cycle analysis (LCA).

DAC RECO2UP Project Objectives:

Objective 1. Conduct applied research and development to decrease the cost of DAC from atmospheric air and mixtures of air and simulated industrial gases available in a test bay at the National Carbon Capture Center (NCCC).

Objective 2. Develop and scale-up an integrated system utilizing energy recovery at the NCCC.

Objective 3. Increase the integrated system's fidelity by validating and demonstrating operations in a simulated commercial environment by maximizing capital efficiency, energy efficiency.

Objective 4. Identify and address key technical barriers, within a representative operating environment, in support of DAC technology commercialization.

Objective 5. Perform a pre-screening techno-economic analysis (TEA) and life cycle analysis (LCA) to determine the environmental sustainability (amount of carbon negativity) and economic viability (cost impacts) of the integrated DAC system.

Project Team Facilities

- 19,000 SQ FT of design, fabrication, manufacturing, laboratory and office space
  - power, water, steam, natural gas, vacuum
- Testing Facilities
  - FAT, analysis in Berkeley
  - Integrated Systems at the NCCC in Wilsonville, Alabama

Synapse Build Labs
(Seattle, SF)

AirCapture Manufacturing, Laboratory & Fabrication Facilities
(Berkeley, CA)

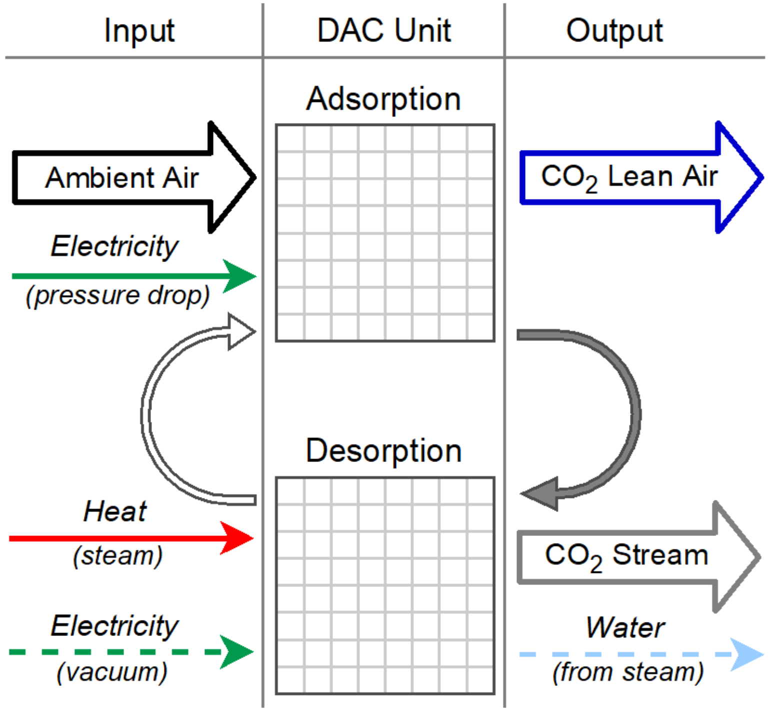
National Carbon Capture Center
https://www.nationalcarboncapturecenter.com

Aircapture · Southern States Energy Board · NC National Carbon Capture Center · Southern Company · SYNAPSE Part of Capgemini Invent · CrescentRI Resource Innovation · Global Thermostat · Colorado School of Mines Earth • Energy • Environment

Technology Background

Step 1 (Capture): CO_2 is collected by moving air or mixtures of air and CO_2 rich gases across a proprietary contactor which adsorbs CO_2.

Step 2 (Regeneration): The contactor is moved into a regeneration box where low-temperature steam flows across the contactor, removing CO_2 from the contactor, and the CO_2 is collected.



Polymeric Amine Sorbent

- Monolithic Contactor
- Low pressure drop
- Low thermal mass
- High geometric surface area
- Compatible with various construction methods

Adsorption

- 900 seconds / monolith in ambient air

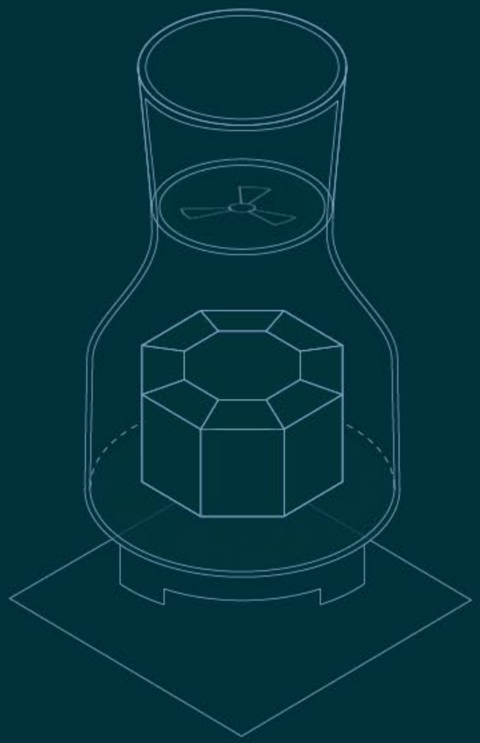
Desorption

- Saturated Steam in less than 90 seconds

Modular technology platform enables scaling and low-cost, volume manufacturing with reasonable install cost factors.

Monoliths & sorbents provided by Global Thermostat

Process Animation



Project Design

Goal: Developed an integrated DAC system design with thermal recovery and downstream processing to increase overall system fidelity and demonstrate in commercially relevant field testing at NCCC.

3 skids:

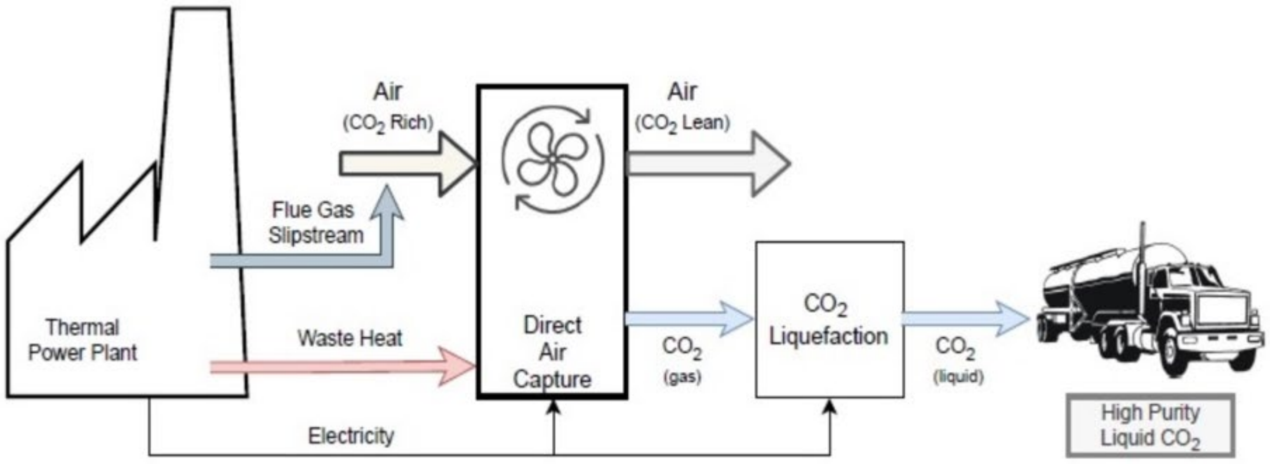
- Heat Integration/Recovery
- DAC
- CO_2 Liquefaction

Heat skid will enable simulation of varying qualities of industrial waste heat

DFM DAC will run in multiple modes of operation to demonstrate integration

CO_2 Liquefaction skid to produce high purity liquid CO_2 onsite

Integrated process will demonstrate economics, LCA and product carbon footprint.



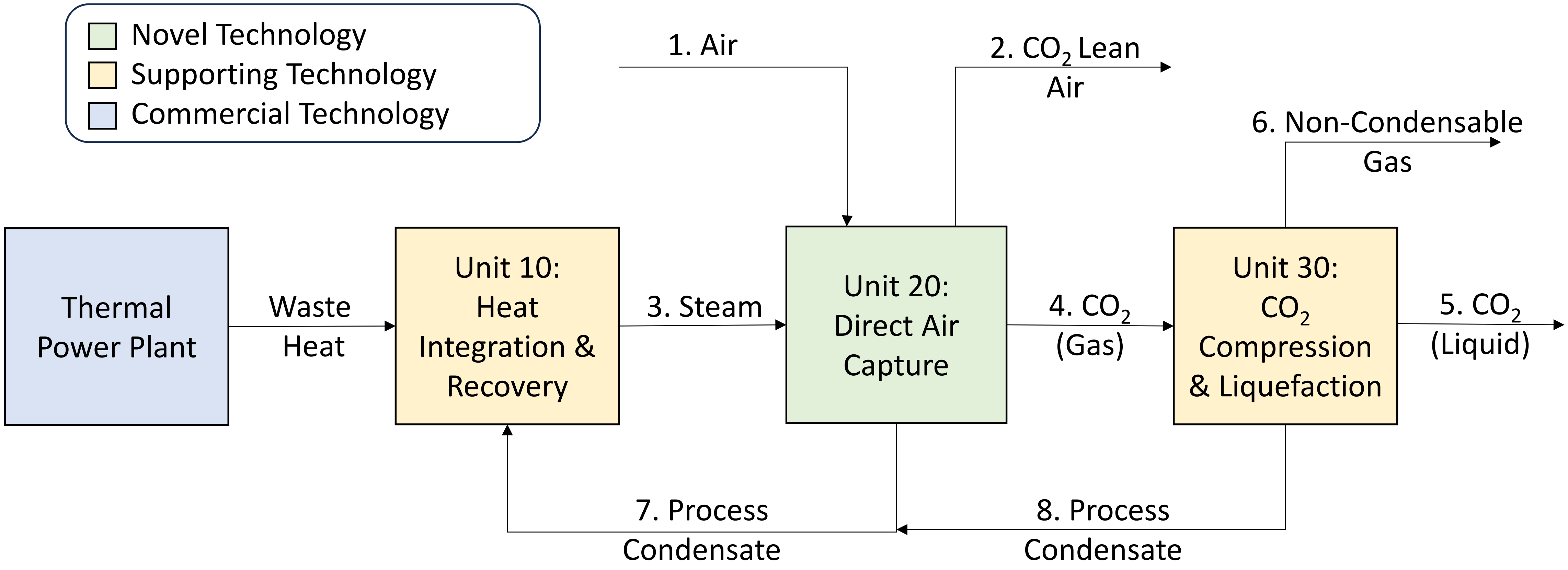
Project Schedule

✓ Design Phase I (BP1)
- 10/1/20 – 10/31/21

✓ Construction Phase II (BP2)
- 11/1/21 – 10/31/22

➢ Integrated Systems Testing Phase III (BP3)
- 11/1/22 – 7/31/24

System Design

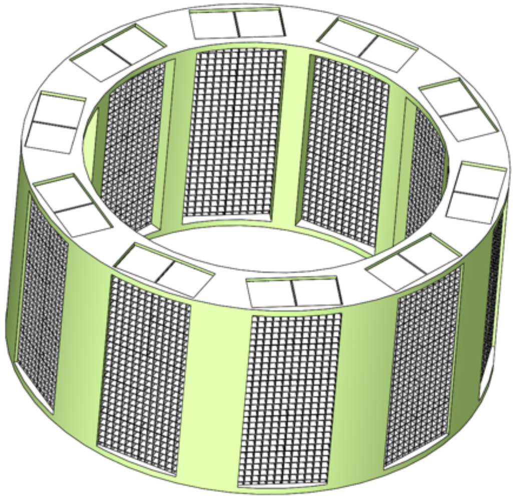


BP-1 DAC Conceptual Design

Goal: Evaluate conceptual designs for contactor configuration.

Considerations: Minimize pressure drop, sealing mechanisms, system volume, moment of inertia, equipment availability, etc.

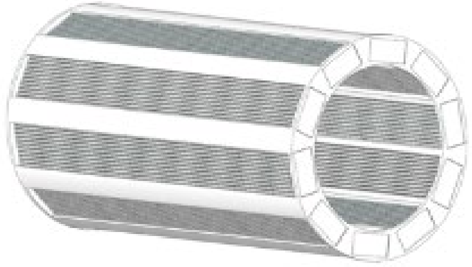
Modular, Scalable, DFM



2x5 Contactor Arrangement
(100 tonne/yr)

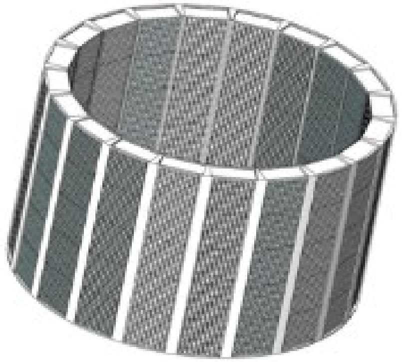
1 X 10 Flat

- Air Flows from the inside
- Air Flows out the outside
- Reference Volumes
  - Outer = 5.48 m^3
  - Net = 2.53 m^3
- Brick I = 220 kg*m^2
- Pros
  - Smallest OD = 1500mm
  - 2 choices for Steam Chamber
    - Steam chamber seals on Inside and Outside length of Cylinder. Cylinder rotates
    - Steam chamber moves along
- Cons
  - Over 10 feet long



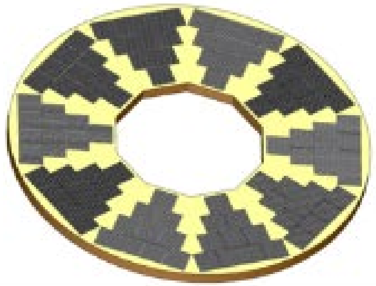
5 x 20 ring

- Air Flows from the inside
- Air Flows out the outside
- Steam chamber seals on inside and outside of Cylinder
- Reference Volumes
  - Outer = 6.72 m^3
  - Net = 1.85 m^3
- Brick I = 616 kg*m^2
- Pros
  - Direct air flow
  - Low net volume
  - Lots of room in the middle for stuff
- Cons
  - Large OD, 2500 mm (7.7 feet)



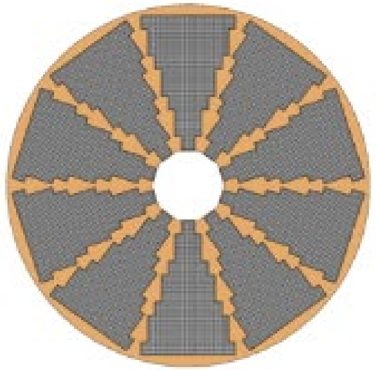
12 inch brick flat

- Air comes in the bottom
- Air goes out the top
- Steam chamber seals on top and bottom face
- Reference Volumes
  - Outer = 5.38 m^3
  - Net = 4.50 m^3
- Brick I = 1724 kg*m^2
- Pros
  - Best layout for airflow
  - Thinnest
- Cons
  - Large OD 4700mm (Over 15 feet)
  - Largest moment of Inertia
  - Difficult Sealing



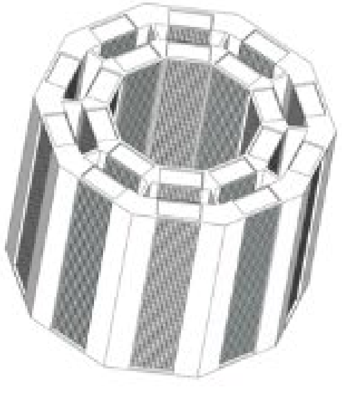
6 inch brick flat

- Air comes in the bottom
- Air goes out the top
- Steam chamber seals on top and bottom face
- Reference Volume
  - Outer = 4.09 m^3
  - Net = 3.94 m^3
- Brick I = 1089.002 kg*m^2
- Pros
  - Best layout for airflow
  - Thinnest
- Cons
  - Needs 6 x 6 inch bricks
  - Large OD 4100mm (Over 13 feet)
  - Large moment of Inertia
  - Difficult Sealing



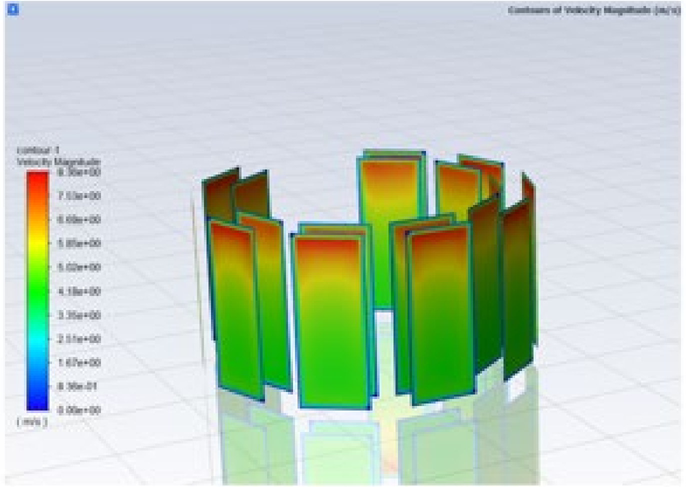
Dual Ring

- Air flows in between inner and outer ring of bricks
- Air Flows out the interior and exterior of Ring
- Steam chamber seals on top, Inside, and outside of cylinder
- 2000mm OD
- Reference Volumes
  - Outer = 4.87 m^3
  - Net = 3.65 m^3
- Brick I = 312 kg*m^2
- Pros
- Cons
  - Complicated ducting to get air between rings.
  - 3 sealing surfaces

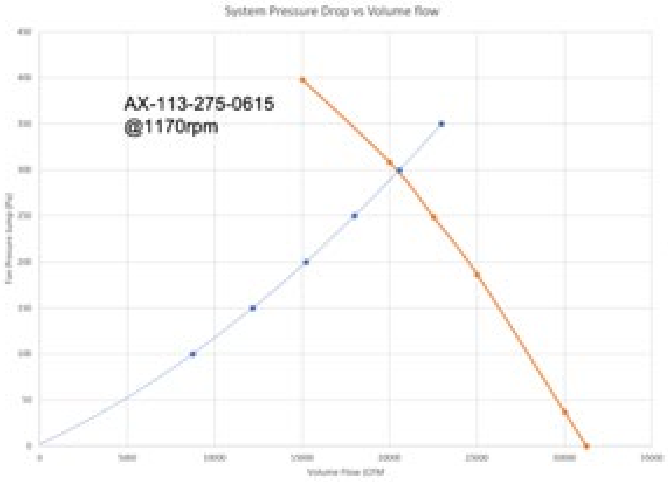


BP-1 Adsorption CFD Results

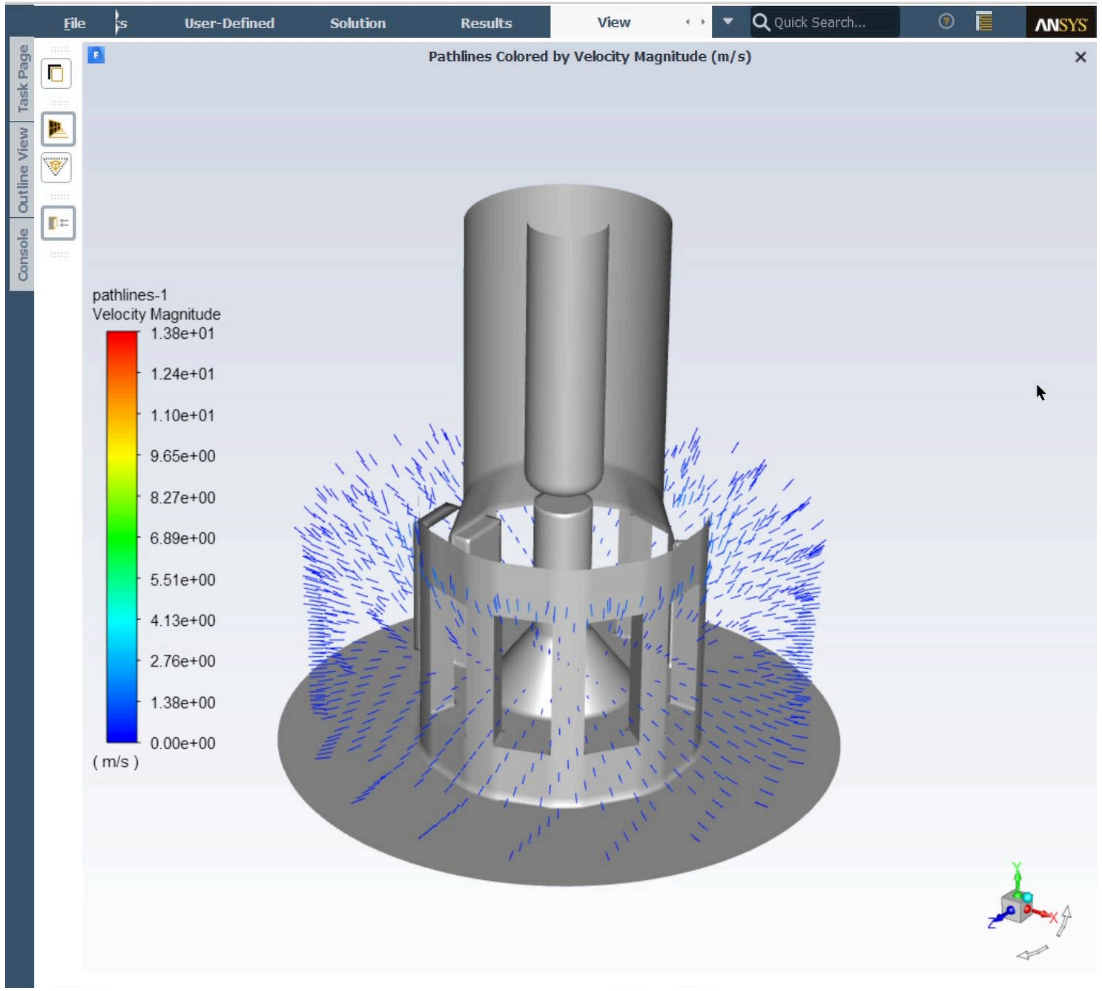
- Detailed CFD analysis of 100 contactor circular / radially oriented design basis
- CFD results lead to basic design configuration with internal taper, fan diffuser, preferred orientation of fan inlet to contactor arrangement
- Acceptable flow distribution and airspeed velocities across contactors
- Overall system pressure drop is within energy budget
- System air flowrate ~23,000 CFM, 350Pa dP Target



Velocity distribution through bricks



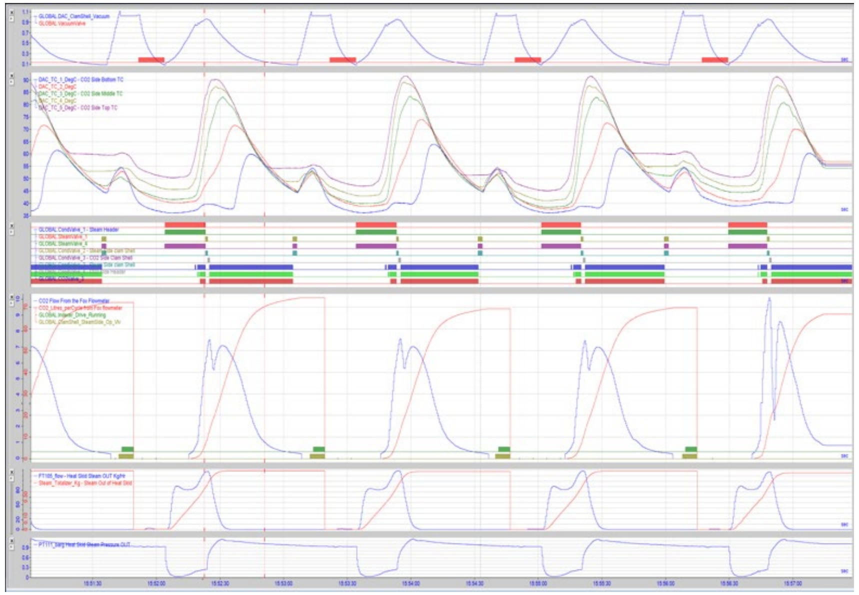
System Pressure drop vs Volume Flow



BP-2 Milestones

- ✓ Milestone 4.1.a. Initiate Construction of Skids – 2/15/22
- ✓ Milestone 4.1.b. Finish Construction of Skids – 7/31/22
- ✓ Milestone 1.3.b. NCCC Technology Collaboration Agreement– 10/31/22
- ✓ Milestone 4.3.a. Phase II Commissioning Report and Test Matrix– 10/31/22

Completed Multi-mode Heat Integration Skid

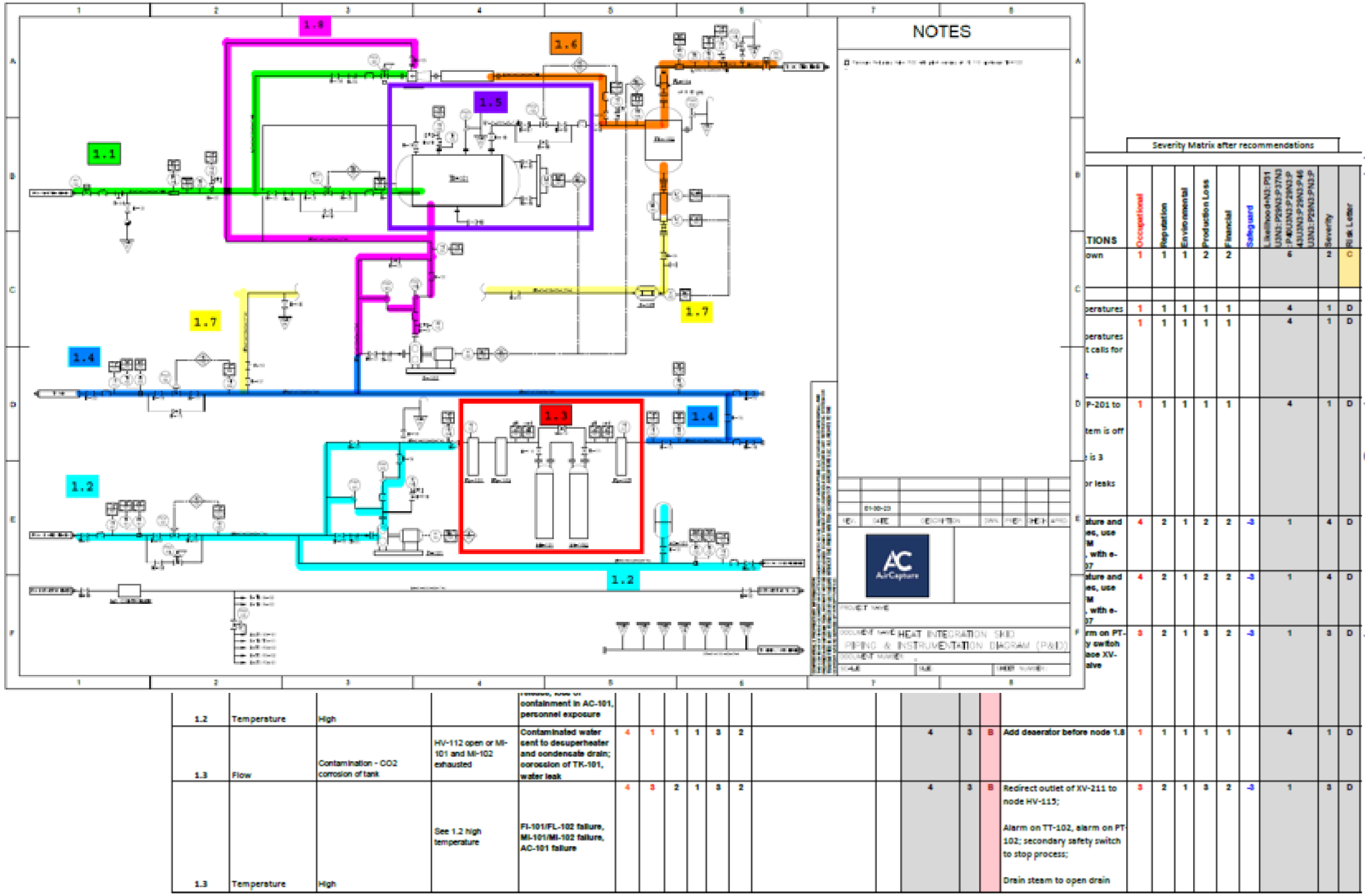


Automated data traces from integrated PLC (DAC & Heat Skid)

100 tpy DAC SN1 & Heat Skid

BP-3 Integrated Systems Testing (Q1 2023 – July 2024)

- ✓Milestone 2.3 Pre-operational risk workshop and operational HAZOPs review – 1/30/2023
- ✓Liquefaction HAZOP review submitted on 9/25/2023



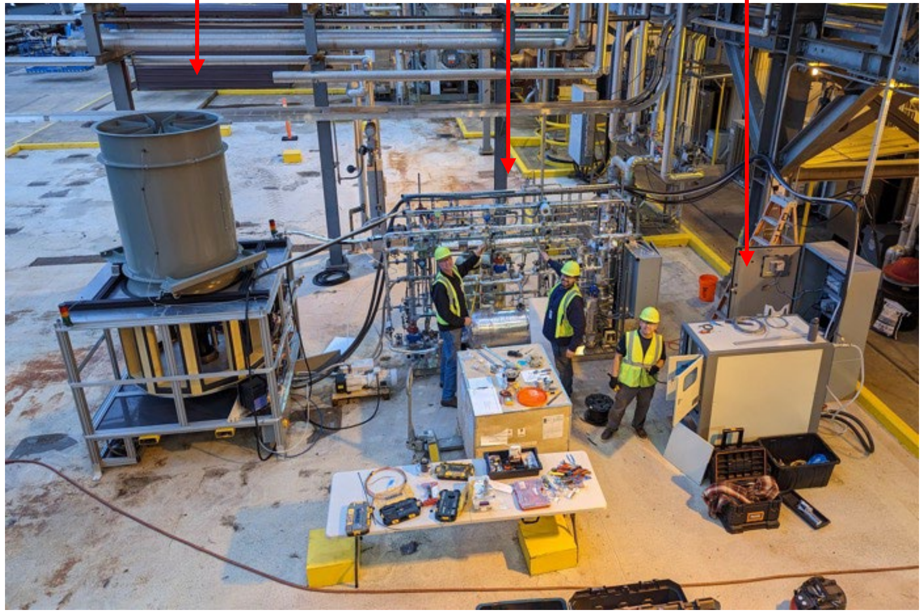
Aircapture | Southern States Energy Board | National Carbon Capture Center | Southern Company | Synapse | CrescentRI | Global Thermostat | Colorado School of Mines

BP-3 Integrated Systems Testing (Q1 2023 – July 2024)

✓Milestone 5.1.a. Skids Transported to NCCC – 2/7/23

Shipment to NCCC

NCCC Pilot Bay Test Area



Installation at NCCC

BP-3 Integrated Systems Testing (Q1 2023 – July 2024)

✓ Milestone 5.1.b. Completed Site Commissioning at NCCC – 5/12/23

DAC Skid (left)
Heat Skid (right)

Aircapture Commissioning
Engineers at NCCC

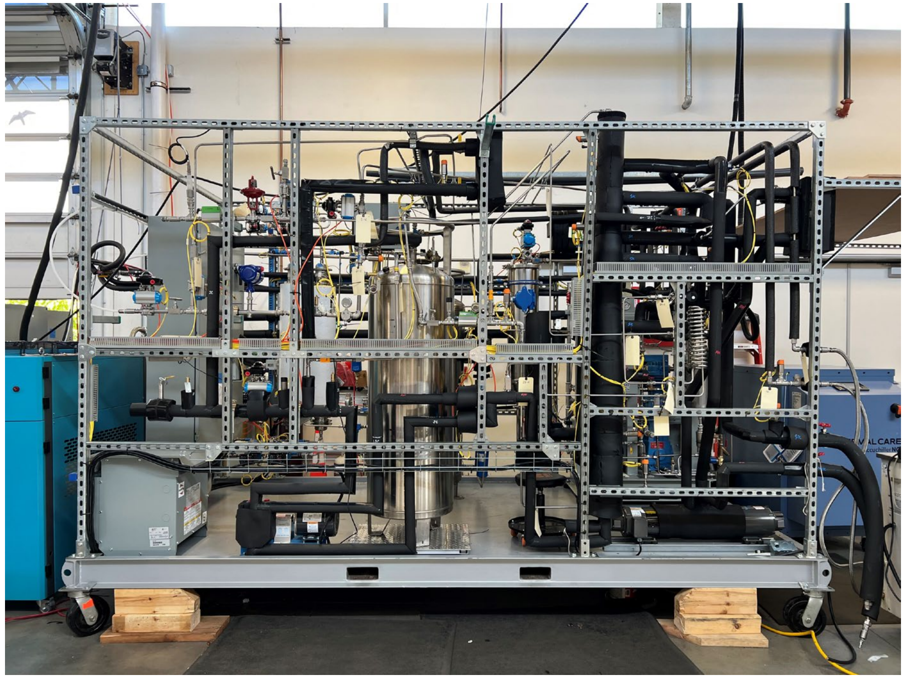
Start of automated operations at NCCC

First DAC Produced CO_2 at NCCC

Aircapture · Southern States Energy Board · NC National Carbon Capture Center · Southern Company · Synapse Part of Capgemini Invent · CrescentRI Resource Innovation · Global Thermostat · Colorado School of Mines Earth • Energy • Environment

BP-3 Integrated Systems Testing (Q1 2023 – July 2024)

✓ Liquefaction on-site and running – February 2024



Liquefaction Skid

Liquefaction Skid Operating Inside Container

SN1 + Liquefaction at NCCC

BP-3 Integrated Systems Testing (Q1 2023 – July 2024)

Campaign Learnings

- From three planned campaigns five were completed due to longer availability of test bed by NCCC
- The three skids operated and survived in conditions ranging from summer heat, tropical storms, and a deep freeze
- SN3 operational in April of 2024 has many learnings incorporated
    - Reduced Cost by 50% with respect to CAPEX, Increased reliability and decreased utility demand
- Importance of the support from NCCC and Southern personal was critical in all the onsite learnings

Test Campaign	1	2	3A & 3B	4	5
Hours Completed	700+ hrs	700+ hrs	1110+ hrs	690+ hrs	180+ hrs
Goal Achieved or Key Learning	Optimization and initial Run-data	>90% Availability	>99.9 Mol% Liquid CO_2	Qualifying Alternative Suppliers, Cont'd Run Data	Fatigue Testing, Ran alternative cycle times

Key Learnings and Operational Performance

Total Operational Hours: 3,300+ Hrs, 3,030 of which was during recorded campaigns
Total Available Operational Uptime: ~94%, exceeding commercial uptime performance target (90%)

Aircapture · Southern States Energy Board · NC National Carbon Capture Center · Southern Company · SYNAPSE Part of Capgemini Invent · CrescentRI Resource Innovation · Global Thermostat · Colorado School of Mines Earth • Energy • Environment

BP-3 Decommissioning (July 2024)

Milestone 5.2 – Complete DAC Testing at NCCC

- Aircapture concluded testing on July 7 remotely shutting down DAC skids and informing NCCC staff. NCCC ceased steam supply at that time.

Milestone 5.3a - Decommissioning July 12

- Aircapture & NCCC decommissioned skids from July 8 to July 12, Aircapture staff worked on site with NCCC staff to break interconnections and pack up the DAC-100 and all supporting skids.

Milestone 5.3b – DAC Removal from NCCC Site ,July 25 liquefaction, July 29 SN-1 DAC-100 + Heat Skid

- AirCapture & NCCC removed the skids from host site. Liquefaction shipped on July 25, DAC-100 + Heat Skid July 29

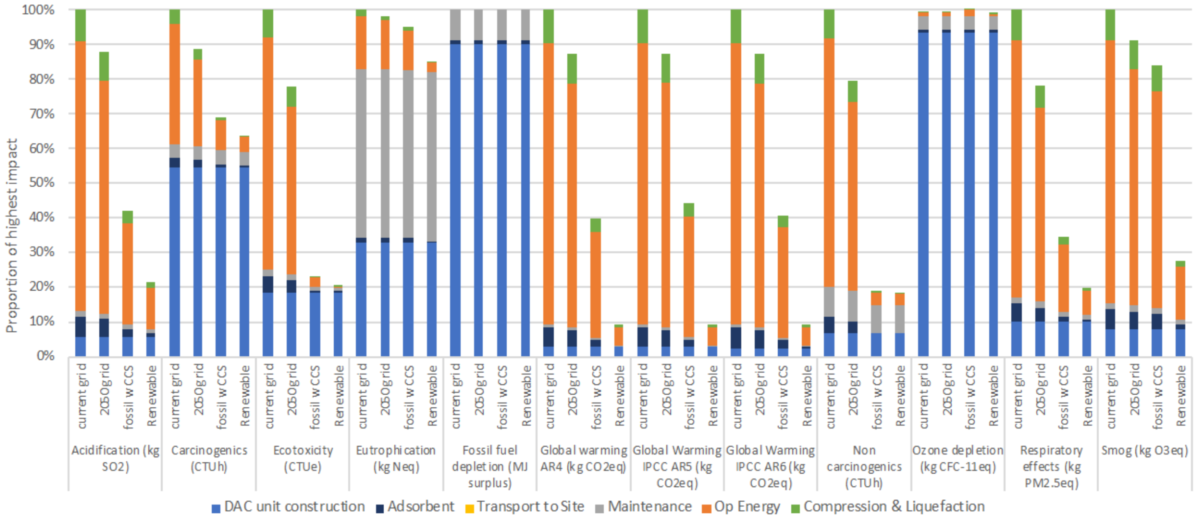
DAC-100 + Supporting Skids Decommissioning on July 8th-12th

BP-3 Pre-Screening TEA & LCA July 2024

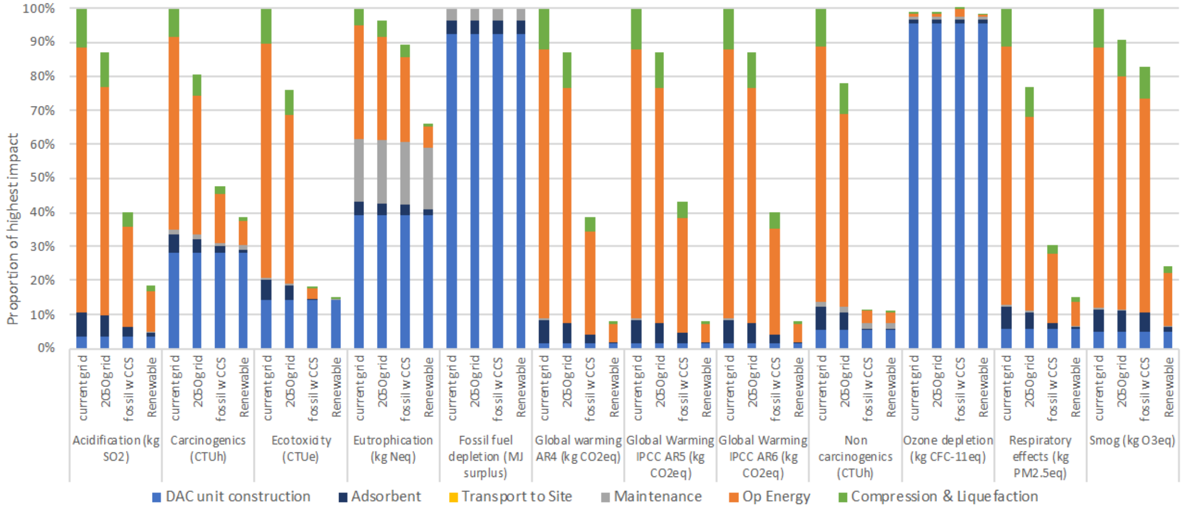
Milestone 6.1 TEA & LCA

- TEA shows promising results for initial commercial prototype
- SN-3 Design is already 50% below SN-1 CAPEX and more than 20% more efficient.
- Dr. Amy Landis conducted an LCA for the project utilizing a detailed model created specifically for Aircapture that uses the complete BOM for both the SN-1 DAC-100 Design as well as the newer SN-3 DAC-100 Design that integrated key learnings from the NCCC operations.

SN - 1



SN - 3



Performance Attributes & Requirements

Performance Attribute	Performance Target	Status / Test Range	Comments / Justification for Performance Requirement
Capture Efficiency	>50%	30-60%	Dependent on contactor, airspeed, environmental conditions. Ideal economic case may be below 50% depending on environmental conditions and local energy costs.
Gas CO_2 Purity	>95%	> 97%	Purity ranges between 95-99% have been achieved. Depends on process control set points for desorption rough down.
Liquefaction efficiency	> 95%	>95%	Liquefaction efficiency should be above 95% to avoid excessive product losses which increase overall cost. 95% is a suitable target based on preliminary TEA work.
Liquid CO_2 purity	99.9%	>99.9%	Liquid CO_2 purity should exceed the proposed target to achieve minimum purity required by various industries. Greater than 99.9% has been achieved at Berkeley and at NCCC.
Desorption Temperature	80 – 110^{o}C	80-95^{o}C	Acceptable range for desorption given the technology. Waste heat available from a large number of industrial sources in this temperature range. Utilization of low-grade waste heat in this range will reduce overall CO_2 production costs.
Adsorption:Desorption Cycle Time	900s : 90s	Achieved, Various	9:1 adsorption to desorption ratio. Timing model flexible due to system design. Efficiency maximization depends on contactor performance.
Remote Operations	Uninterrupted Remote Operations	Achieved	No specific performance targets for uninterrupted performance stated as MTBF is unknown for FOAK.

*TMP includes additional performance attributes

Wrap Up

Objective 1. Conducted applied research and development to decrease the cost of DAC from atmospheric air and mixtures of air and simulated industrial gases available in a test bay at the National Carbon Capture Center (NCCC).

- Long-term testing at NCCC was required to demonstrate mechanical reliability, established operational parameters in real-world environment
- Laboratory tests of various simulated industrial gases were performed

Objective 2. Developed and scaled-up an integrated system utilizing energy recovery at the NCCC.

- DAC scaled from lab to commercial unit and operated over 3,300 hours at NCCC using steam on site
- Project target of TRL 5+ has been achieved

Objective 3. Increased the integrated system's fidelity by validating and demonstrating operations in a simulated commercial environment by maximizing capital efficiency, energy efficiency.

- DAC system platform designed for increased technology advancement
- Modular design and manufacturing enables scale out project approach

DAC-100 SN2 (Berkeley, CA) Nov 24

Wrap Up Cont'd

Objective 4. Identify and address key technical barriers, within a representative operating environment, in support of DAC technology commercialization.

- 5 main testing campaigns completed with over 3,300 hours run at NCCC
- Optimizing running conditions and identifying areas of maintenance
- Over 90% availability for DAC, Liquid CO_2 Production on Site, Simulated flue gas using High Purity CO_2

Objective 5. Perform a pre-screening techno-economic analysis (TEA) and life cycle analysis (LCA) to determine the environmental sustainability (amount of carbon negativity) and economic viability (cost impacts) of the integrated DAC system.

- TEA and LCA work shows promising results for initial commercial prototype. Critical design and operations lessons learned informed next generation design for soon to come online commercial project (Project Hajar).

DAC-100 SN3 (Berkeley, CA) Apr 24

Acknowledgements

Special Thanks to:

- Southern States Energy Board
- David Lang
- Naomi O'Neil
- NCCC Team
- Southern Company

Cost Share Partners:

- Aircapture
- Southern States Energy Board
- Synapse
- Crescent Hill Resources

8x DAC-100 + Supporting BOP Skids for Project Hajar, June 2024 >50% cost reduction from SN-1

Questions?

Direct Air Capture Recovery of Energy for CCUS Partnership
(DAC RECO2UP)
Project Number: DE-FE0031961