Pilot-Scale Evaluation of an Advanced Carbon Sorbent-Based Process for Post-Combustion Carbon Capture

Project Review Meeting

June 21, 2016

Project Objectives

- Demonstrate the advanced carbon sorbent-based post-combustion capture technology in a 0.5 MWe slip-stream pilot plant.
- Achieve >90% carbon dioxide (CO_2) removal from coal-derived flue gas.
- Demonstrate significant progress toward the achievement of the U.S. Department of Energy (DOE) cost target of <$40/ton of CO_2 captured.

Basic Principles

- Physical adsorption of CO_2 from flue gas on a selective and high capacity carbon sorbent.
- Ability to achieve rapid adsorption and desorption rates (no solid state diffusion limit).
- Minimize thermal energy requirements.
- Ability to produce pure CO_2 stream suitable for compression and pipe line transportation.
- A continuous, falling micro-bead sorbent reactor geometry integrates the adsorber and stripper in a single vertical column
  - Provides a low pressure drop for gas flow and minimize physical handling of the sorbent.

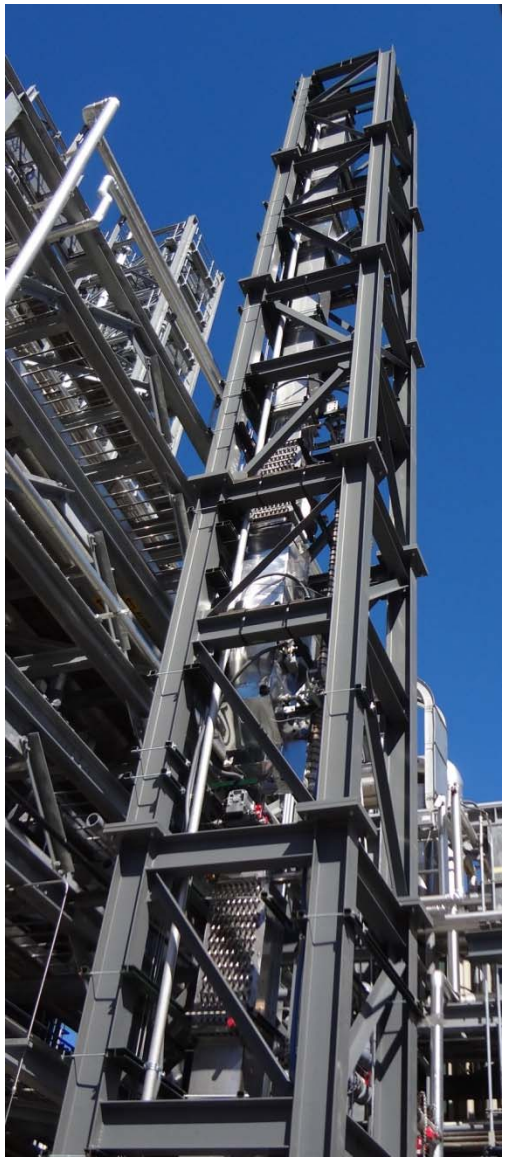
Large Bench-Scale Testing at NCCC

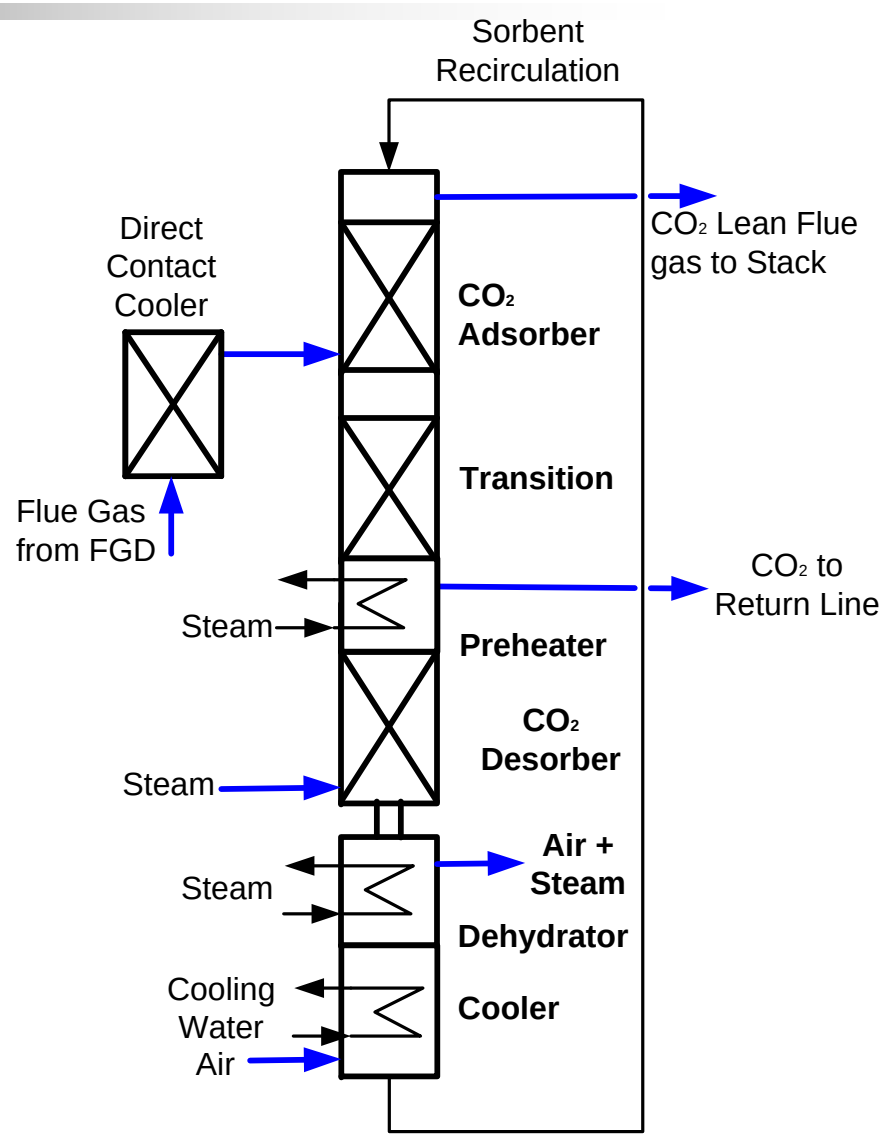
- Previously tested at SRI using air-CO_2 mixture and with steam boiler flue gas at the University of Toledo.
- Testing with a flue gas from a PC-fired boiler.
- Test goal: 150 h of continuous operation; 600 h of total operation.
- Completed ~250 h of operation.

Design of Integrated Reactor for Testing at NCCC

- System Dimensions:
  - 50 ft tall; 4 ft x 4 ft foot print
  - Adsorber: 9-ft tall; 18 inch square
  - Stripper: 15-ft tall; 12 inch square
- A heat exchanger to recover sensible heat from hot, regenerated sorbent and use it to preheat the sorbent from the adsorber.
- Pneumatic transport of the sorbent microbeads.
- Nominal flue gas flow: 70 cfm (2000 liters/min).
- Goal: 90% CO_2 capture and >98% CO_2 purity product.
- CO_2 capture capacity: ~1 ton/day.

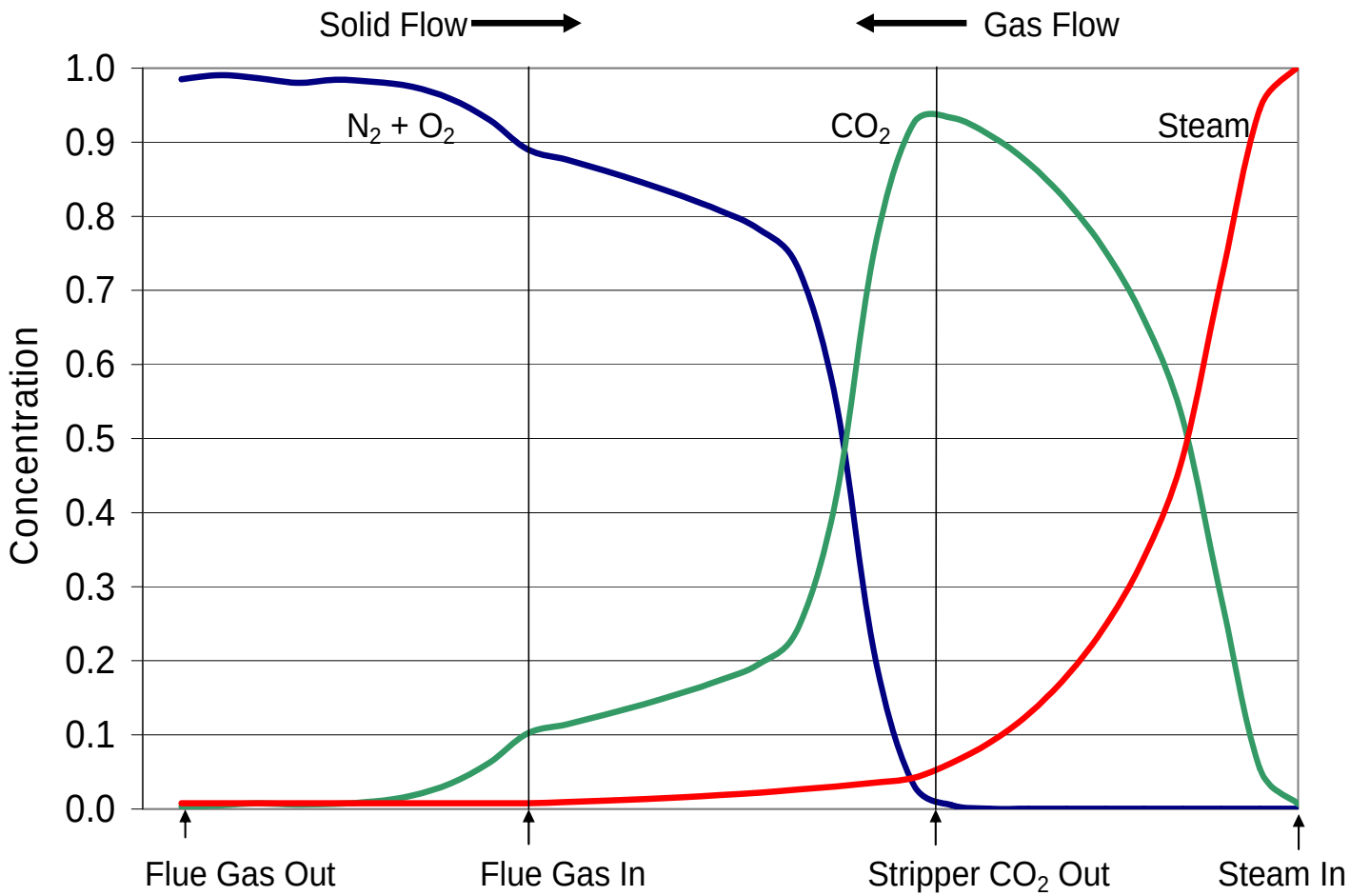
Installed Structure at NCCC Pad





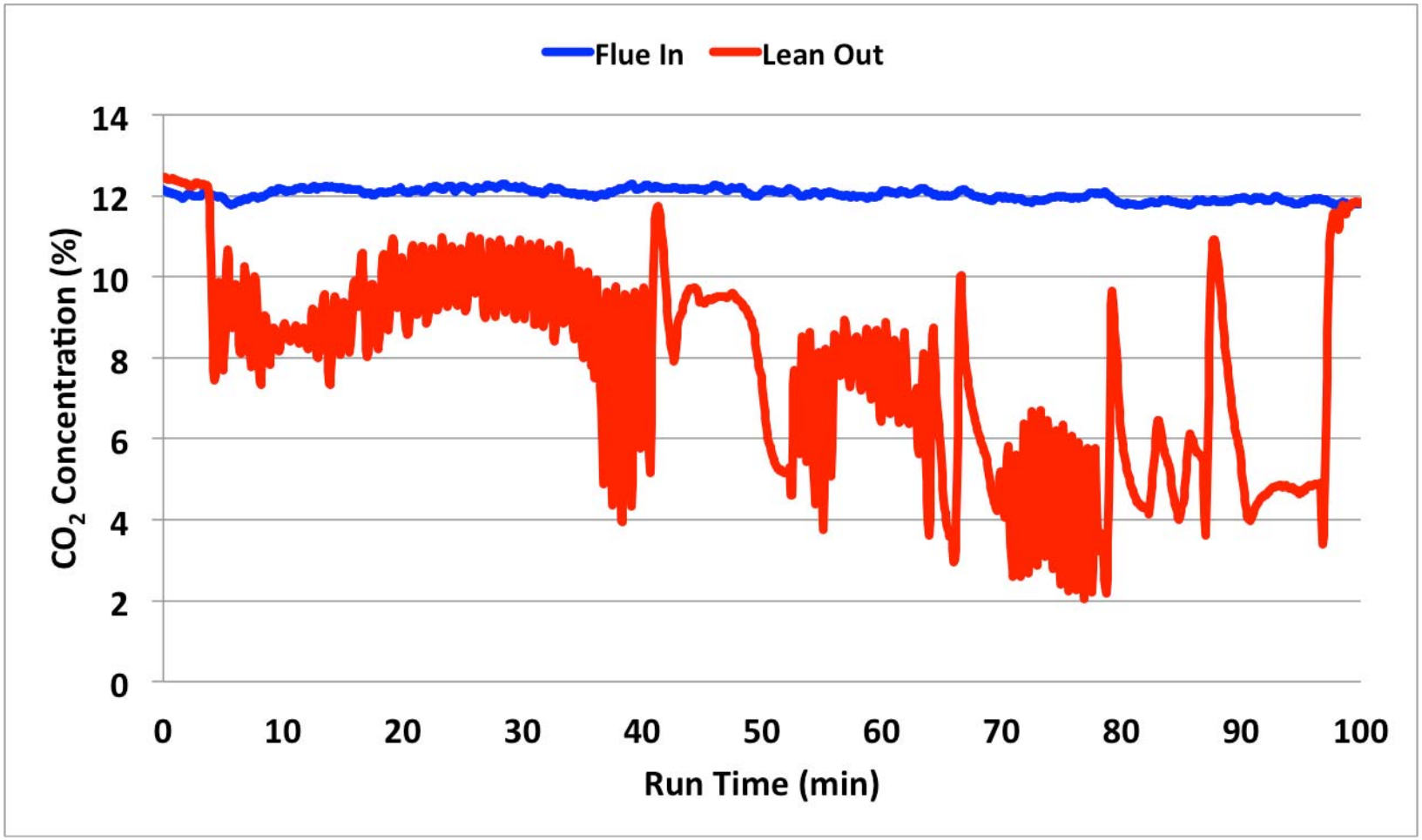
Sorbent flow is controlled at the top of adsorber, bottom of stripper, and bottom of sorbent cooler.

Composition Profiles in the Reactor Column



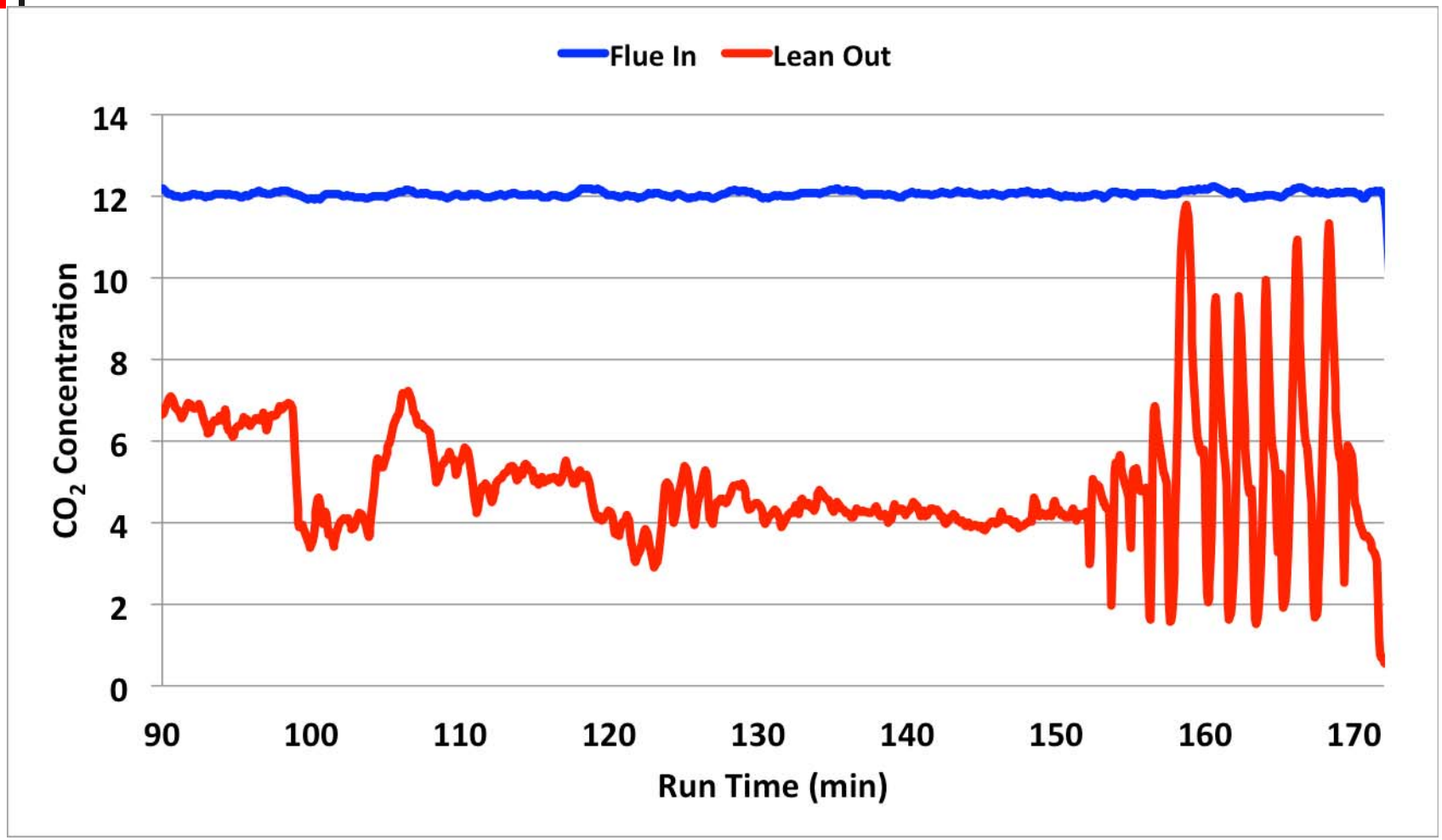
Achieving a high capture efficiency and product purity requires establishing proper composition profiles at various stages.

Sorbent Flow Instability –Pressure Effects



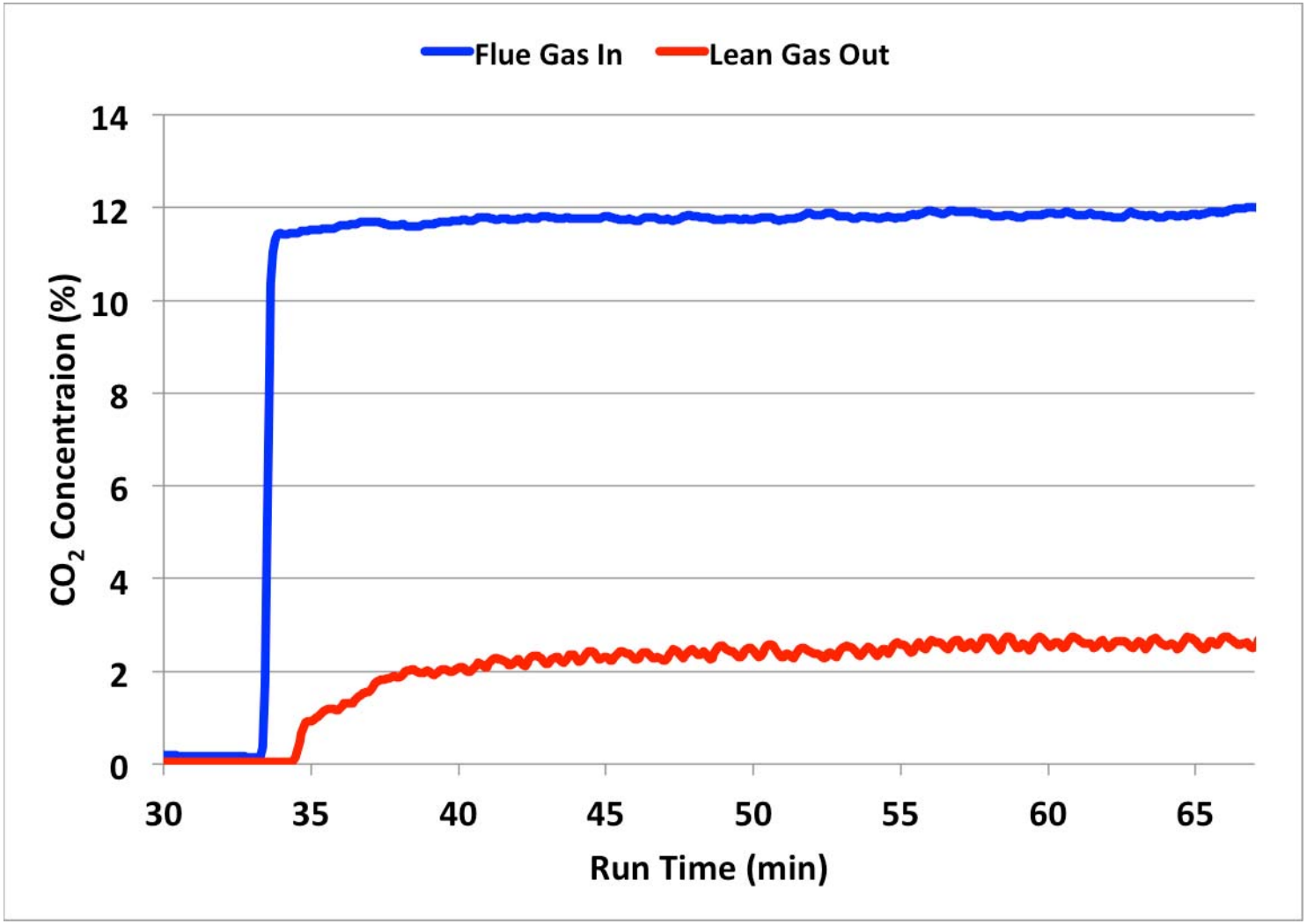
Pressure fluctuations in the reactor can interrupt sorbent flow which can vary the CO_2 capture rate.

Sorbent Flow Instability – Moisture Condensation



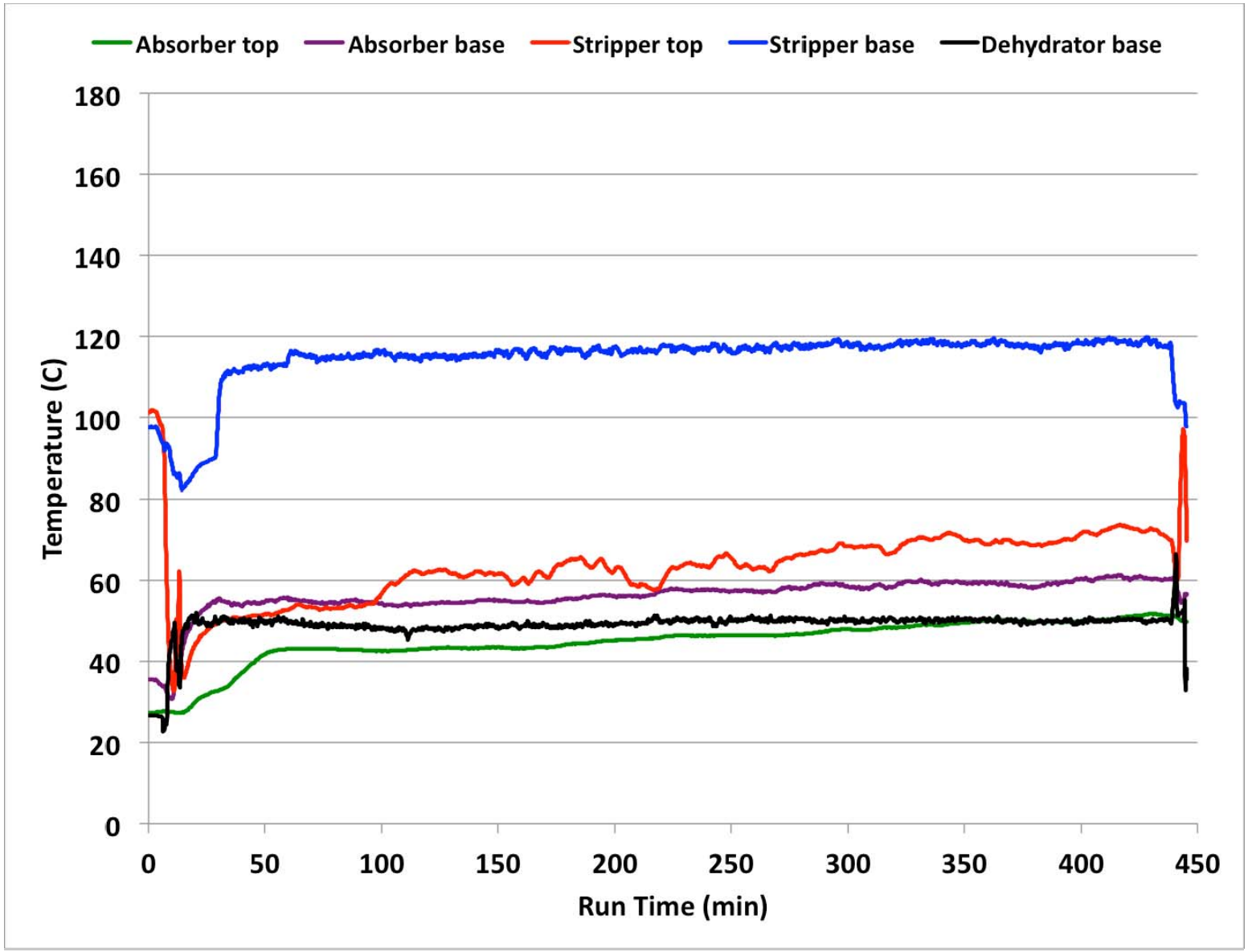
Condensation of moisture in the reactor can interrupt sorbent flow which can vary the CO_2 capture rate.

Stable Solid Flow



Stable flow can be achieved by preventing moisture condensation and proper pressure at various locations.

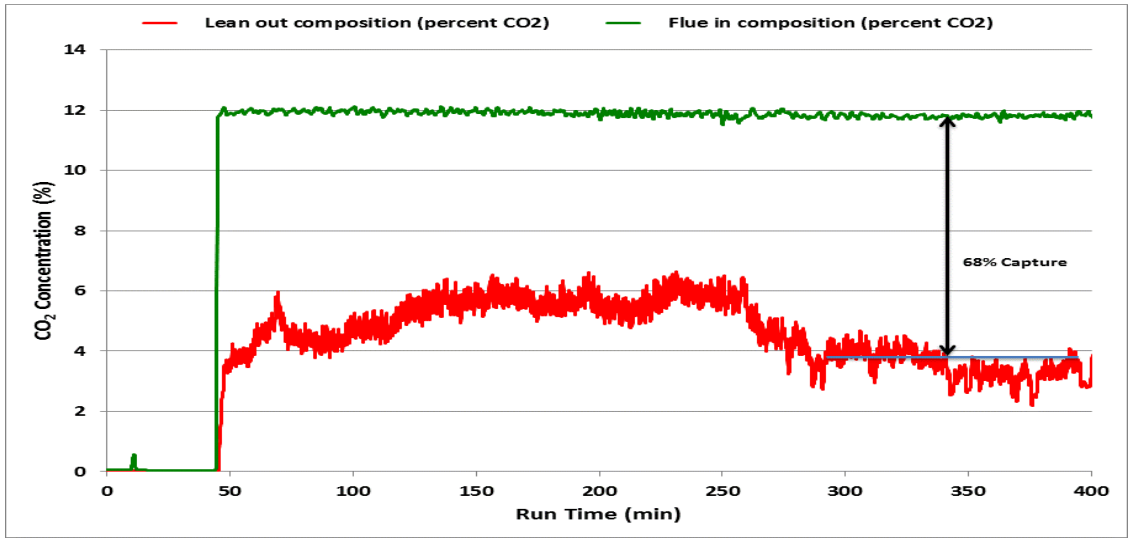
Temperature Profiles in the Reactor Column

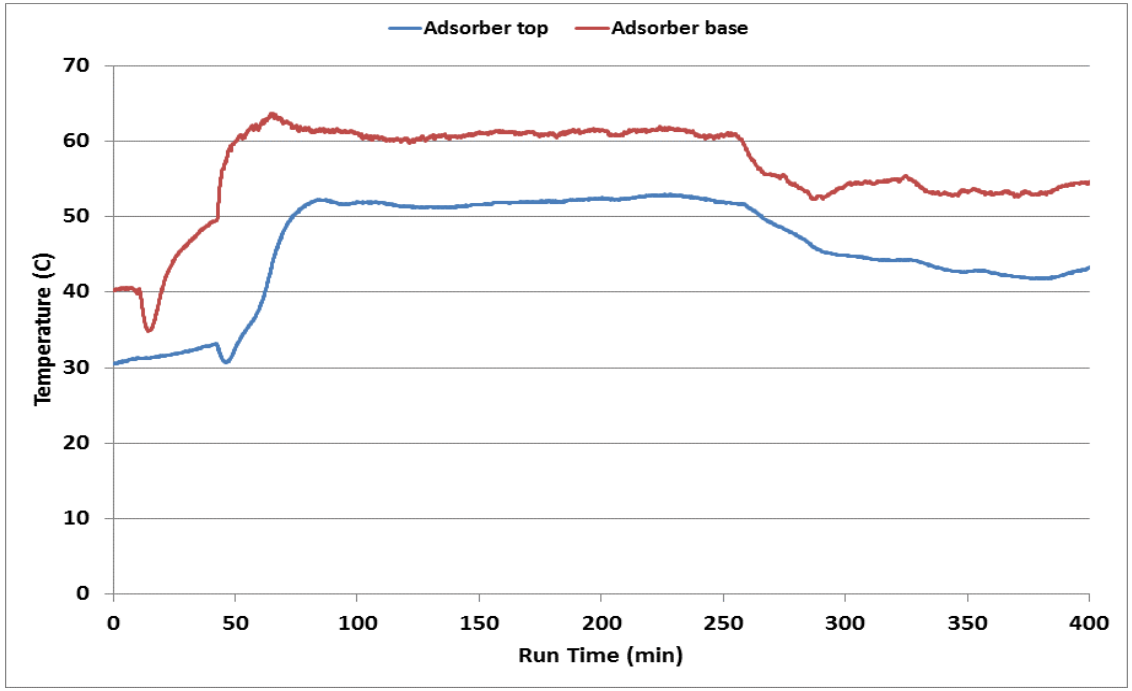


Design and Operating Temperatures

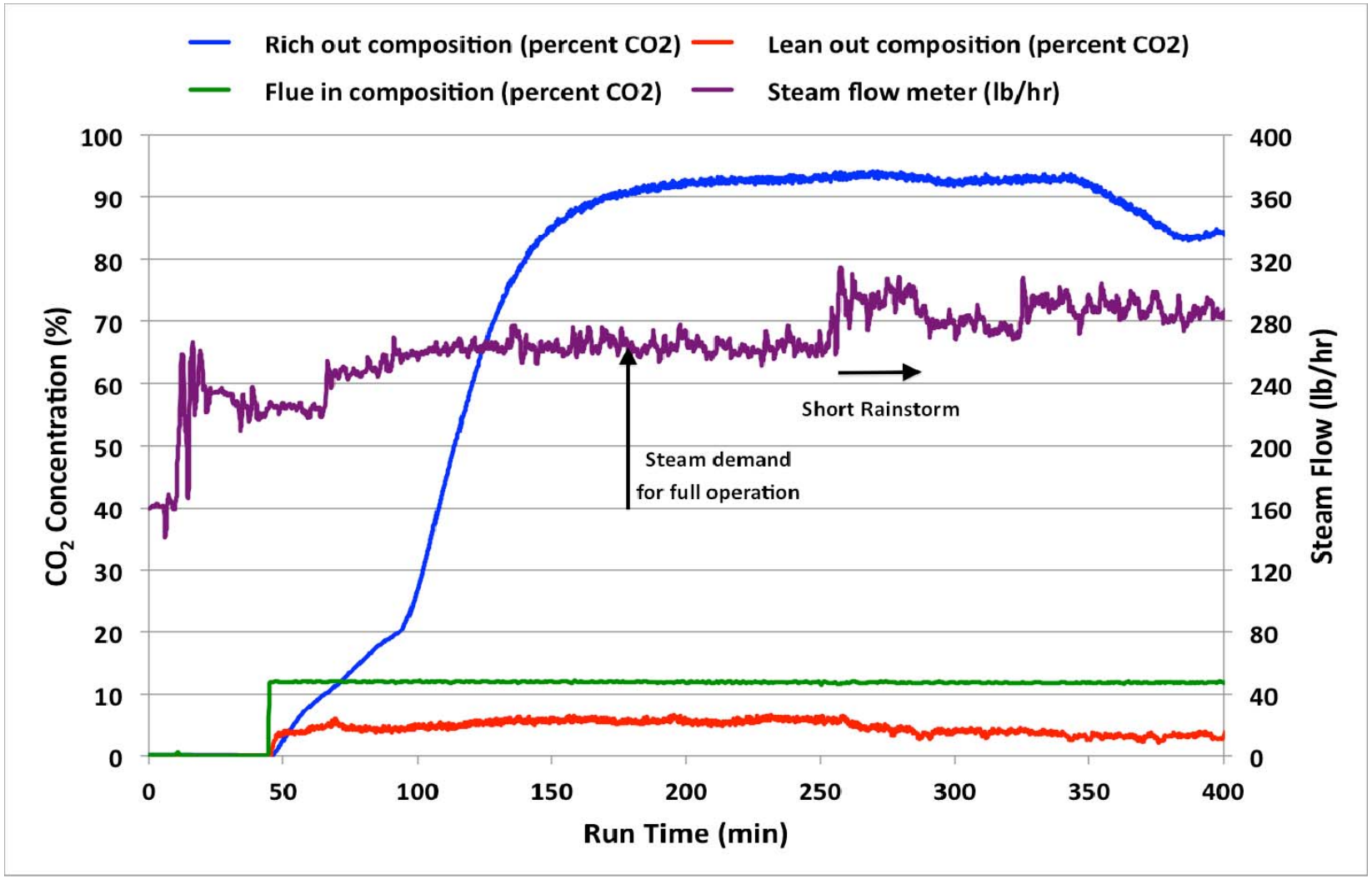
Parameter	Design Value	Operation Nominal Value
Adsorber temperature (°C)	20 to 30	50 to 60
Stripper temperature (°C)	100 to 120	120
Dehydrator top temperature (°C)	120	130
Cold Sorbent temperature (°C)	25 to 35	45 to 50

Capture Efficiency vs Adsorber Temperature





Stable Operation



Adsorber not insulated; Sorbent temperature affect the CO_2 capture rate; rainstorm cools the adsorber – temperature is lowered and capture efficiency increases; steam demand in the column increases.

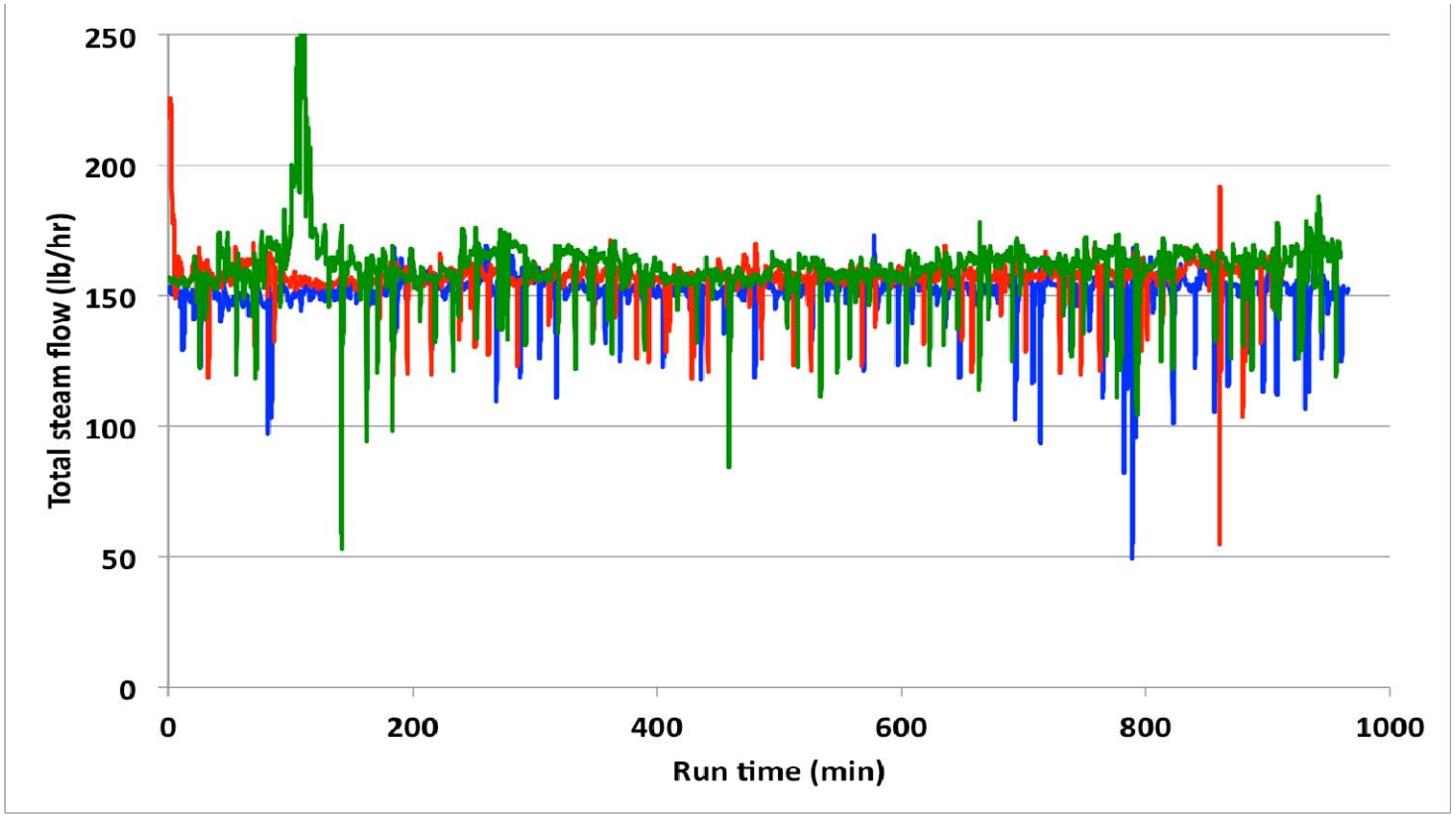
Parameters Affecting CO_2 Capture Efficiency

- Adsorber temperature.
  - Temperature at NCCC (50° to 60°), higher than at SRI or at Toledo (10° to 30° C).
- Residence time in adsorber.
  - Residence time at NCCC was ~16 s compared to previous tests (~24 s).
  - Height was shortened to provide increased disengagement section at pneumatic transport.
- Spacing in the structural packing.
- Rapid adsorption – desorption equilibrium
- Solids/Gas ratio - Similar ratio as previously.

Steam Demand Measurement

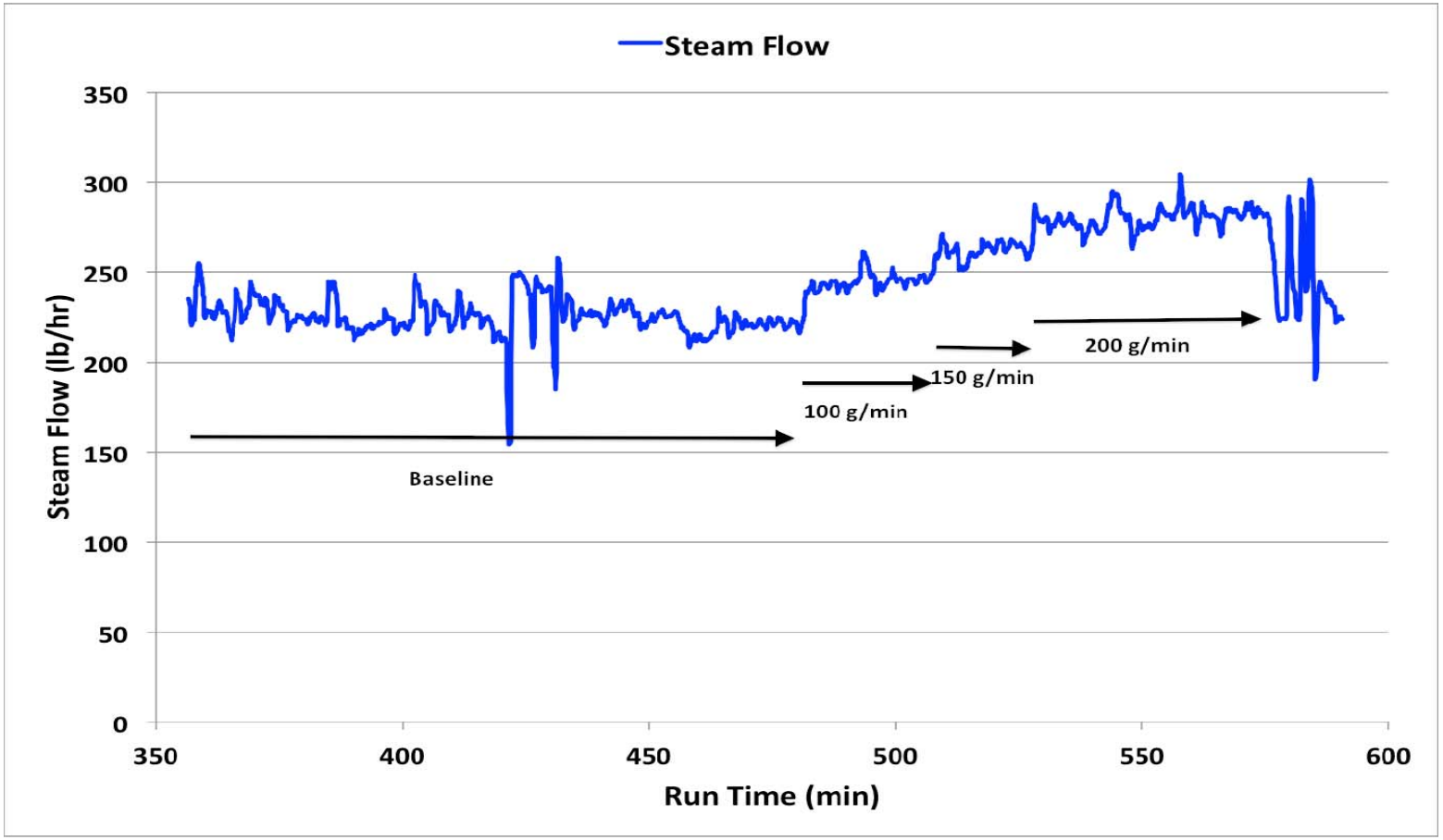
- Steam (40 psig) is supplied to the reactor column from NCCC supply:
  - Sorbent preheater.
  - Generating steam for direct steam injection to the stripper.
  - Sorbent dehydrator. Steam recovered in the dehydrator can be used to preheat the sorbent.
- Low steam flow for each demand. A vortex meter measured total steam supplied.

Baseline Steam Consumption



Steam was measured with no sorbent or flue gas flows at 3 different nights. Possible heat losses: Reactor areas that are not insulated; loss of steam through the condensate traps.

Steam Generation from Water



Water Injection Rate (g/min)	Steam Generated (lb/hr)	Increase in steam load (lb/hr)	Efficiency
100	13	23	57%
150	20	41	49%
200	26	59	45%

Steam Demand for CO_2 Desorption

- Steam demand of ~280 lb/h:
  - ~160 lb/h for baseline demand
    - Large systems will be adiabatic
  - ~80 lb/h for sorbent preheating by 60° C
    - For heating 15 kg/min sorbent flow – 50 lb/h steam
  - ~40 lb/h for generating of 20 lb/h steam for injection into the stripper.
- CO_2 desorbed: 24 lb/h – increased at a high capture efficiency
- Sensible heat dominates sorbent heating.
  - Steam/CO_2 ratio: 2 lb/lb; Preheat by heat recovery
  - stripper steam: 0.8 lb/lb CO_2; Goal is 0.5 lb steam/lb CO_2

Lessons Learned at NCCC Testing

- Pneumatic lift operation
  - Disengagement at the top of the adsorber due to bouncy nature of the sorbent.
  - Use resilient material at the point of impact.
  - Used the structural packing as an impact separator.
- Pressure balance inside the column
  - The pressure at the flue gas feed and return points highly variable.
  - Caused instability in the column operation.
  - Pressure could be controlled better by using backpressure control valves.
- Heat recovery step requires pressure balance at the dehydrator stage.

Conclusions

- A CO_2 capture efficiency of 67% was achieved;
  - 90% capture efficiency is achievable by decreasing the sorbent temperature and increasing the adsorber height.
- A CO_2 purity of 93% was achieved;
  - >98% CO_2 purity is feasible if the transition section is modified to have a tall height and narrow cross section.

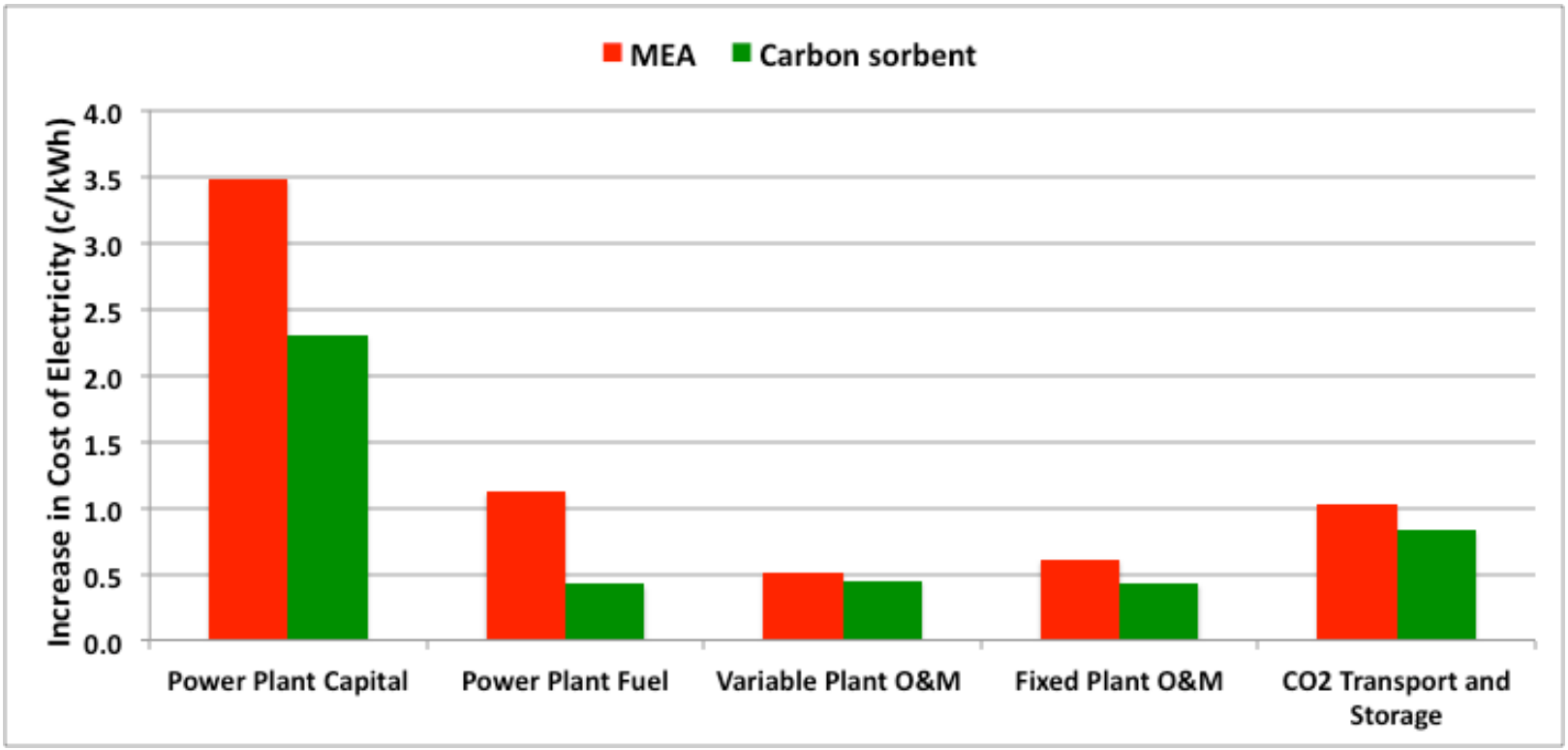
Conclusions (continued)

- Steam demand was larger than anticipated due to severe external heat losses.
  - Data analysis of the data indicates that the heat requirements can be close to the original assumed value of 50 kJ/mole of CO_2 when a more adiabatic system is used.
- Sorbent breakage was mainly due to high velocity impact collisions in the pneumatic transport and disengagement sections.
  - Addition of a soft material at the point of impact reduced the sorbent breakage.

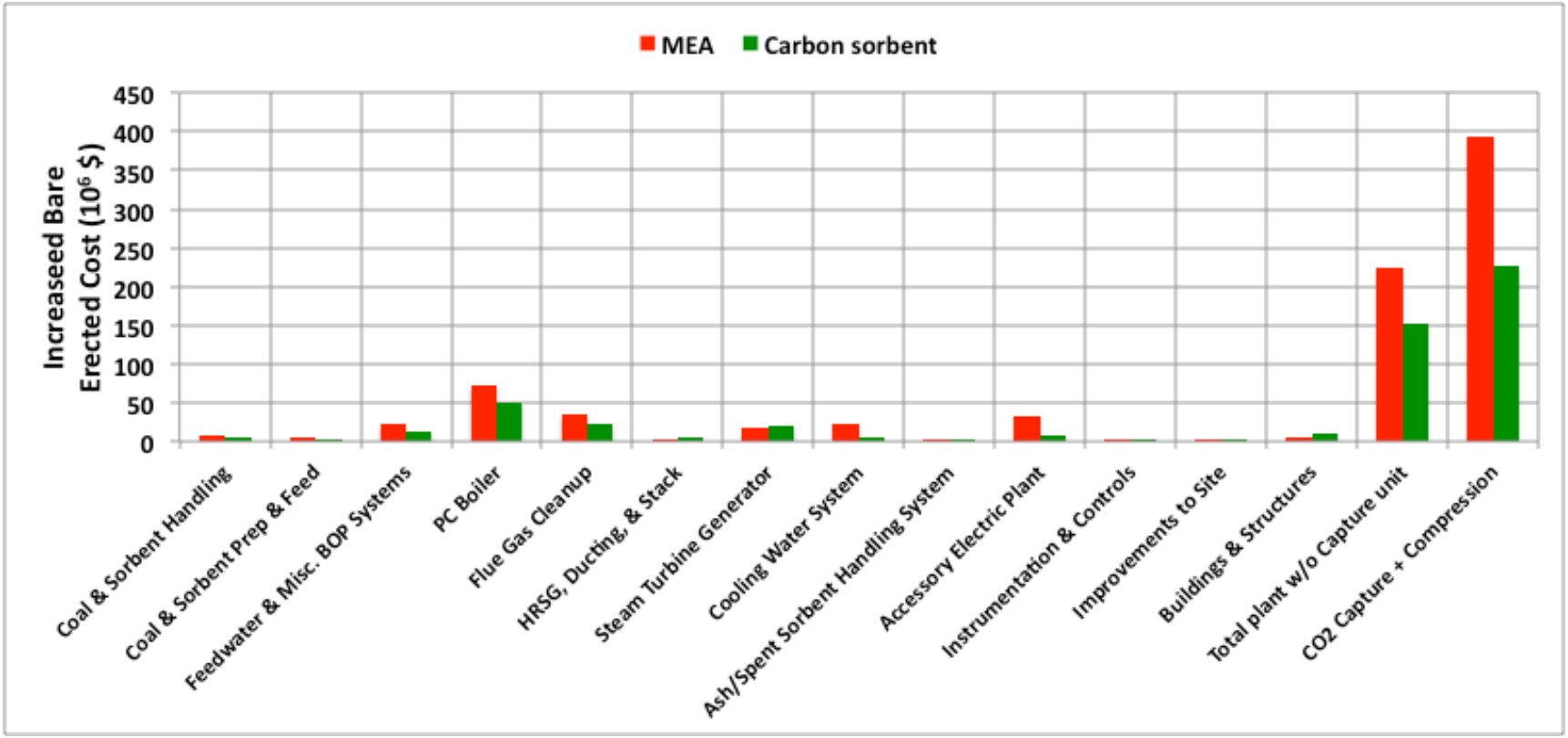
Preliminary Techno-Economic Analysis

- Steam-Pro modeling was used to generate the equipment sizing and heat and material flows.
- Use DOE cost models.
- Base case is an air-fired greenfield supercritical PC plant (660 MWe nominal) with no CO_2 capture.
- Compare a similar-size plant using CO_2 capture with carbon sorbent subsystem.

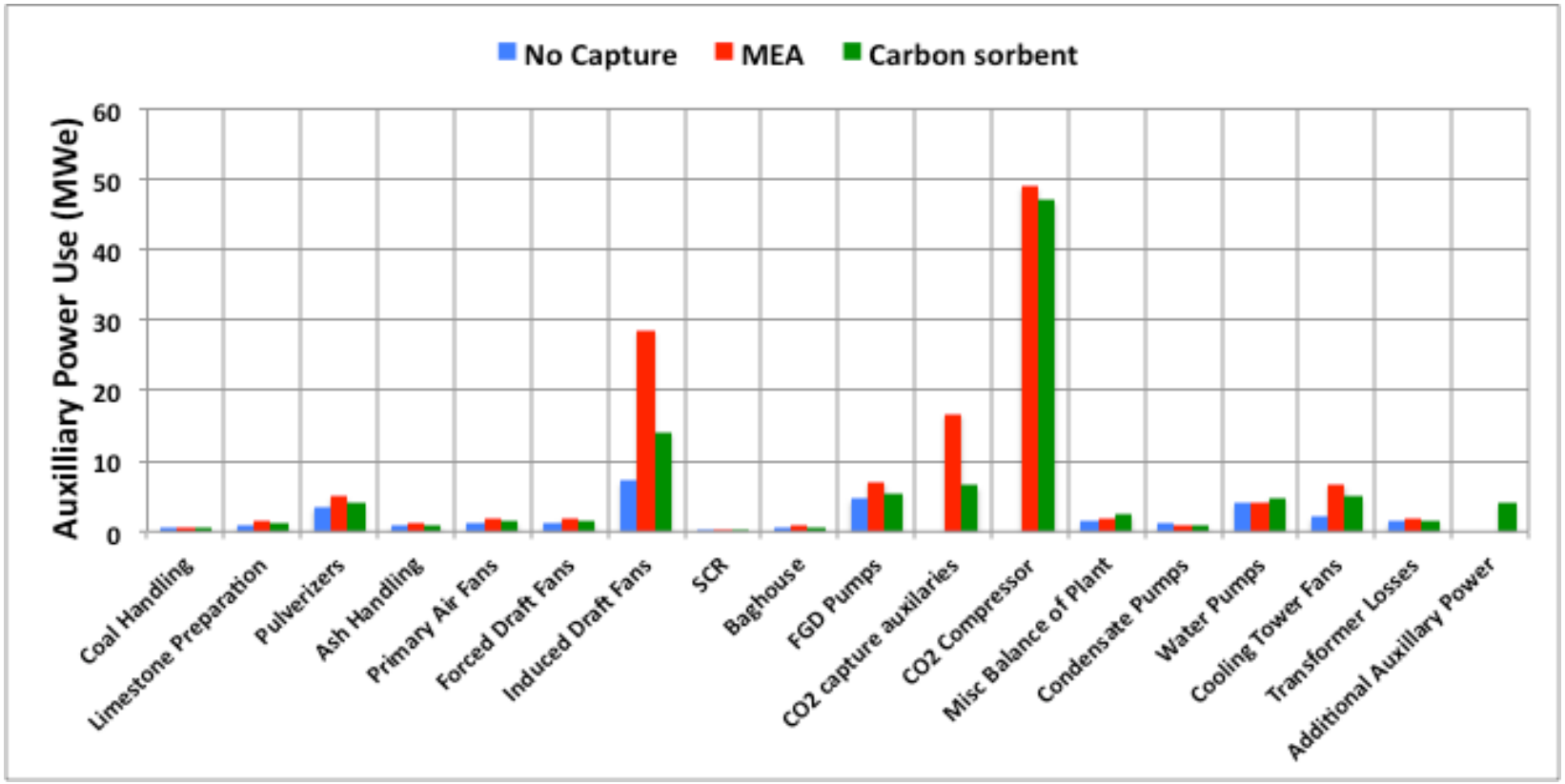
Breakout of factors in ICOE



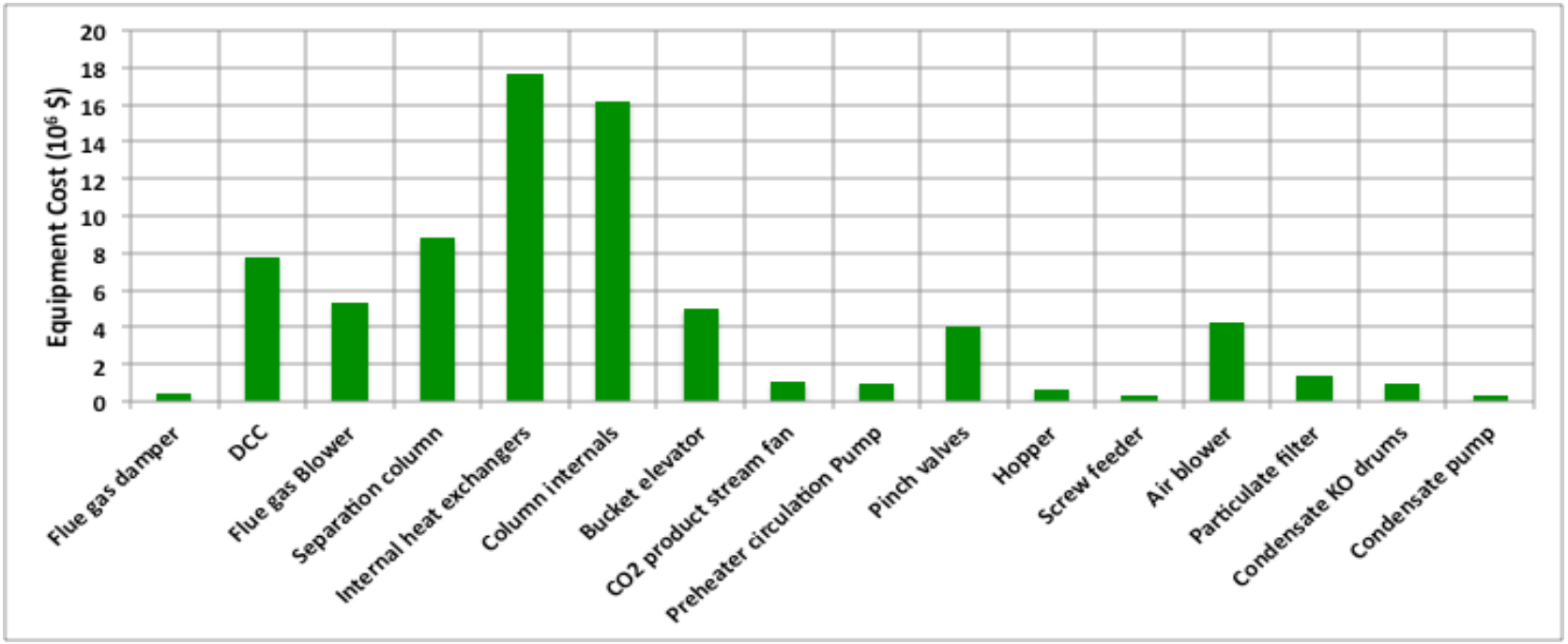
Detail of Power plant capital increase



Auxiliary Electrical Loads



Major Capital Items for Capture Unit



TEA Summary

- Preliminary TEA shows:
  - Increase cost of electricity is mostly due to increased plant CapEx.
  - Power plant CapEx increase is a result of steam use.
  - Capture unit CapEx is dominated by column internals and heat exchangers.

Sorbent Specification

- Specify 2 sorbent formulations for pilot testing
- Evaluate ton-scale manufacturing

Sorbent formulations

Material Designation	N2 BET Surface Area (m2/g)	Description
Baseline (ACS-3)	1100	"Standard" material
ACS-2	950	Modified surface functionality
ACS-3A	1100	Modified surface functionality
Activated ACS-3	1800	Higher surface area carbon

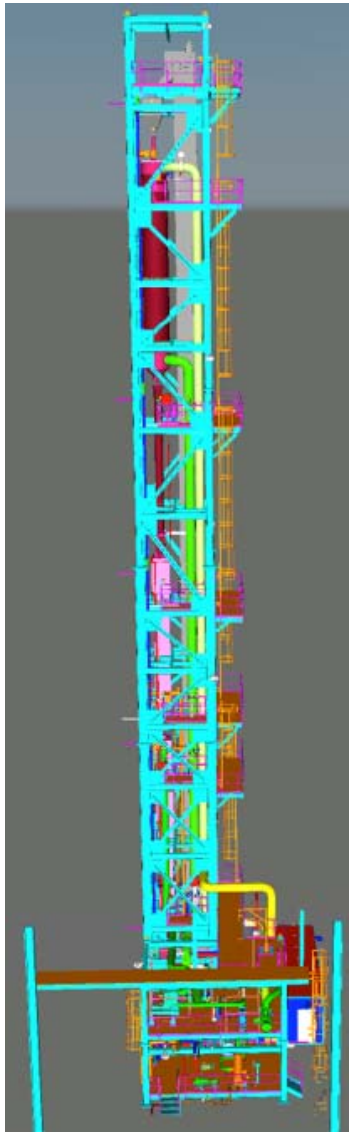
- Lifetime and SO_x/NO_x Sensitivity tests not yet performed

Ton-scale production capability

Pilot Plant Design

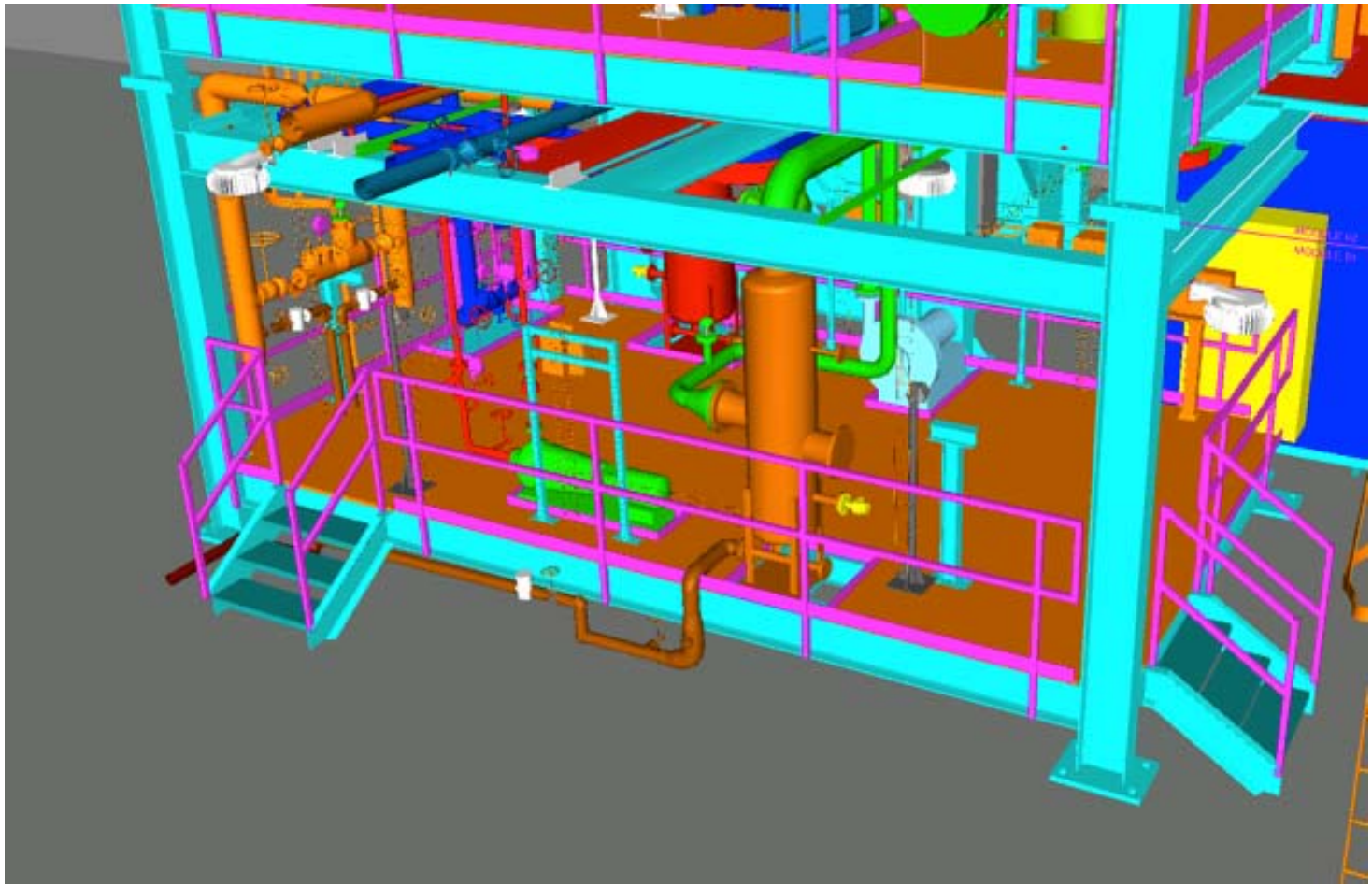
- Basic engineering performed by Linde, including HazOp and Project Safety Review
- Detailed engineering performed by Roeslein & Associates, Inc.

Complete System

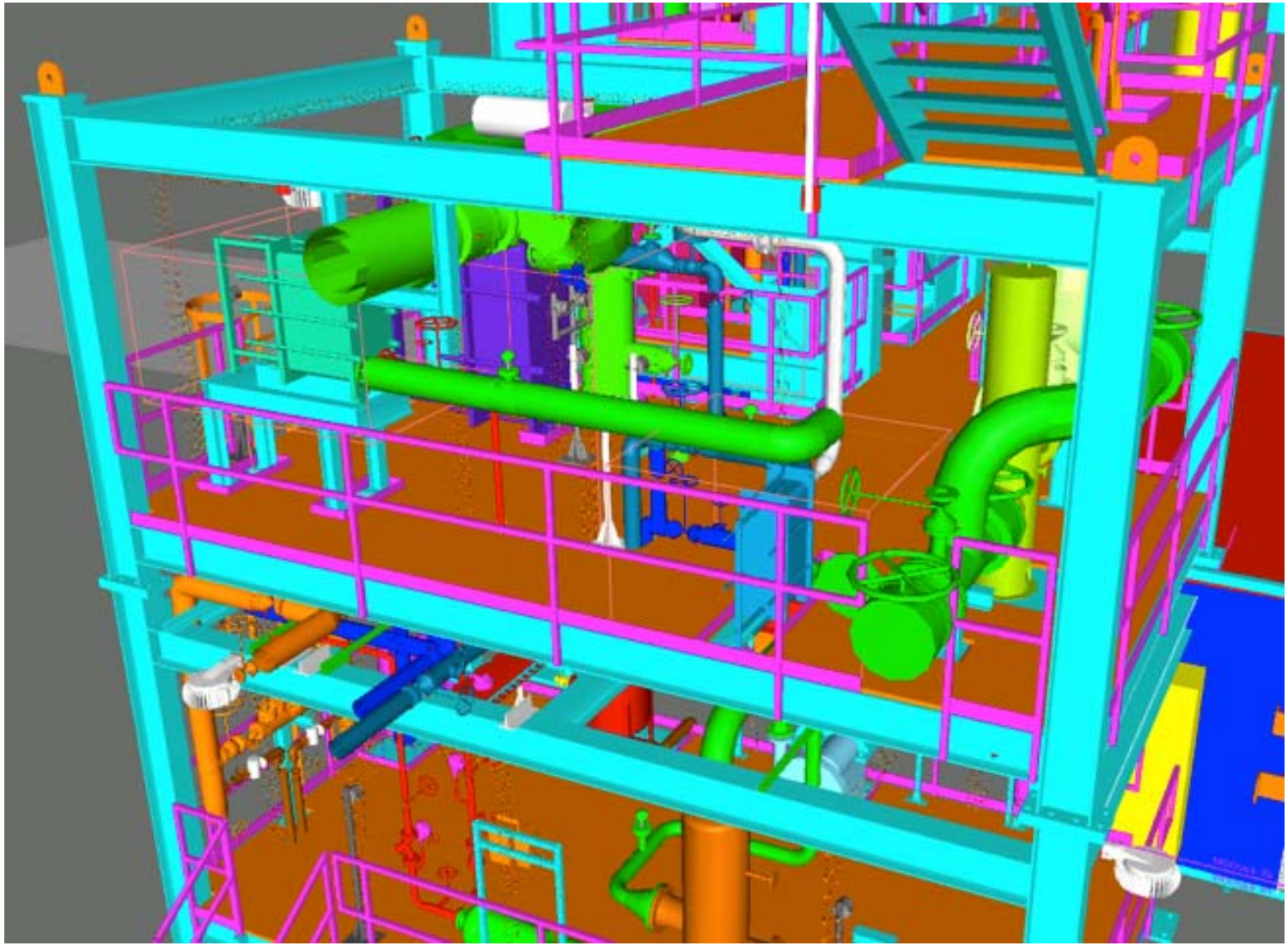


- System Height: ~170ft
- Footprint: Half of pilot bay 2 at NCCC

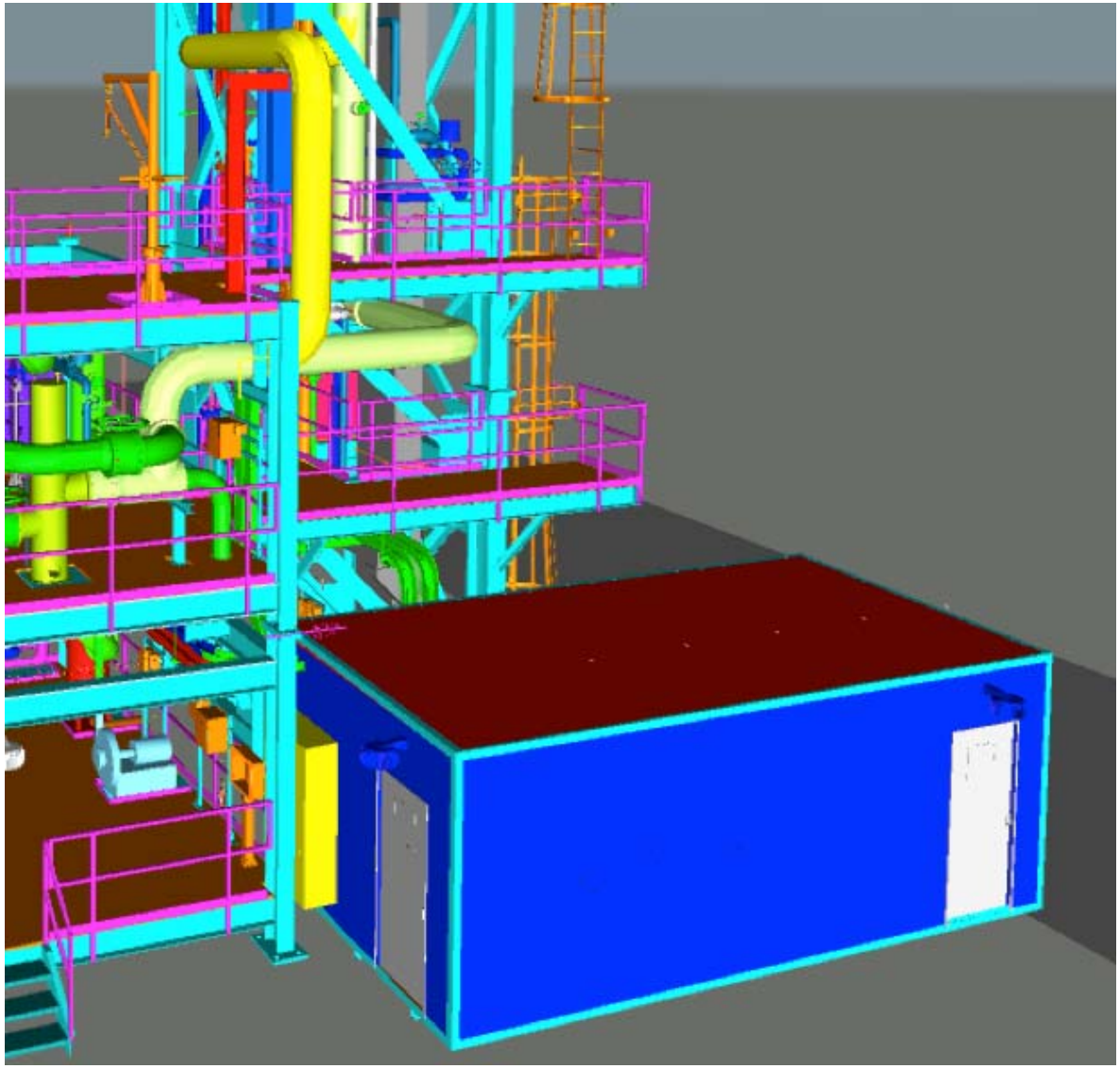
Lower Module



Upper Module



Sample Analysis Shelter



Cost to Construct

	Description	Price	Comments
Project Management, Fabrication, Assembly & Field Installation			
	Project Management & Project Support	$554,579	Includes PM, PC, CM, Expediting, Accounting, Shop Supervision, Quality Control, Safety, & Detailed Engineering
	Structural Steel	$648,307	
	Piping & Supports	$444,419	
	Equipment	$933,326	
	Instrumentation	$240,089	
	Heat Trace & Insulation	$191,221	
	Electrical	$461,386	Includes Analyzers and Sampling Systems
	Consumables	$56,445	
	Assembly (in shop)	$179,509	
	Analyzer Building	$85,481	
	Field Erection	$371,901	
	Subtotal	**$4,166,664**	
Shipping			
	Freight	$105,935	
	Total	**$4,272,599**	

Initial estimate:

BP1: $654K

BP2: $4,594K

Total: $5,248K

Recommendation

SRI recommends that this project be put on hold until the recently announced sale of the Entegris BrightBlack business unit is resolved.