Progress Update on the Carbon-dioxide Absorber Retrofit Equipment (CARE) Program

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Performance Breakthroughs

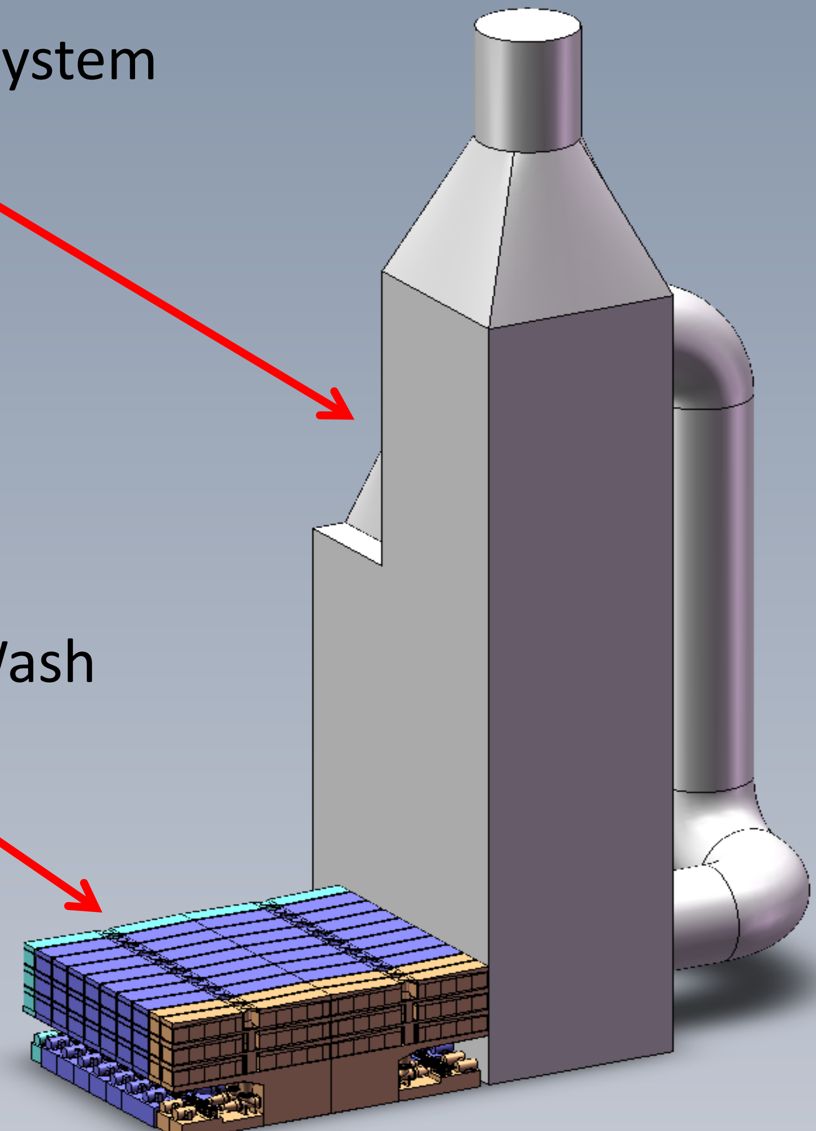
Proprietary Jets

Parameter	Benefit
High flat jet specific surface area: a_s >1000 m^2/m^3; High overall volumetric mass transfer kinetics, 10 x $K_L a_s$ over conventional systems	High process efficiency; Greatly reduced column footprints; Reduced column/orifice manufacturing and lead time costs
Low ΔP_{Gas} ~ 0.03 psi/ft; Low ΔP_{Liq} = <10 psi	Reduced hydrodynamic/ auxiliary power
Aerodynamic shaped jets	Reduced liquid entrainment in the gas flow
Factory fabrication of modular/serviceable units	Standardization/lower cost fabrication; Rapid scaling per customer needs

NeuStream®-C Absorber
Size Comparison

Commercial Carbon Capture System
SO_2 and CO_2 Absorber Towers
~ 306,000 ft^3

NeuStream® Absorbers:
CO_2, FGD, Polish and Amine Wash
~ 54,000 ft^3



> 80% decrease in absorber size!

CARE Program

Project Objectives

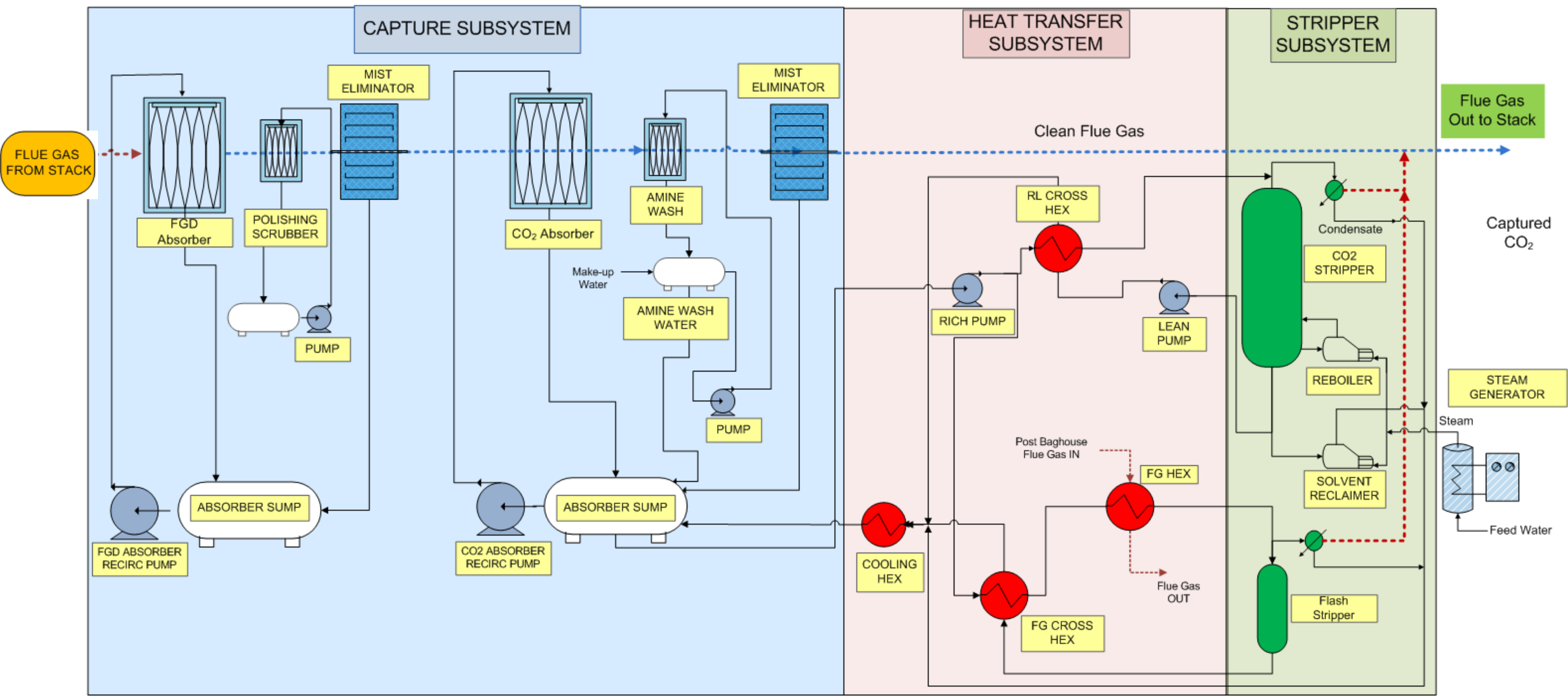
- Design and fabricate 0.5 MW system
- Minimize parasitic power through efficient design
- Demonstrate
  - 2 month steady-state operation with Multi-Stage Absorber and Innovative Stripper
  - 90% CO_2 capture efficiency utilizing best available solvent (piperazine at 8m)
- Show unit traceability/scalability to commercial scale – Final TEA

CARE Program
Partners

- DOE/NETL
  - Award FE-0007528
  - Funds: $7,164,192 / 32 mo
  - NETL PM: Andrew O'Palko
- Energy and Environmental Research Center (EERC)
  - Techno-Economic Feasibility Study
  - Environmental Health & Safety risk assessment for carbon capture and storage
- URS – Bob Keeth
- Colorado Springs Utilities
  - Host Site (Martin Drake Power Plant)
  - Significant Cost Share
- UT Carbon Management Program
  - Dr Gary Rochelle
  - Dr Eric Chen
- Service Partners
  - Althouse Electric
  - Swartz Electric
  - Vision Mechanical
  - ICM Construction
  - Palmer Holland/Huntsman (Chemical Providers)

CARE System Design

Process Flow Diagram



- **NSG flat jets are incorporated into the FGD, Polishing FGD, CO_2 Absorbers, Amine Wash, and Stripper**

CARE System
Enclosure

Enclosure (with insulation) installed around the test stand

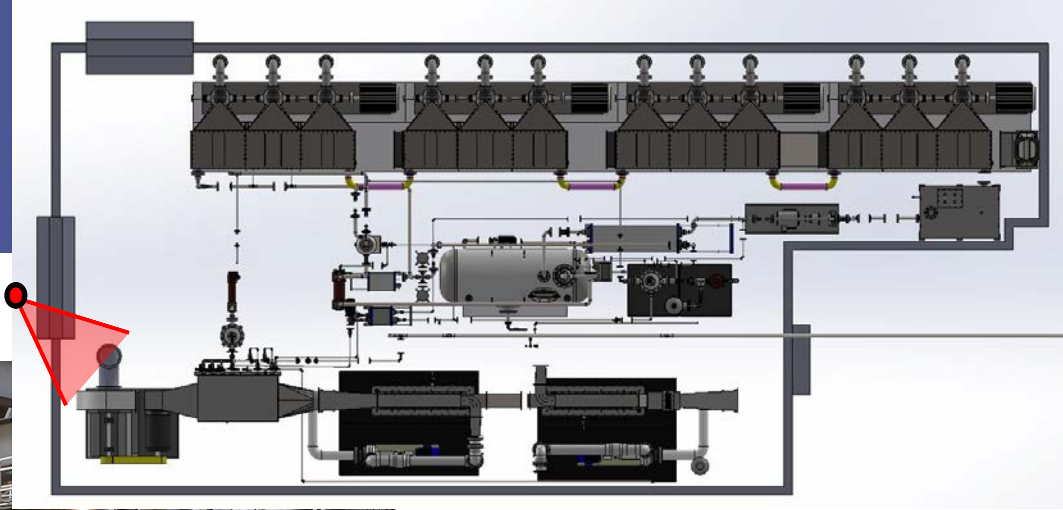
Climate Controlled
- Conc Pz Solvent

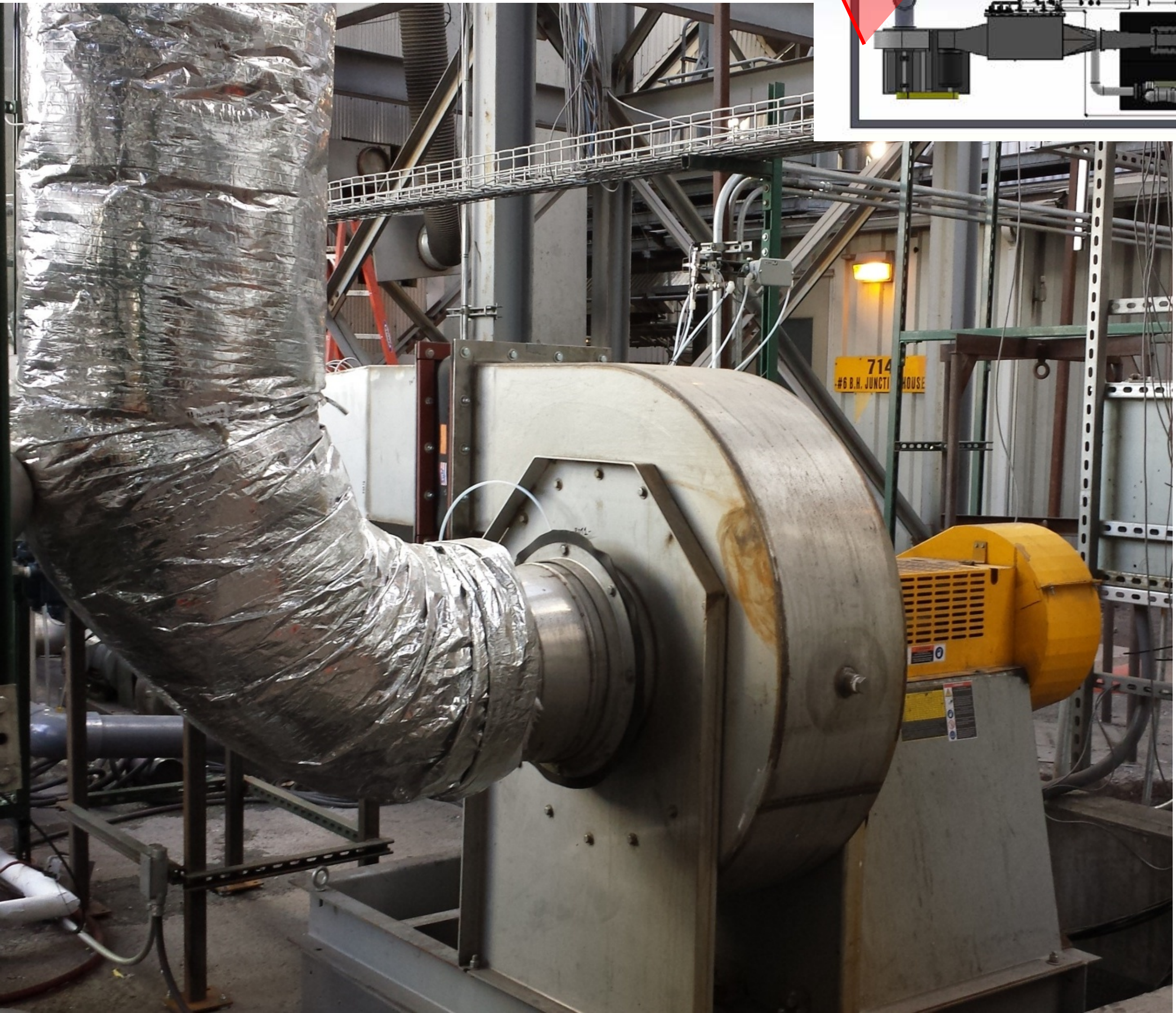
Limit Access

Hazard Containment

Capture Subsystem

FD Fan

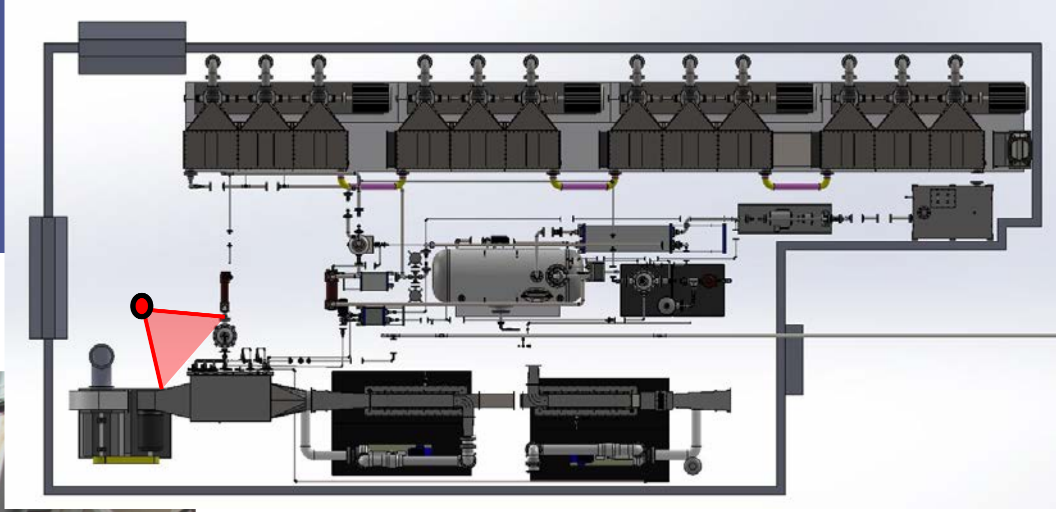




- Forced Draft Fan
- Connected to inlet ducting
- VFD controlled
- Flow and composition verified using Airtech Environmental Services Inc.

Capture Subsystem

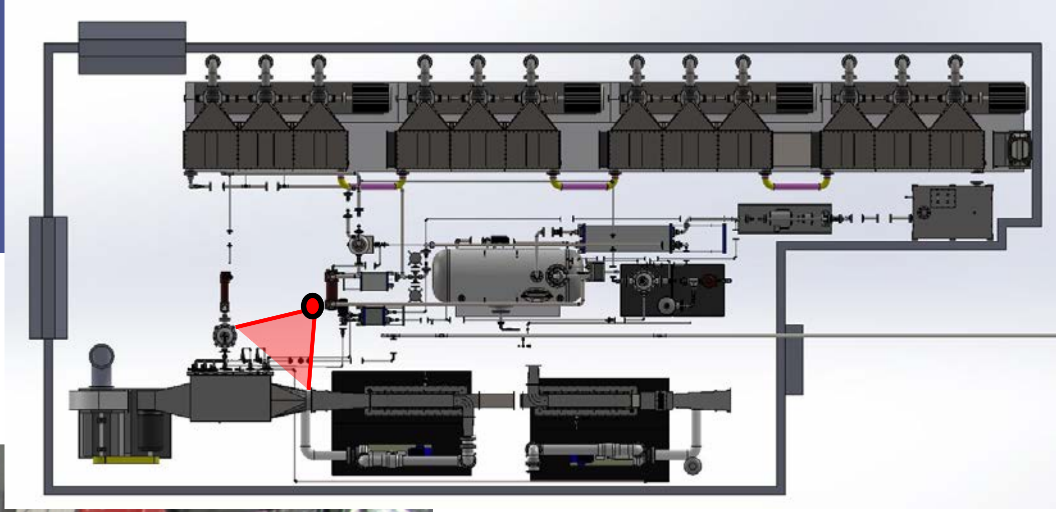
FGHR HEXs



- Flue Gas Heat Extraction
- Re-Heat HEXs used to bring flue gas to representative temperature (350ºF)
- Steam from electric boiler produces heat

Capture Subsystem

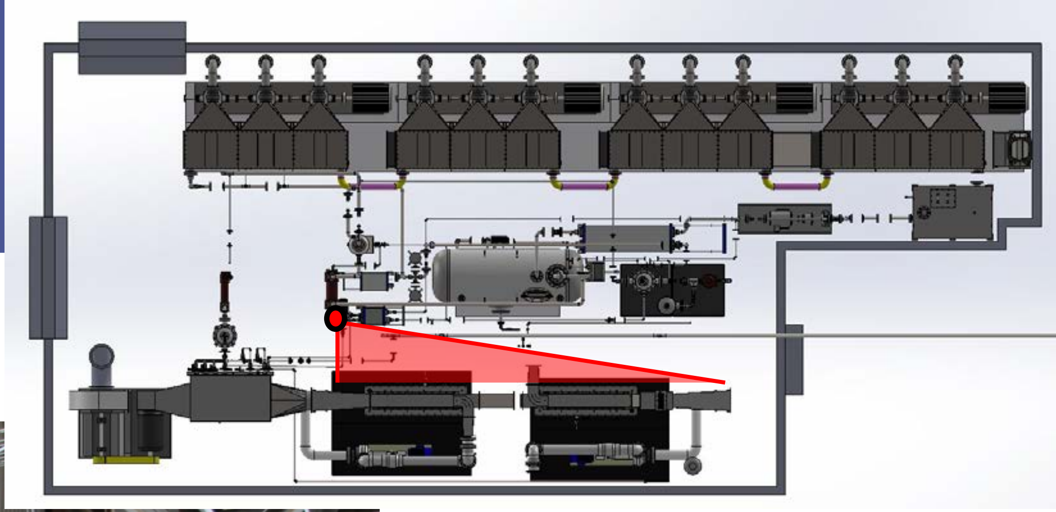
FGHR HEXs



- Flue Gas Heat Extraction
- Solvent HEXs extract heat and offset steam use

Capture Subsystem

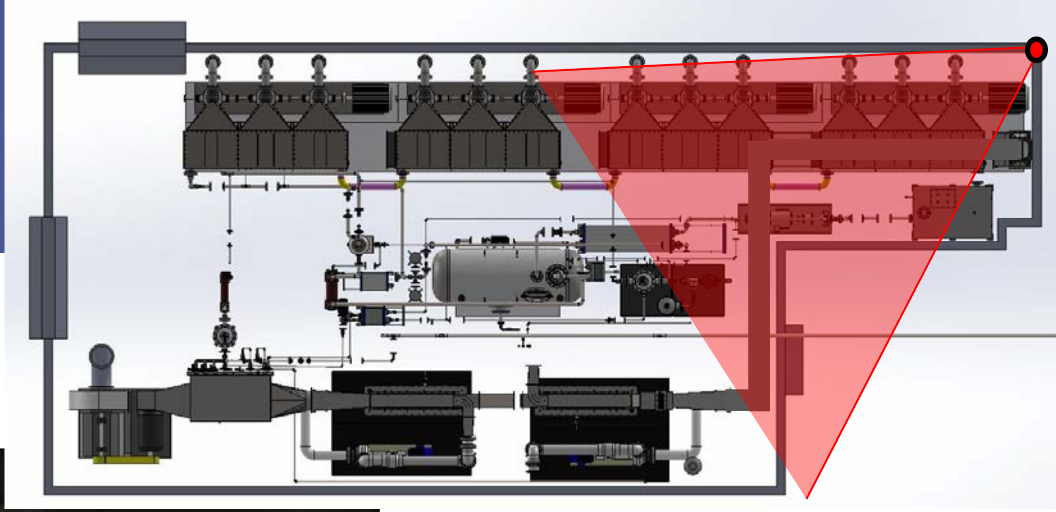
NeuStream™-S FGD



- Existing equipment carried over for use on CARE
- 2 stages of SO_2 scrubbing
- No sorbent processing system on FGDs

Capture Subsystem

Ducting to CO_2 Absorbers

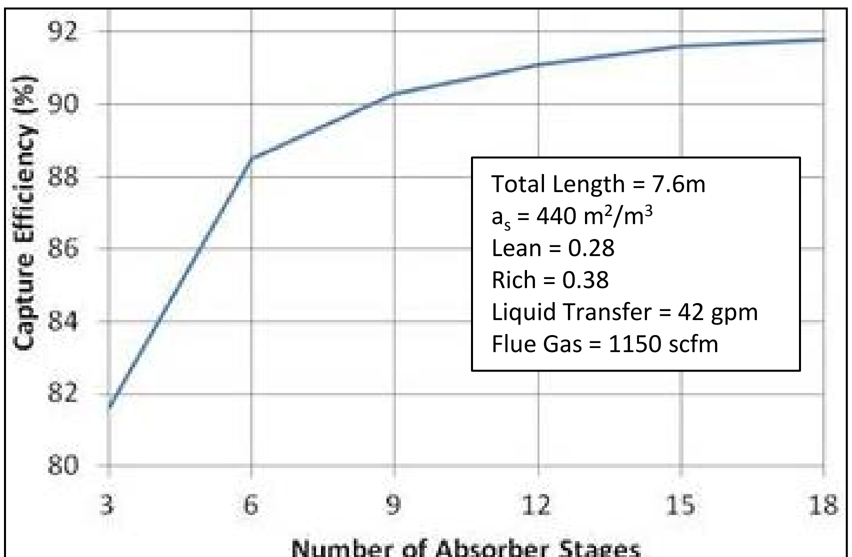


- Ducting to CO_2 absorbers
- Connects FGD mist eliminator to CO_2 absorbers

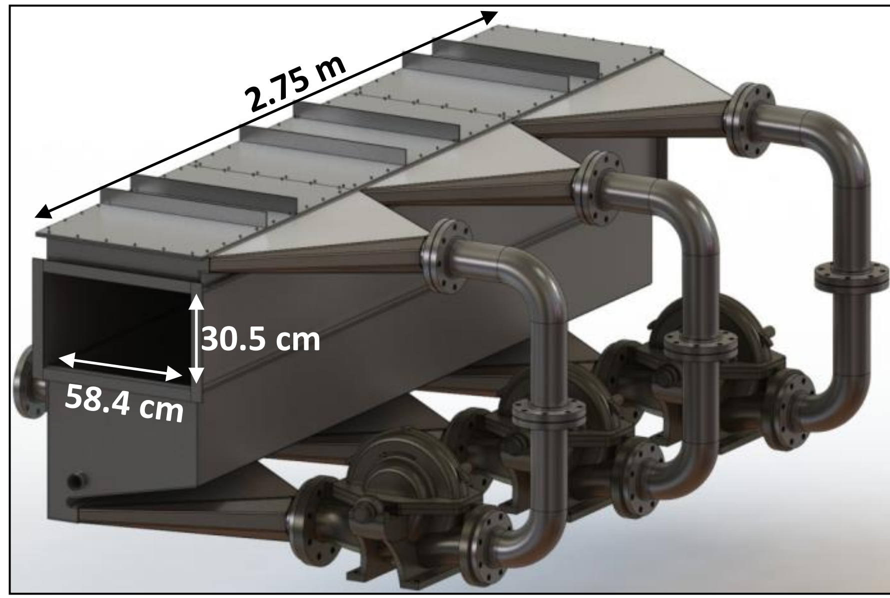
Absorber Module

Absorber Design

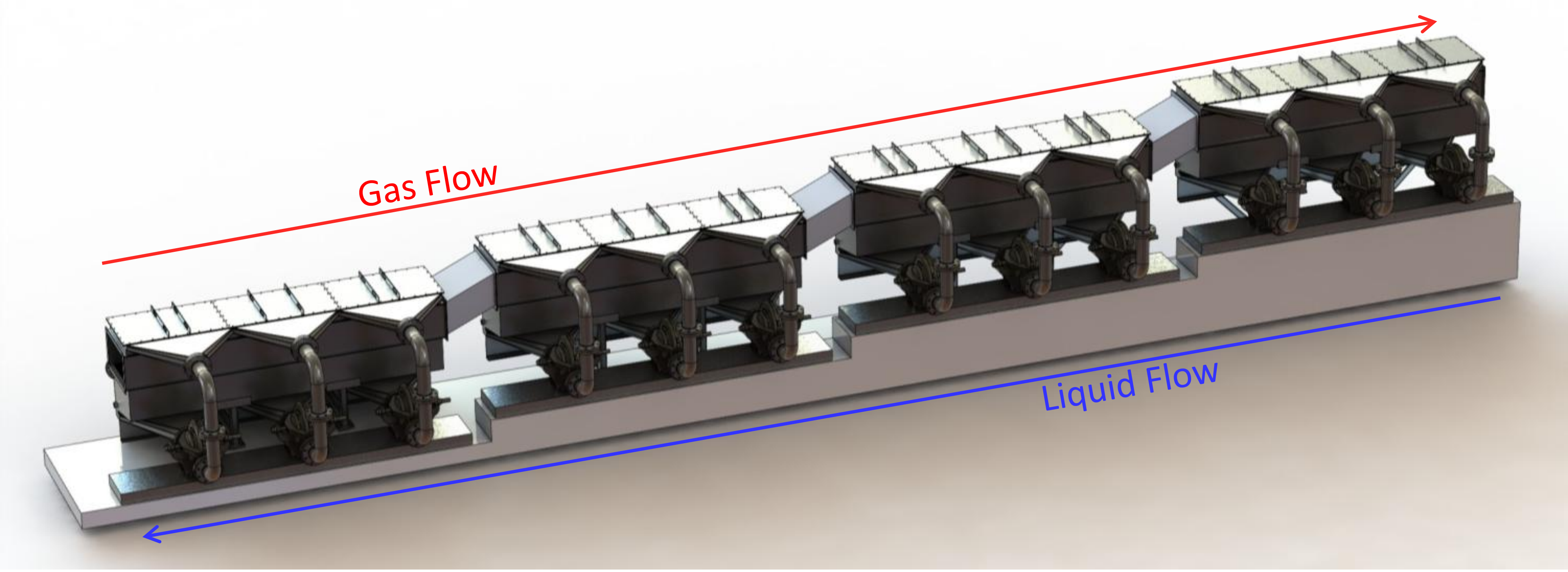
Parameter	Value	Units
Stage Width	58.4 (23)	cm (in)
Stage Height	30.5 (12)	cm (in)
Stage a_s	440	m^2/m^3
Stage Length	2.75 (108.3)	m (in)
Capture Efficiency	90%	
Number of Stages	12	



4x Absorbers at 2.75 m each = 11 m Total Length



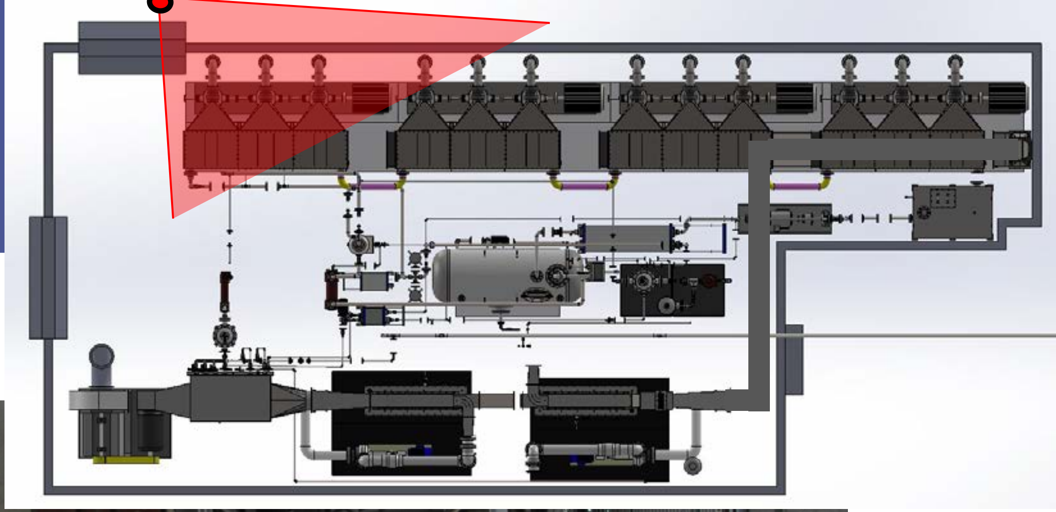
Absorber Module
90% Capture of 0.6MW

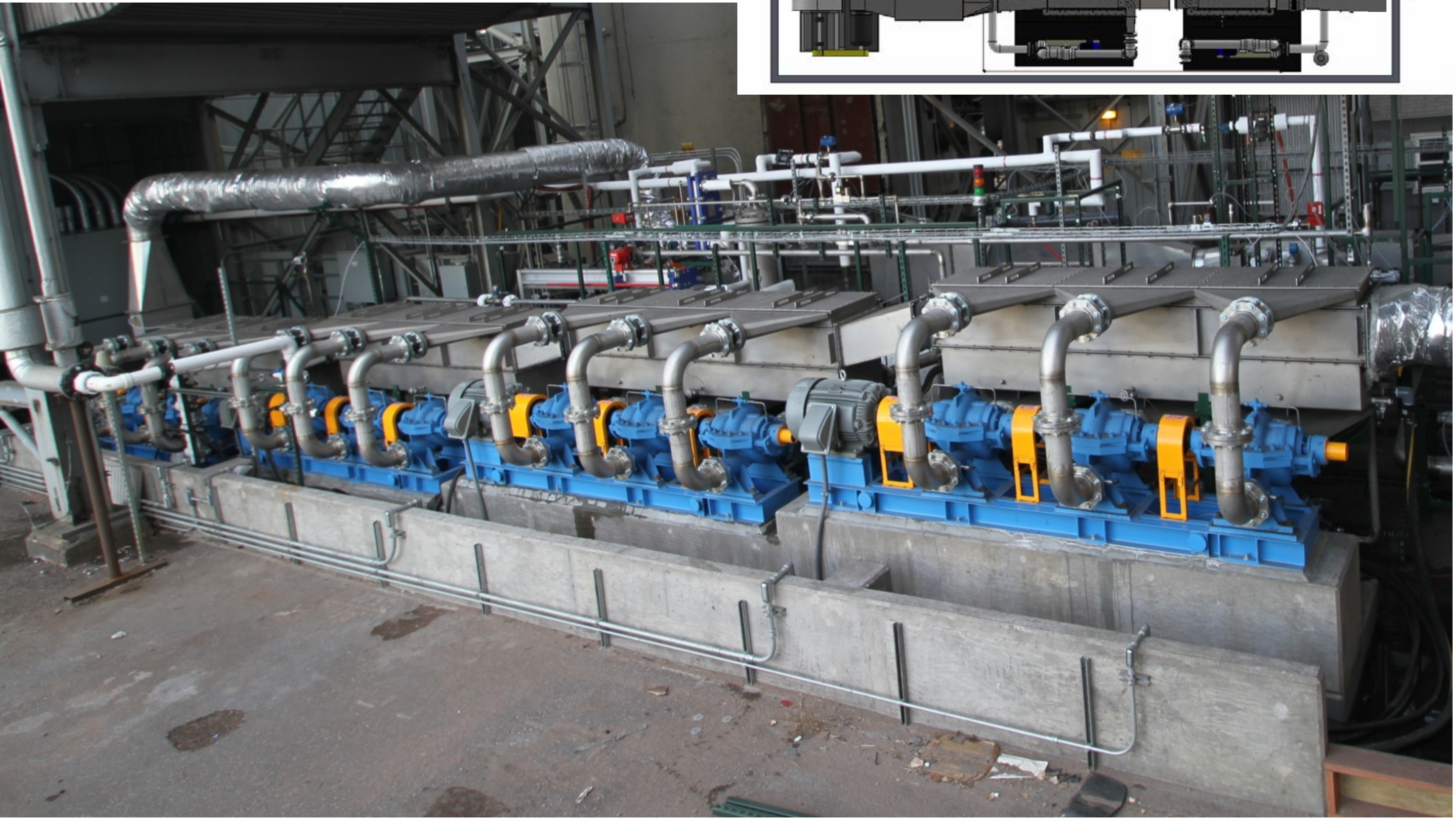


- At CSU's Drake: 2300 SCFM/MW, 12.5% CO_2 and 0.8 atm requires **11 meters** with 12 stages to get the necessary 2.2 sec residence time
- Using NETL Case 9/10: 2007 SCFM/MW, 13.5% CO_2 and 1 atm requires **7.6 meters** with 12 stages to get the necessary 2.2 sec residence time

Capture Subsystem

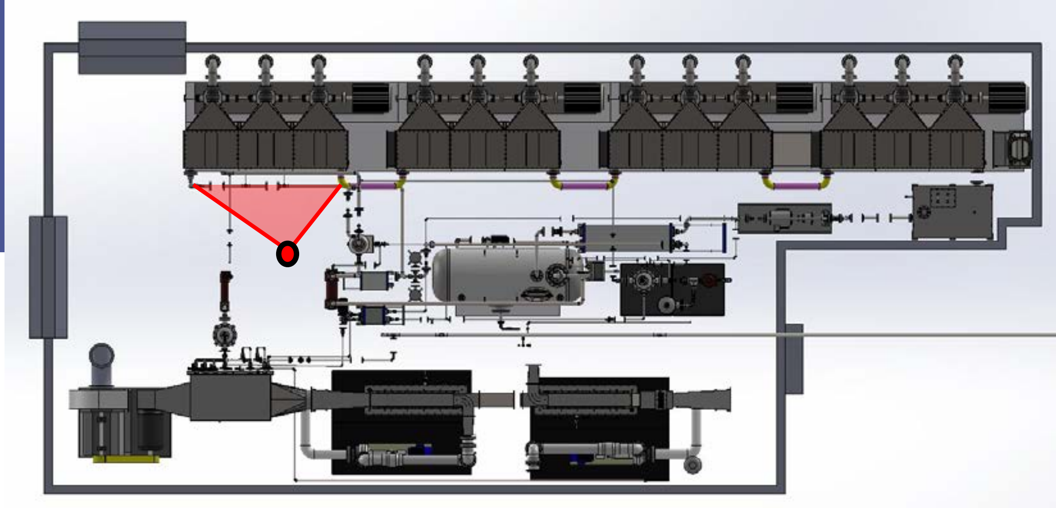
CO_2 Absorber Train





Capture Subsystem

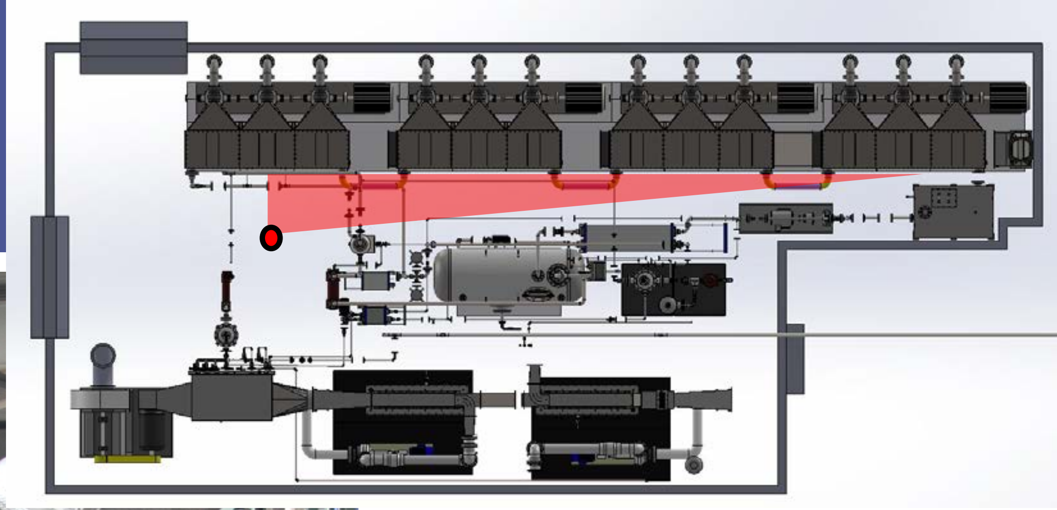
Absorbers

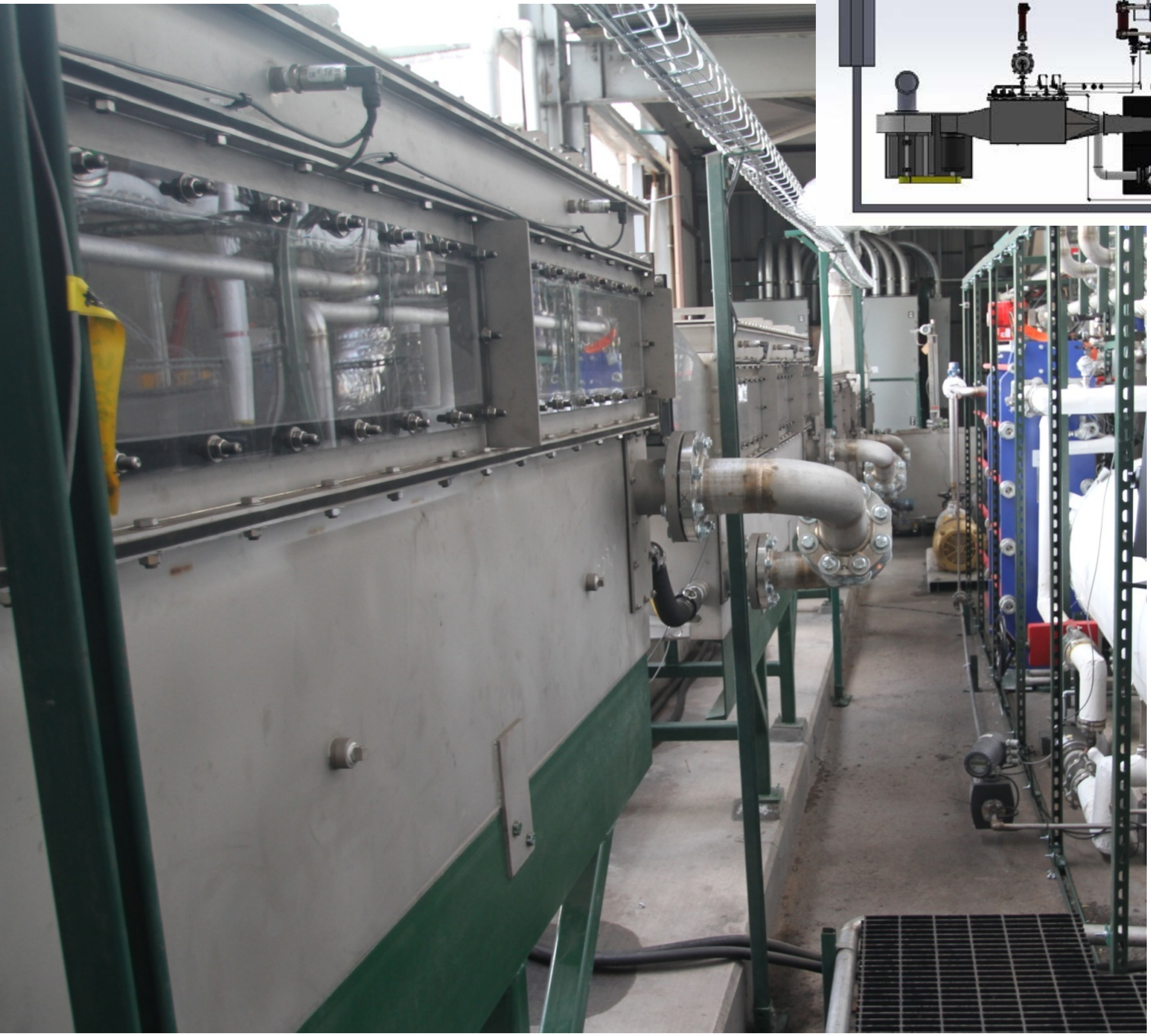


- (1 of 4) Single Absorber Module
- Three stages incorporated into design

Capture Subsystem

Absorbers

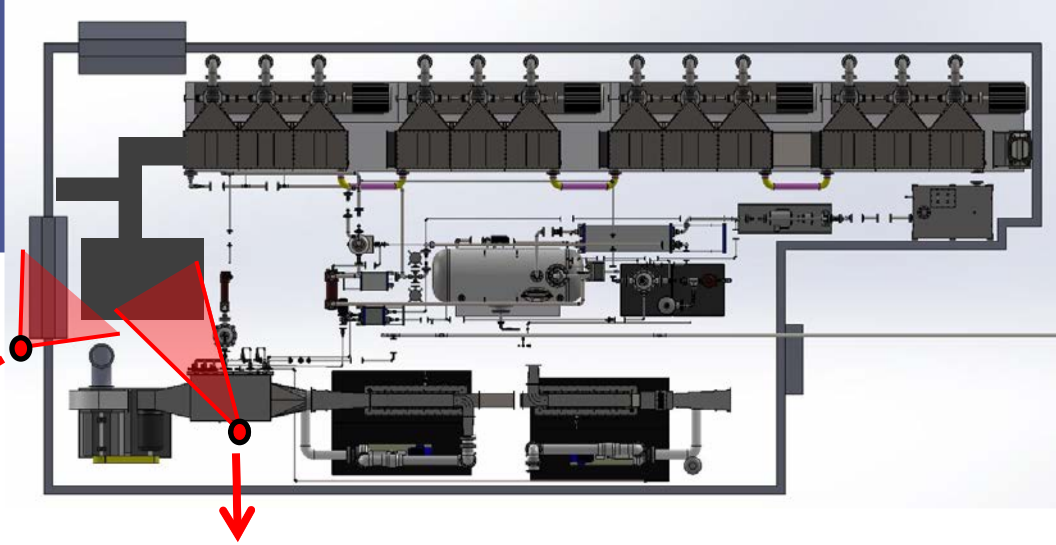




- Gravity feed overflow through 4” pipes to maintain liquid level in absorbers

Capture Subsystem

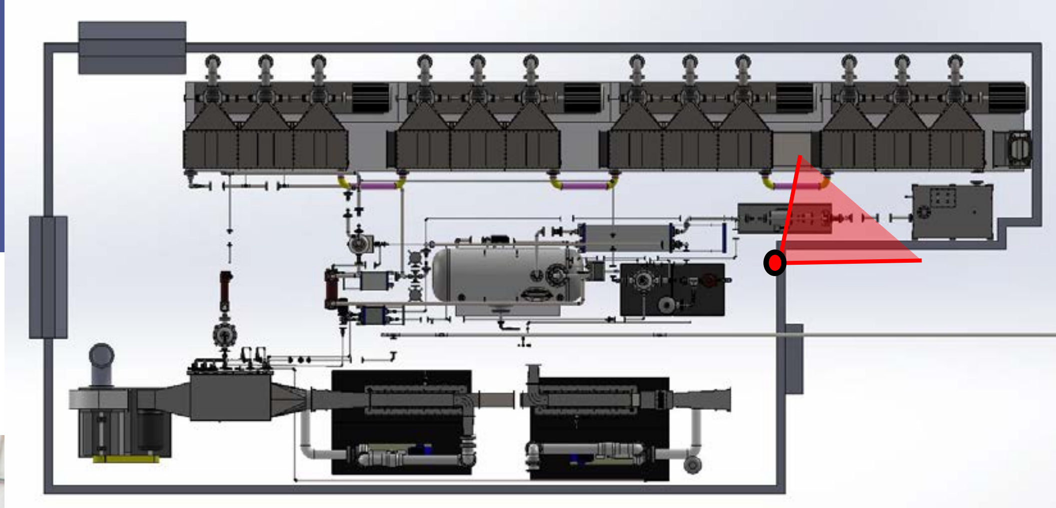
Amine Wash



- Existing test stand that required some slight modifications (plumbing changed from PVC to stainless)
- Expected reduction of Amine slip to <1ppm

Capture Subsystem

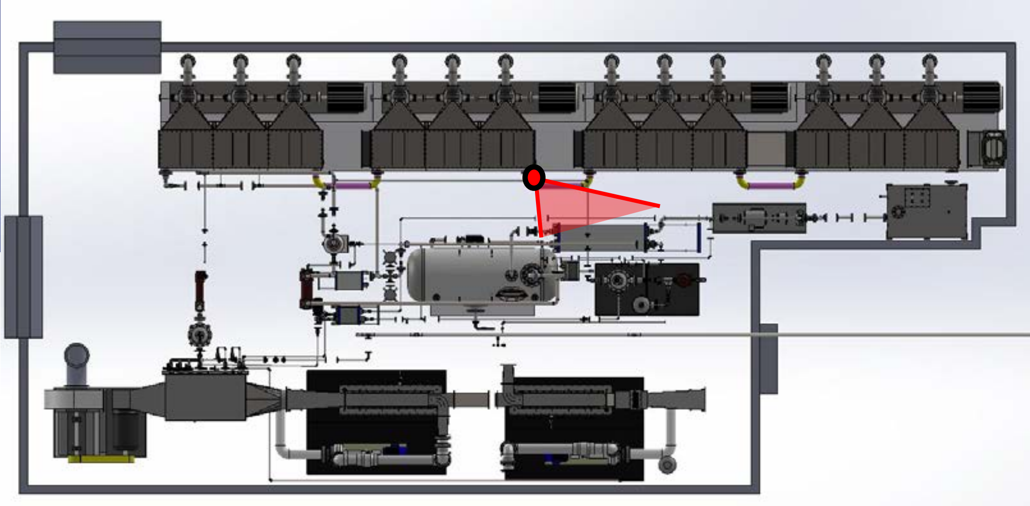
Rich Overflow Tank and Pump



- Absorber 4 – overflows into the rich overflow tank
- The rich overflow tank is a solvent holdup vessel for the system
- Rich pump pulls from rich overflow tank and pushes solvent through the cross HEX to the Stripper

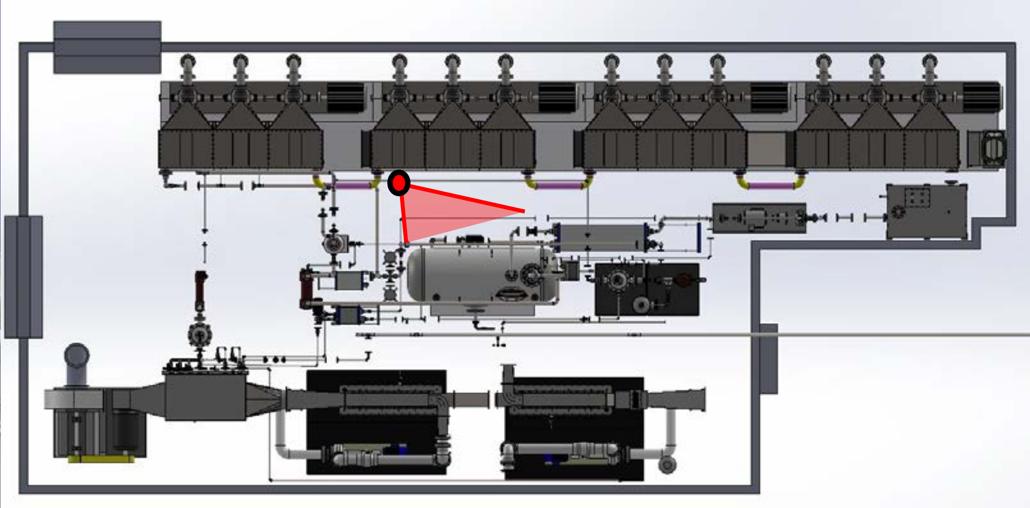
Heat Transfer Subsystem

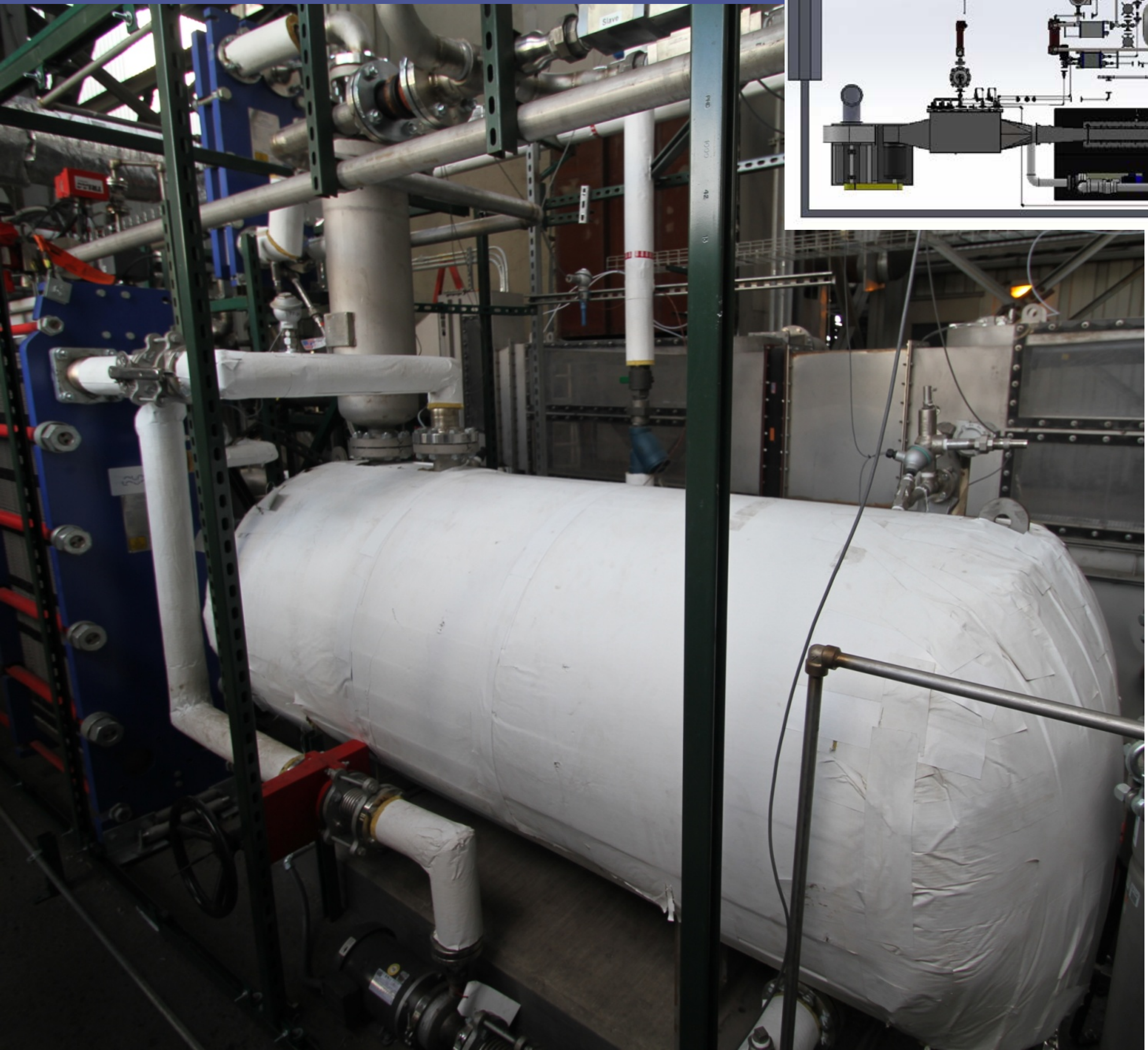
Main Cross HEX



- Primary Cross HEX
- 10°C approach temperature
- Maximum operating pressure of 200 PSIG

Stripper Subsystem
NSG Stripper





- Innovative stripper design – designed with Dr. Rochelle
- Stripper operational temperature of 150°C
- Stripper operating pressure of 8 bar

Mar – April Check Out Testing

- Validated performance of all major components
- Check out testing on single stages with various nozzle configurations
  - Validation of previous small scale DVT work
  - Tested new nozzles
  - Tested various configurations of the nozzles
- Verify sensor performance via mass balance closures
  - Solvent working capacity vs Absorber capture efficiency vs Stripper outlet (Mass Flow)

May 1, 2014 Test Data

- 0.5MW gas flow through the CARE System
- 6m Piperazine solvent
- Lean Loading: 0.28 mol CO_2/mol Alk
  - 8bar Stripper Pressure
  - 150C Stripper Temperature
- 90% capture efficiency based on flue gas monitors
- 88% capture efficiency based on working capacity of the solvent
- Preliminary Results… <u>System Not Optimized</u>

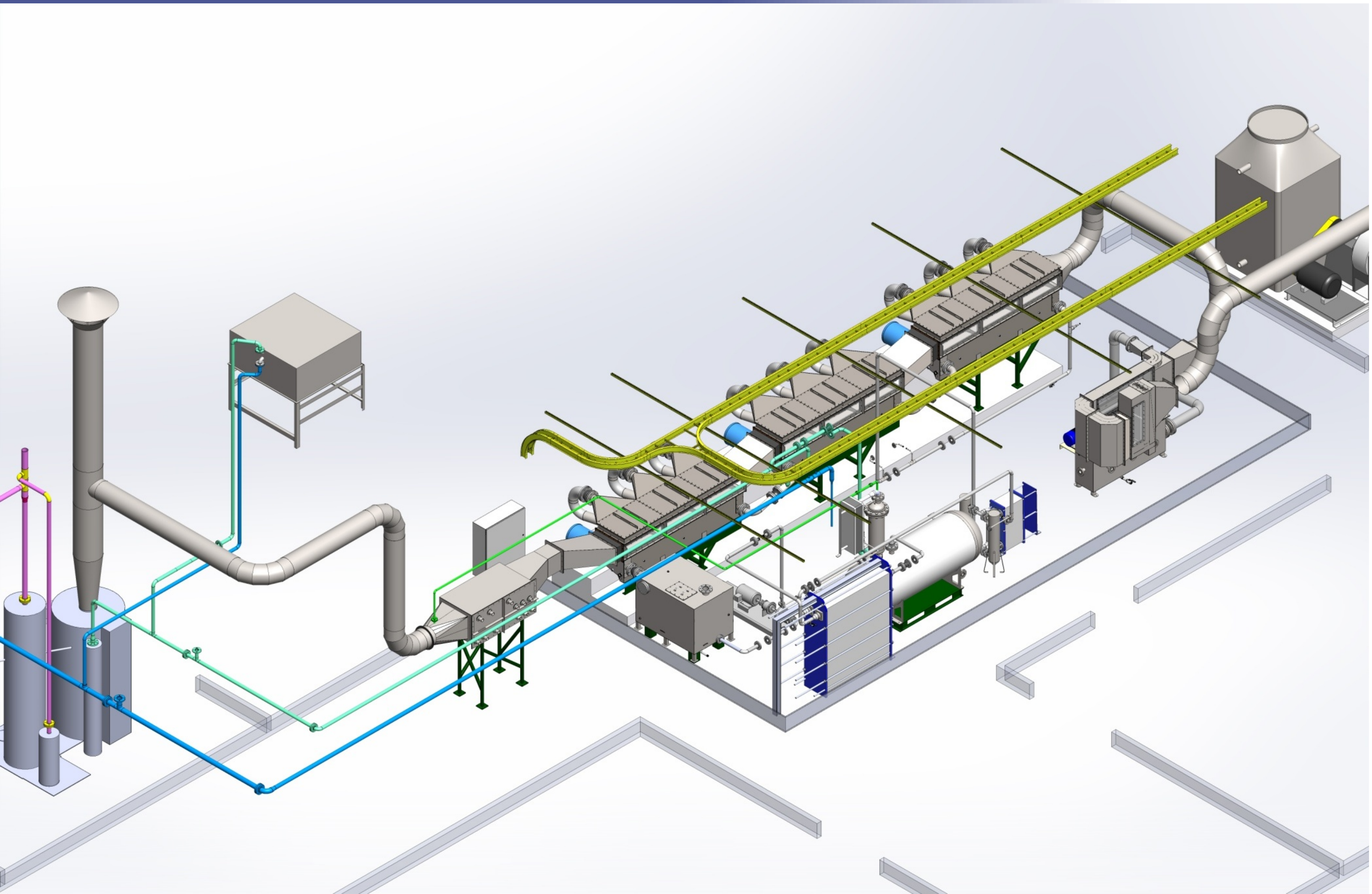
May 5, 2014

- Fire at CSU's Martin Drake Facility
- All three units (5, 6 and 7) taken offline due to fire damage
- Unknown timeline on return to service – Unit 7 still down to date

Revised BP3 Objectives

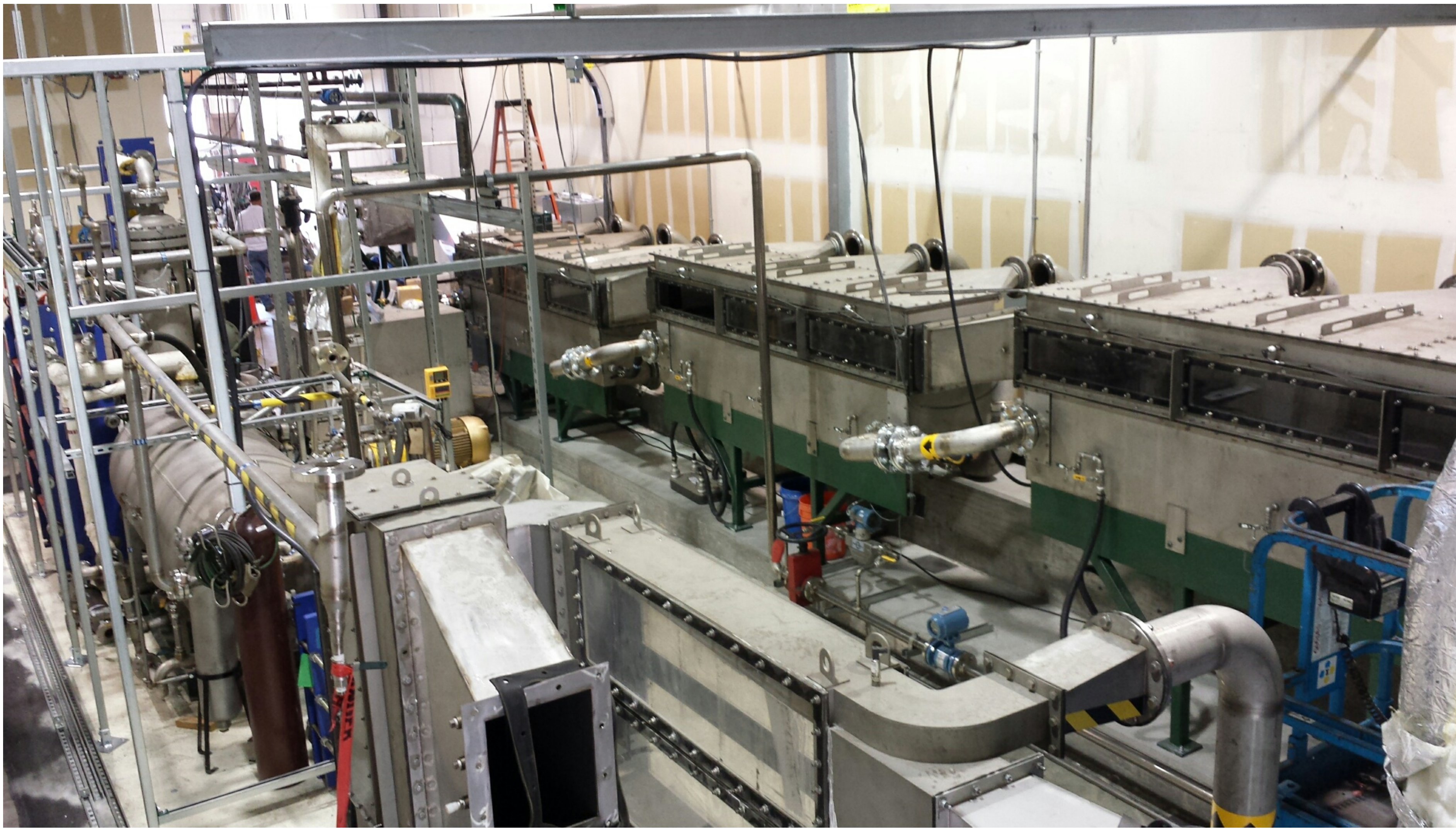
- Move system to NSG facility
  - Move ¾ of the absorbers
  - Simplify the system (no FGD, NOx Control, Flue Gas Heat integration)
  - Run on simulated Coal Flue gas (NG boiler with CO_2 recycle)
- Improve NSG Technology to further drive down costs through lower parasitic power
  - Bench Scale R&D
  - Promising technologies are integrated into the LARGER scale
- Demonstrate capture with multiple (≥3) solvents
  - Solvent agnostic technology
- Update System Cost for TEA at close of BP3

Installation at NSG



Installation at NSG

Installation at NSG



Technology Development Test Stand

- ~100 kW size
  - Single stage absorber
  - 10-20% Carbon Capture Efficiency
  - Capture and regeneration capability
- Solvent Testing
  - Needs 50gal
  - First Approx. on Performance
  - CO_2 Solutions, Piperazine tested
    - Can't share CO_2 Solutions' data per confidentiality agreement
- Technology Testing
  - Multiple Nozzles and Nozzle Configurations
  - a_s ~ 800 m^2/m^3 achieved
  - Working on design to increase jet length from 12" to 36" at high a_s

CAREtoo System

Test Plan/Schedule

- June-Nov: Bench Scale Testing on Technology and Solvents
- Aug-Sept: Acceptance/Shakedown testing of CAREtoo
- Sept-Nov: Integrating and testing technology improvements
- Oct-Jan: Solvent Testing (2-3 weeks per)
  - Concentrated piperazine (6m-7m)
  - CO_2 Solution's Solvent
  - Monoethanolamine (MEA)
  - Any others?
- Jan: Program Closeout (BP4 - move back to Drake for completion of original objectives)

CARE
NSG's Carbon Capture Pilot Program

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