Status of the Carbon-dioxide Absorber Retrofit Equipment (CARE) Program

2013 CO_2 Capture Technology Meeting

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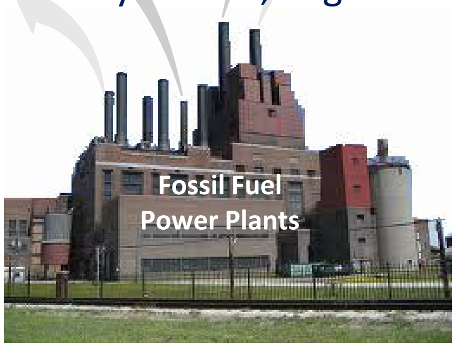
NeuStream® Pollution-to-Products™ Systems

Pollutants

- Sulfur Oxides (SO_X)
- Nitrogen Oxides (NO_X)
- Carbon Dioxide (CO_2)
- Particulates (PM)
- Heavy Metals, Organics



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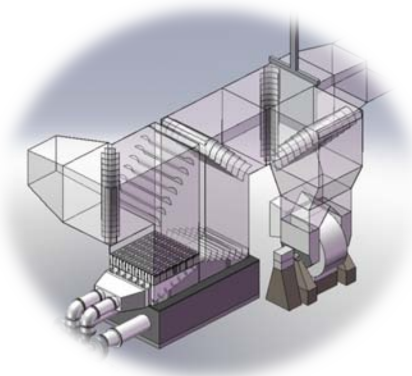
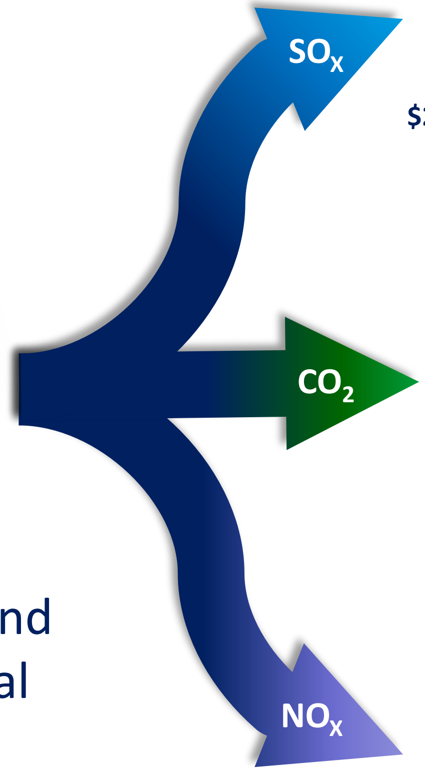
NeuStream®

EDISON AWARDS 2013 NOMINEE



Pollutants captured and transformed into vital industrial products



Industrial Products


Sulfuric Acid $2.3M/yr*


Gypsum $0/yr*

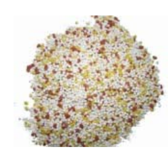

Fertilizer $12M/yr*


Enhanced Oil Recovery $867M/yr*

Fertilizer $1.5B/yr*


Rare Earth Metals $59M/yr*

Nitric Acid $3.8M/yr*


Fertilizer $5M/yr*

>$1 BILLION revenue from P-to-P from a single 550MW coal plant*

Benefits of High Surface Area Jets for Pollution Control

Side view

Gas flow
(cross flow)

View along gas flow

Gas flow

Parameter	Benefit
High specific surface area: a_s >1000 m^2/m^3; High volumetric mass transfer kinetics, 10 x $K_L a_s$ over conventional systems	High process efficiency; Greatly reduced column footprints
Low ΔP_{Gas} ~ 1inWC/m; Low ΔP_{Liq} = <6 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

Flat Jet Gas-Liquid Contactor

- Advantages:
  - Reduced absorber volume due higher contact area
  - Horizontal (gas flow) orientation simplifies installation
  - Ability for turndown of system
    - Vary gas flow through system 4-8 m/s
    - Turn off stages of absorption

- Challenges:
  - Maintaining a high contactor surface area AND a manageable parasitic power

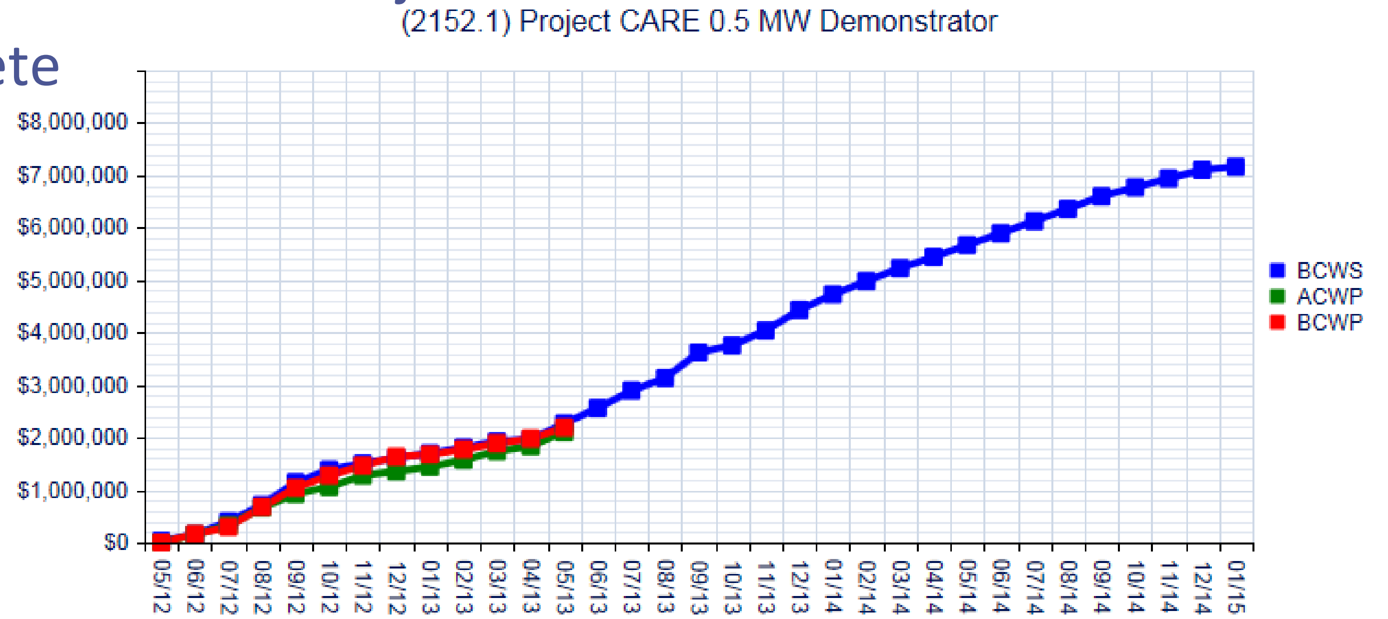
CARE Project Overview

- Project Objectives
  - Design and Fabricate 0.5 MWe Carbon Capture System
    - Demonstrate NSG flat-jet gas-liquid contactor as CO_2 absorber
    - Minimize system parasitic power through efficient design
  - Demonstrate
    - 2 month steady-state operation with Multi-Stage Absorber and Stripper
    - 90% CO_2 capture efficiency
  - Show unit traceability/scalability to commercial scale
- Partners:
  - DOE/NETL
  - Colorado Springs Utilities (Host Site, Resource Provider)
  - EERC (TEA, EH&S, Consulting – System Integration)
  - Mr Robert Keeth of URS (Consulting – Construction/Installation)
  - Dr Gary Rochelle and Dr Eric Chen of UT (Consulting – Solvent Regeneration)

Project Overview:

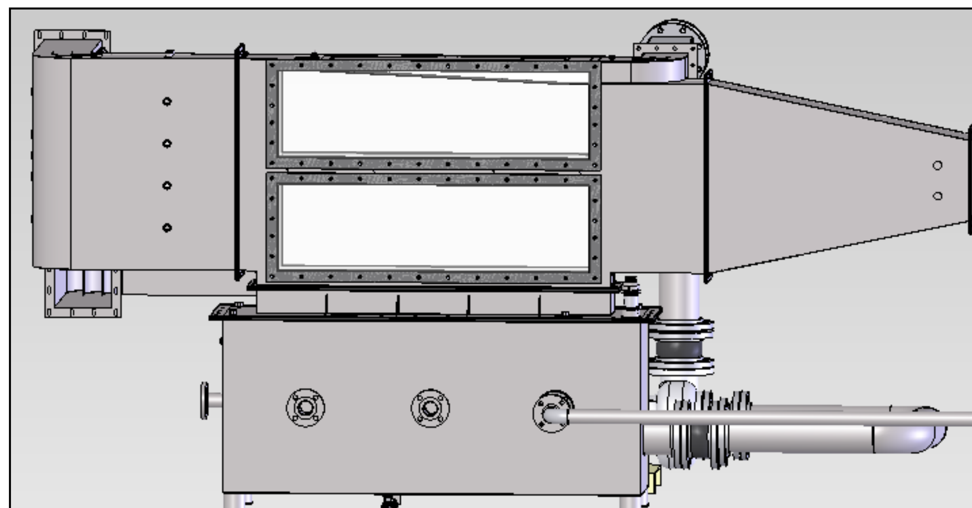
Project Status as of May 31, 2013

- Project CARE: $7,164,392 Federal Funding, started May 2012
  - April 2013: Completed budget period 1 (BP1) – Design Phase
  - May 2013: Started BP2 – Construction Phase (9mo)
  - Feb 2014: Start date for BP3 – Testing Phase (12mo)
- $2,799,662 costed of project total value of $9,098,441 (30.8%); Cost share currently at value of $693,132 (24.8%)
- Earned Value Assessment of Project:
  - 30.6% complete
  - CPI of 1.040
  - SPI of 0.966



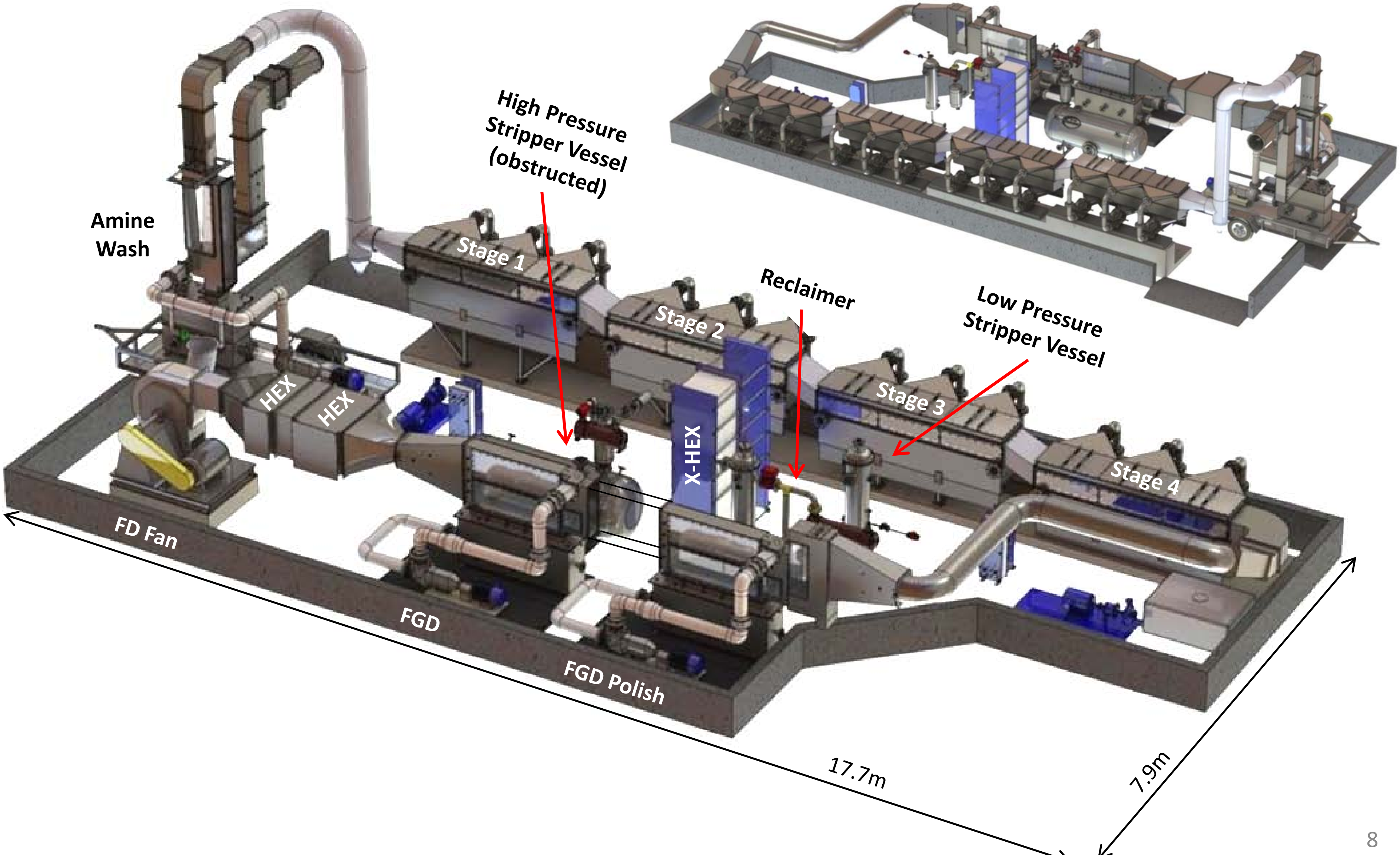
Capture Subsystem
DVT Stand

- 0.8 m (length) x 0.2 m (width) Horizontal Gas, Vertical Jet Absorber
- MEA solvent with flash stripper
- Adjustable gas flow: 4–16 m/s
- Adjustable reactor height: 28-79 cm (11-31 in)
- Adjustable jet pressure: 4-12 psi
- Interchangeable jet plate
  - ULFT or LF nozzles
  - Jet spacing of 3 or 4 mm
- CO_2 capture efficiency measured with Testo & FT-IR and CO_2 Mass flow controller
- Demonstrated specific surface area of **greater than 400 m^2/m^3**



CARE System Layout

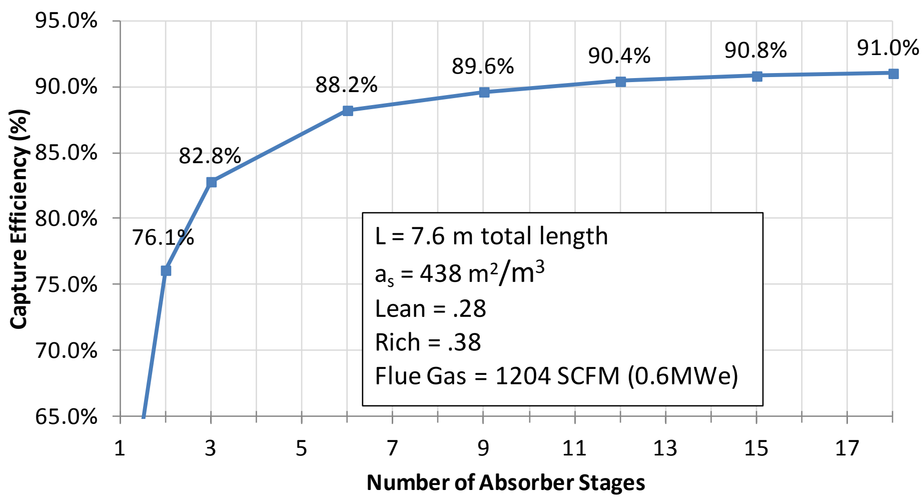
Isometric Views



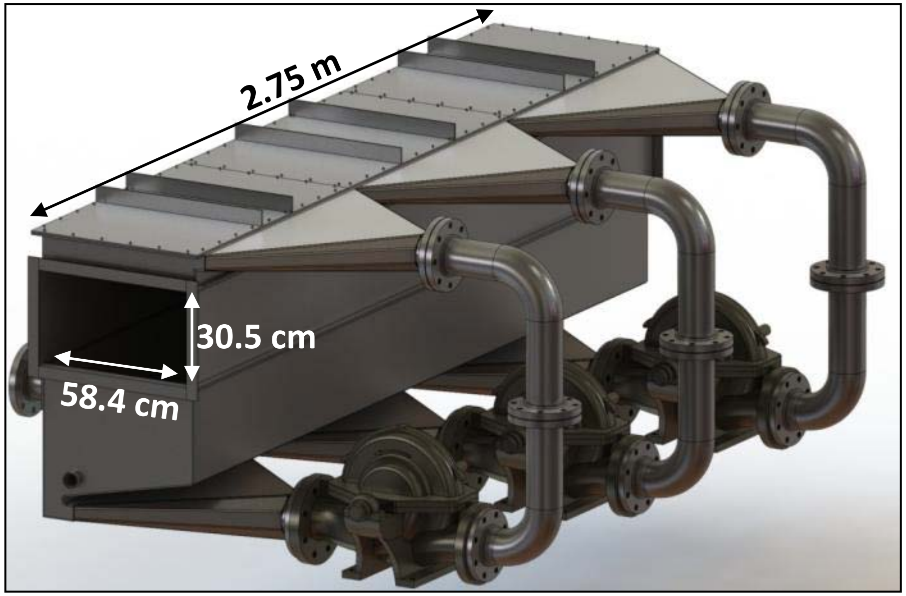
Absorber Unit

Absorber Design

Parameter	Value	Units
Stage Width	58.4 (23)	cm (in)
Stage Height	30.5 (12)	cm (in)
Stage a_s	425	m^2/m^3
Unit Length	2.75 (108.3)	m (in)
Capture Efficiency	90%	
Number of Pseudo-Stages	12	

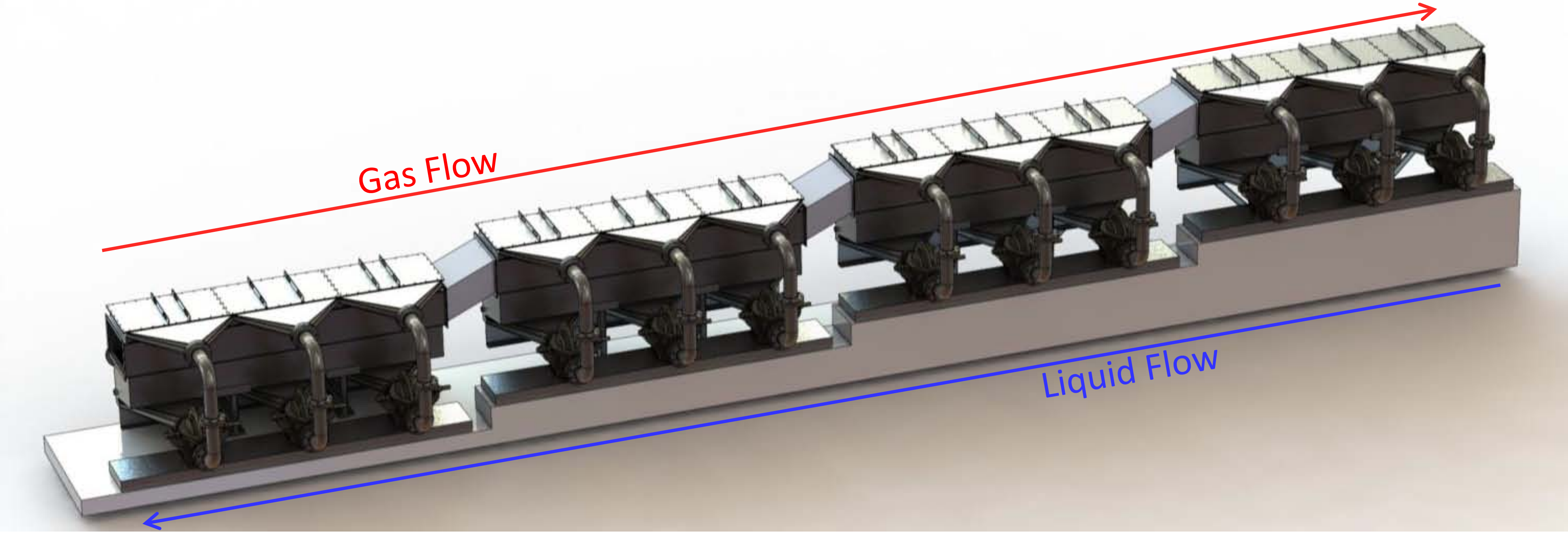


4x Absorbers at 2.75 m each = 11 m Total Length



Absorber Module

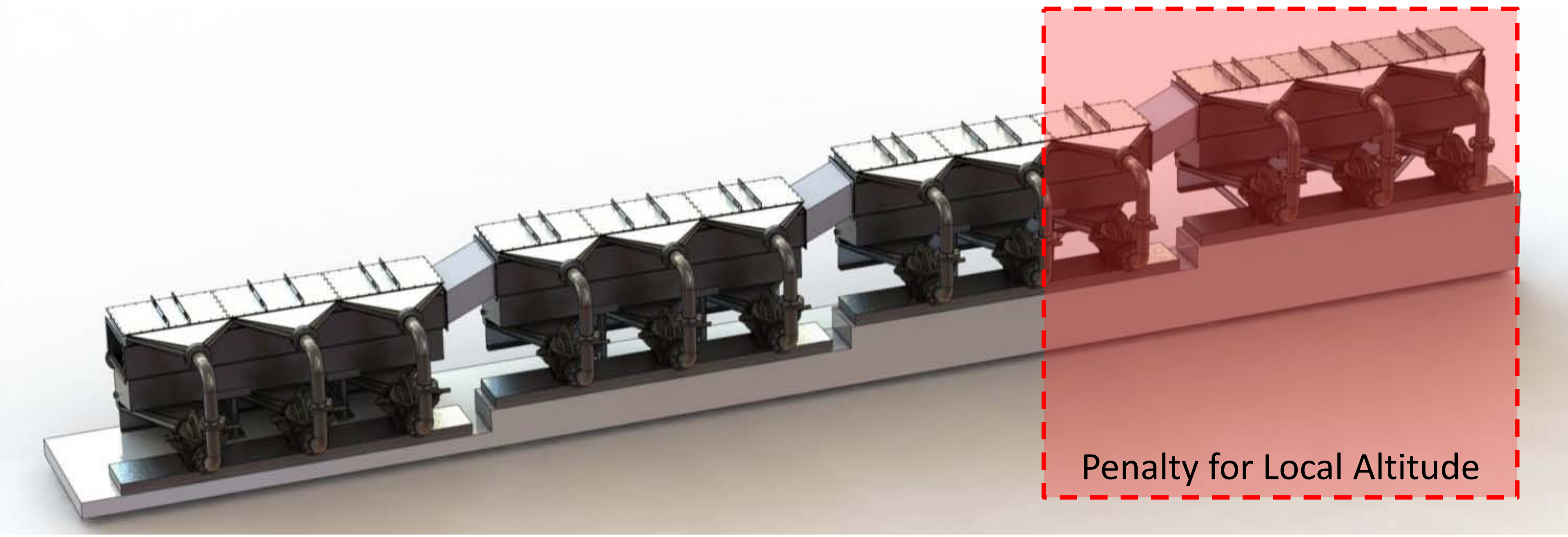
Design - 90% Capture of 0.6MW



- 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.

Absorber Module

Design - 90% Capture of 0.6MW

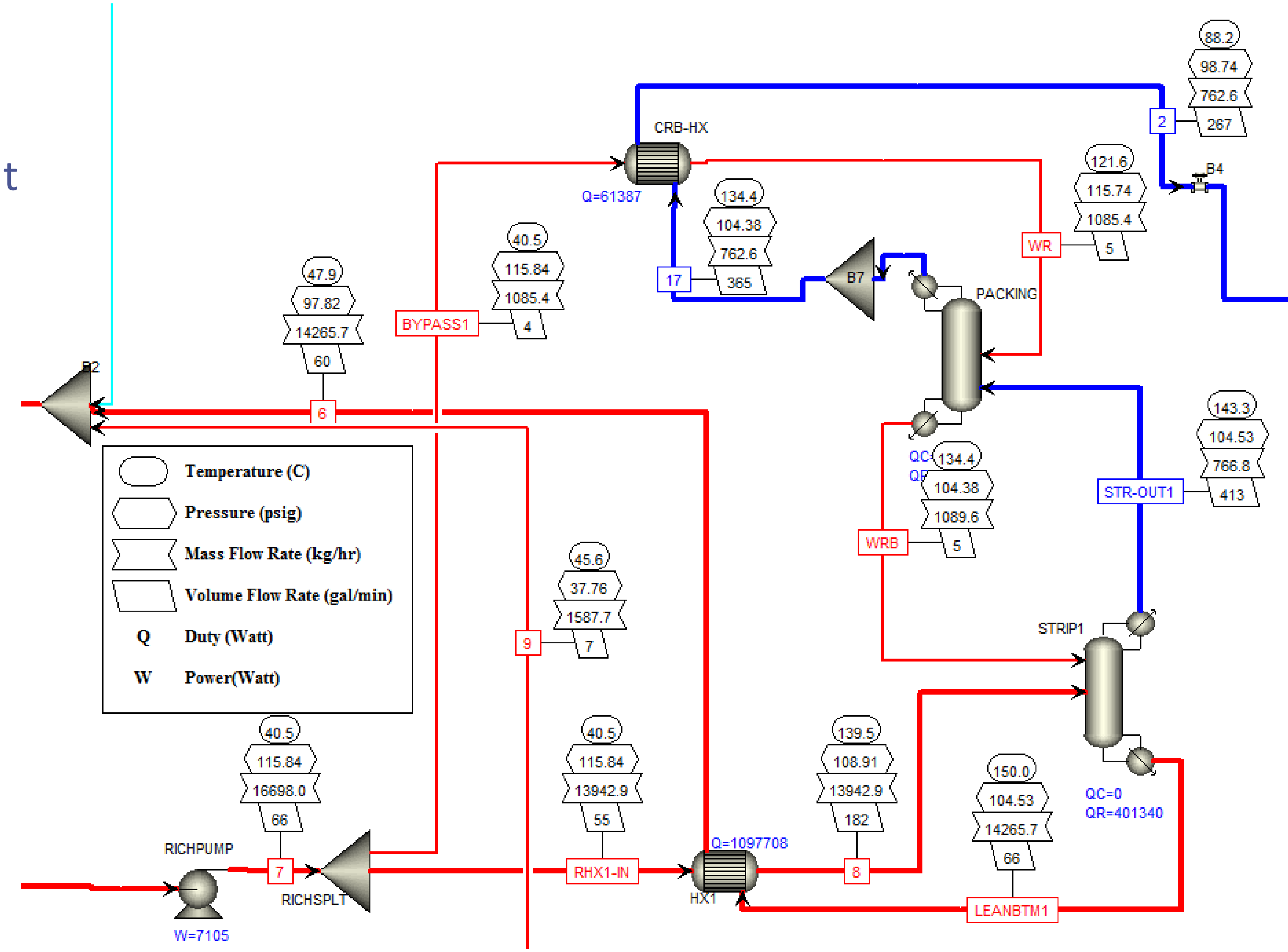


- At CSU's Drake: 2300 SCFM/MW, 12.5% CO_2 and 0.8 atm requires **11 meters** with 12 stages to get the necessary 2.2 sec residence time.
- Using NETL Case 9 Plant: 2007 SCFM/MW, 13.5% CO_2 and 1 atm requires **7.6 meters** with 12 stages to get the necessary 2.2 sec residence time.
- This absorber moved to the Case 9 plant could scrub 0.9MW at 90%

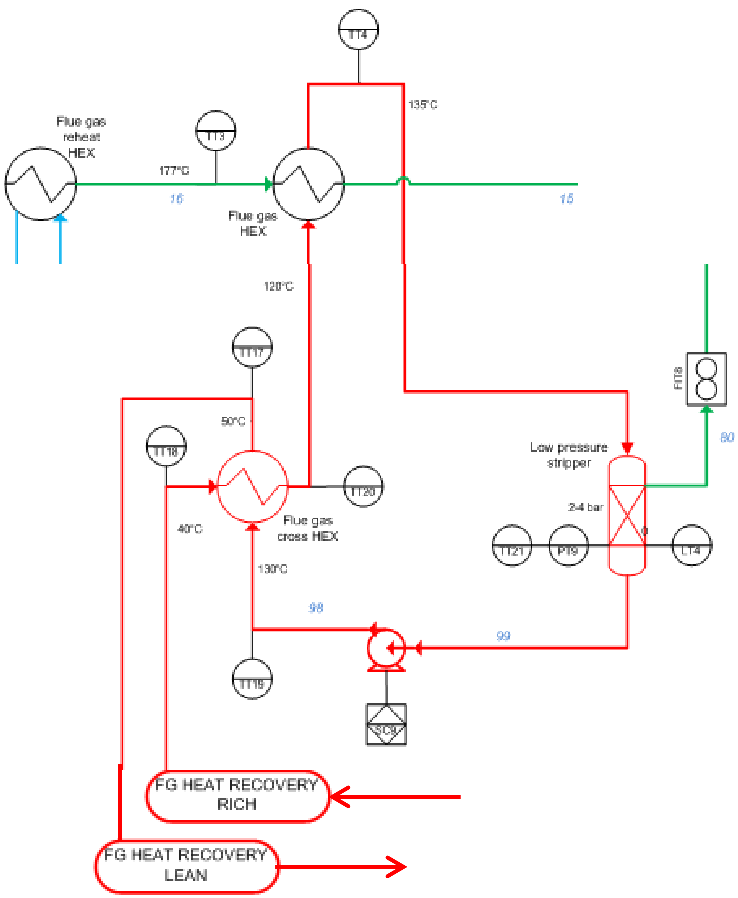
Stripper Module

Aspen/Process Flow Diagram

- Hot rich solvent injected through NSG jets
  - 6 rows x 45 LF nozzles at 6 psi = 55 gpm
- Cold Rich Bypass crosses with CO_2 gas in HEX, becoming warm rich
- Warm rich solvent sprays onto packing where heat transfer occurs through direct contact of gas/liquid
- Reboiler heat supplied through Stab-in-Bundle HEX

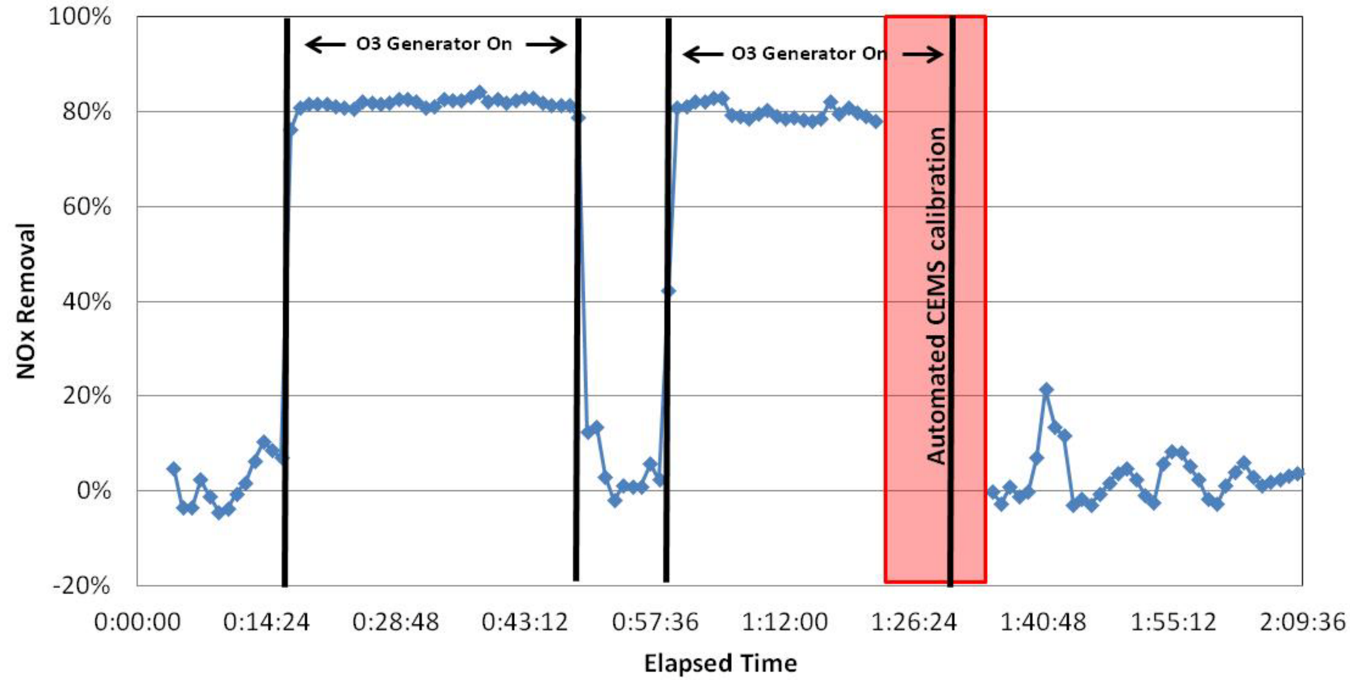


Flue Gas Heat Extraction



- Flue Gas Reheat to 350ºF to simulate NETL Case 9 Flue Gas out of the bag house
- 10% (5gpm) cold, rich solvent pulled to low pressure stripping
- Size flue gas HEX to offset vaporization cooling and maintain higher temperatures
- Simple flash stripper for gas/liquid separation – operated at 4 bar
- Modeled lean loading – 0.30 mol CO_2/mol alk; results in a steam offset of 8%

NOx Removal using O_3



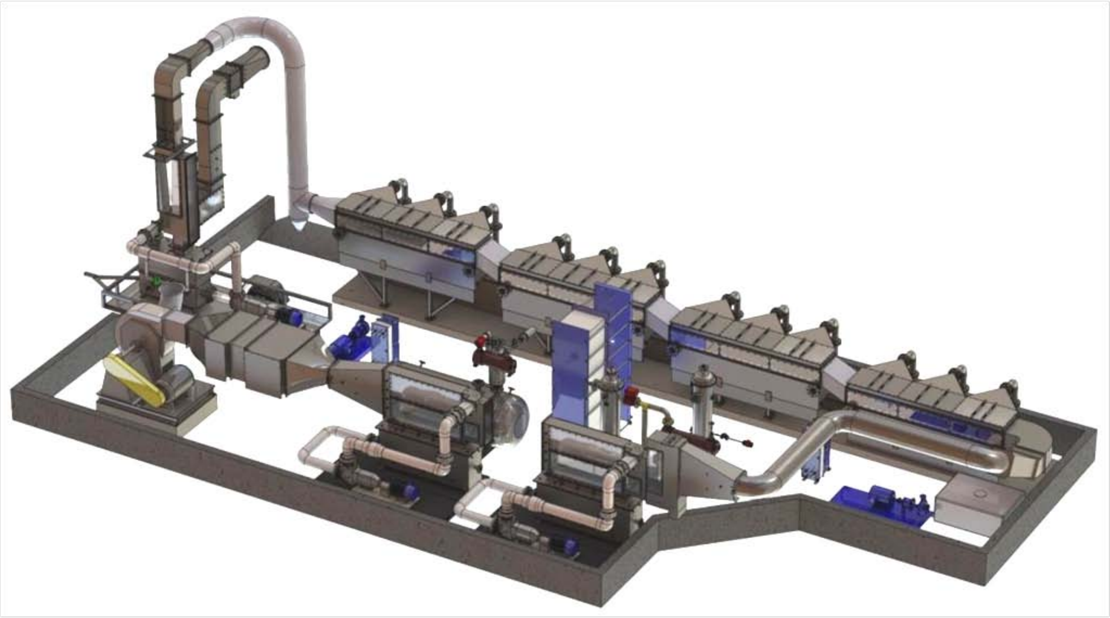
- Gas phase oxidation using ozone:

$$2(NO + O_3) \rightarrow 2NO_2 + O_3 \rightarrow N_2O_5$$

- Total NO_X removal demonstrated at 81% on central Pennsylvania eastern bituminous coal (flue gas concentration of 182ppm)
- Need to increase ozone production to achieve higher capture rate

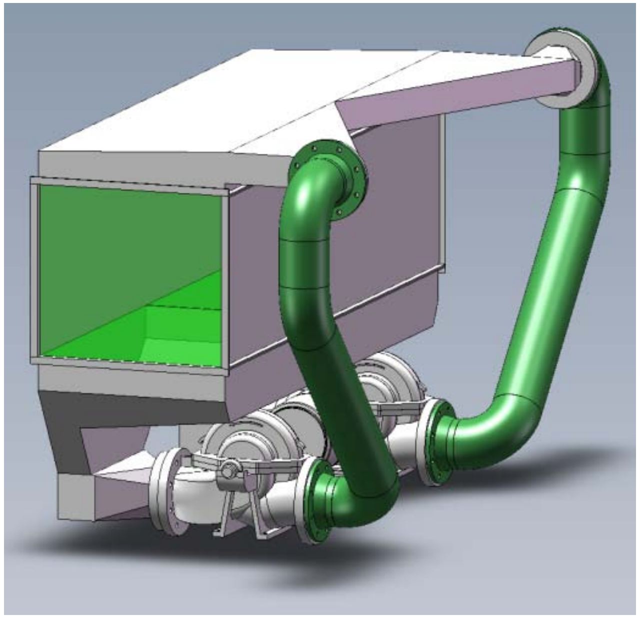
0.5MW CARE Program

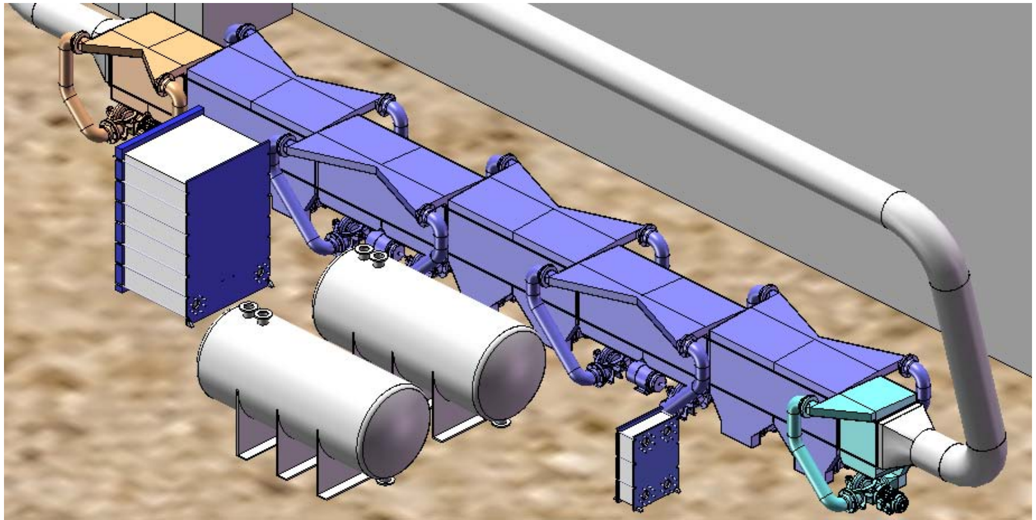
- CARE Innovations
  - NSG nozzles incorporated in FGD, FGD Polish/DCC, CO_2 Absorber, Amine Wash, and Stripper (for heat transfer)
  - NOx reduction through O_3 injection into flue gas upstream of SOx scrubber
  - Flue gas heat extraction to reduce steam usage
  - Custom Stripper configuration to take advantage of the operating properties of the piperazine solvent (developed with Drs. Rochelle/Chen)
  - Designed for use with concentrated Piperazine, although system is solvent agnostic and at the very least will be run with MEA solvent



Capture Subsystem
Future Work: 5MW Design

- Defined unit cell as 5 MW
  - WxH: 0.85 m (33.3”) x 0.76 m (30”)
  - Once 5 MW unit cell performance has been verified; scaling to commercial will have minimal risk utilizing this unit cell.
- 5MW cell:
  - Need 14.5 m of length for 90% capture;
  - Gas velocity is 7. 5m/s
  - Image shows a 2-stage 5 MW unit with 2.9m length (5x units needed in series).

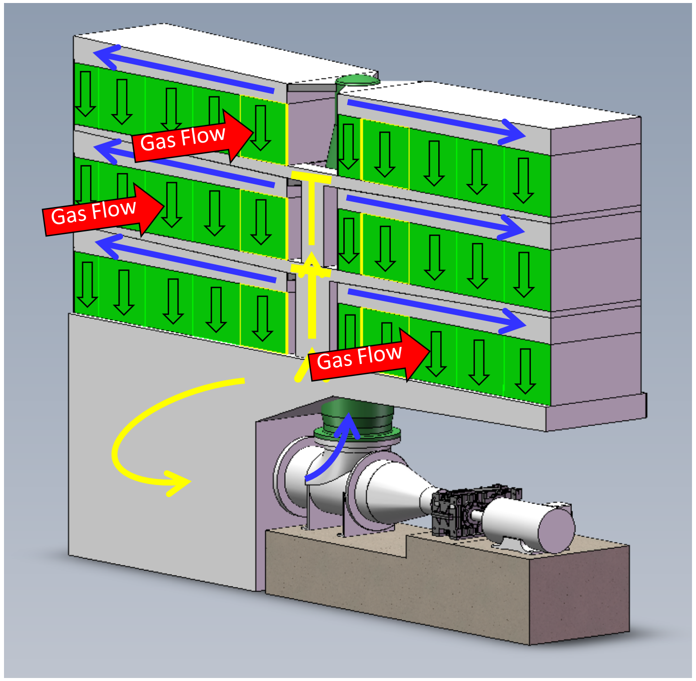




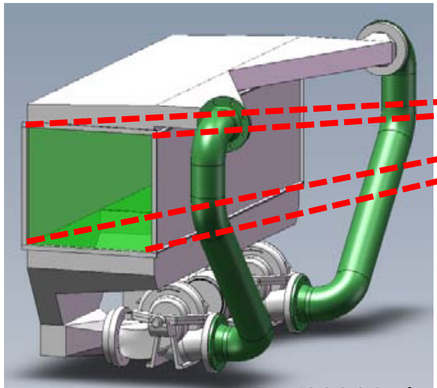
Capture Subsystem

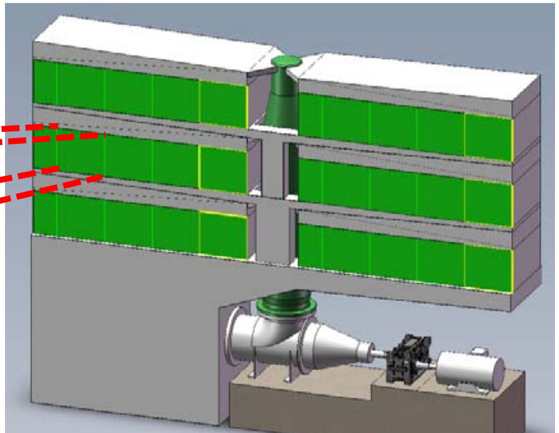
Traceability to Commercial Design

- Commercial module can easily be tailored for specific needs:
  - Can support 2 or 3 levels/tiers
  - Each level/tier can support up to 9x 5 MW unit cells
  - A single stage is shown with the maximum number (27x) of 5 MW cells: 135 MW



- Switch in pump type
  - Axial flow pumps are cheaper than split-case, double-suction pumps


5MW Unit


135MW Unit

Capture Subsystem

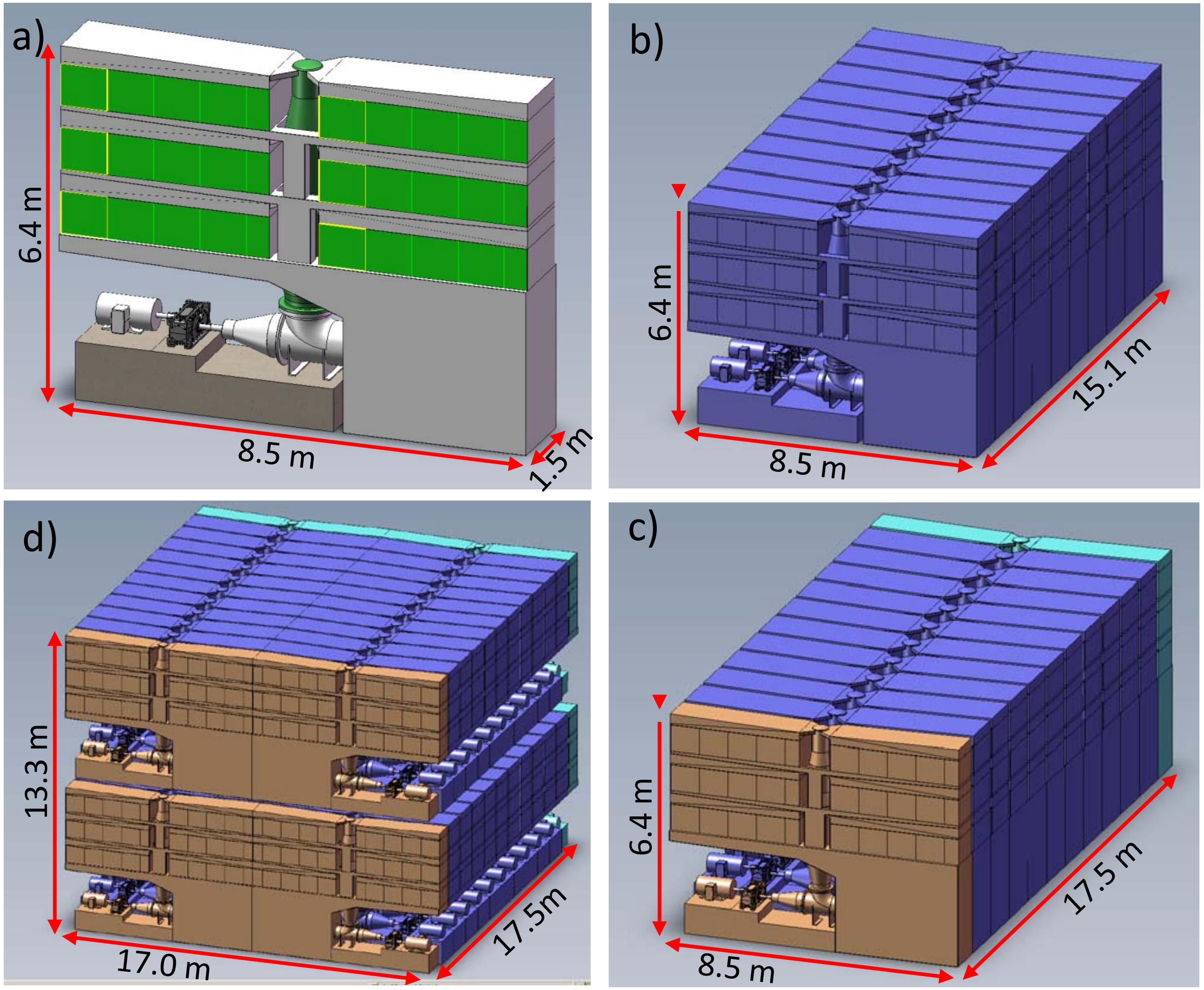
Traceability to Commercial Design

a) Single-stage, 135 MW unit that utilizes 27x 5-MW unit cells

b) 10-units stacked in series to achieve the necessary residence time at 7.5 m/s gas velocity for 90% capture of 135 MW flow

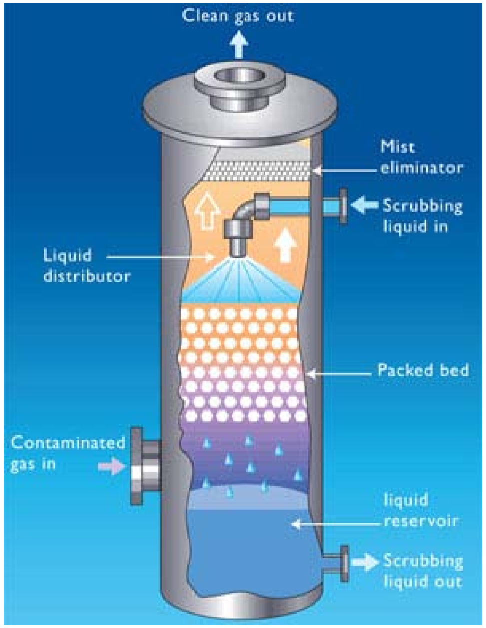
c) A 1-meter (depth) FGD/polishing scrubber and amine wash added to the CO_2 absorber to complete the module

d) 4-135 MW modules in parallel to achieve CO_2 capture of 540 MW

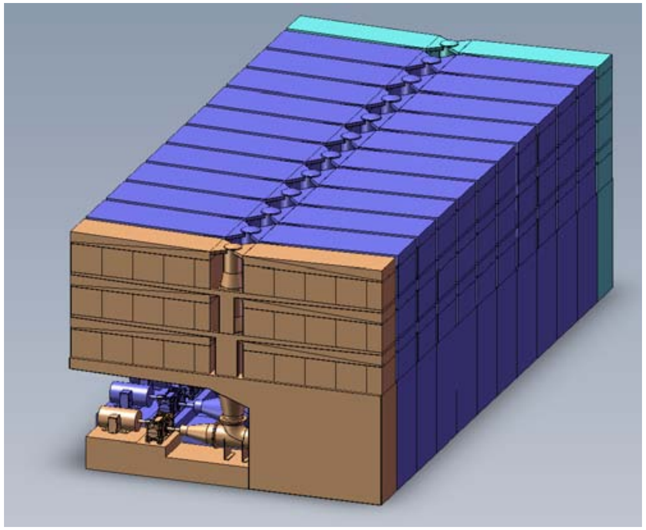


Comparison

Typical Packed Tower vs. *NeuStream®-C*



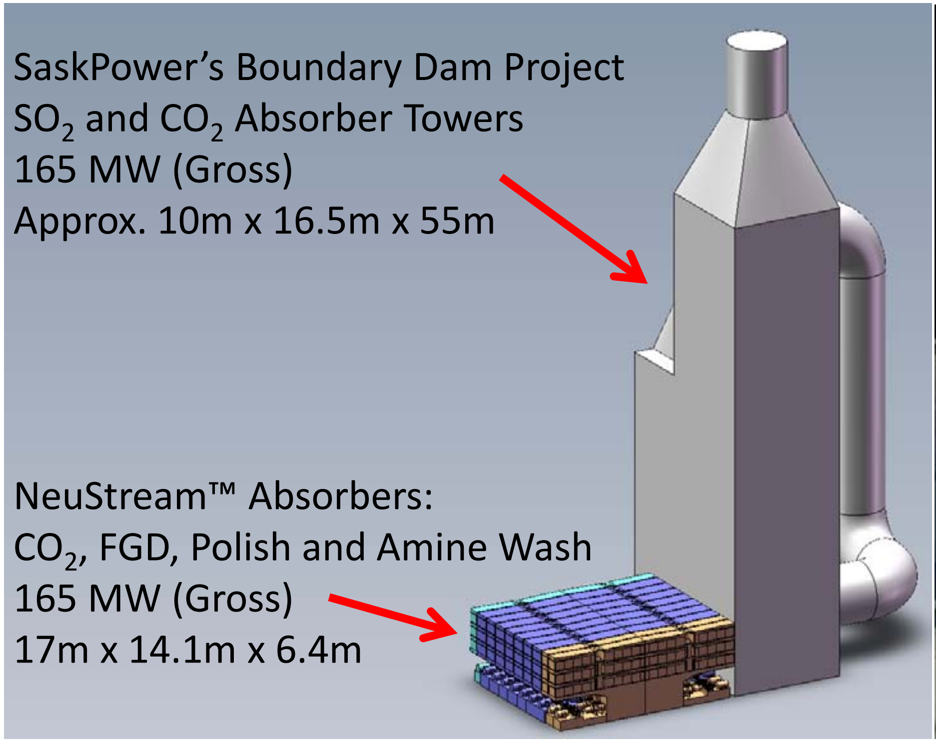
- Counter-current liquid/gas
- Tall height requires expensive support structure
- Contactor area is 100-200 m^2/m^3
- Gas velocities limited to 1-2 m/s
- High pressure drop across packing (1-2 inWC per meter)

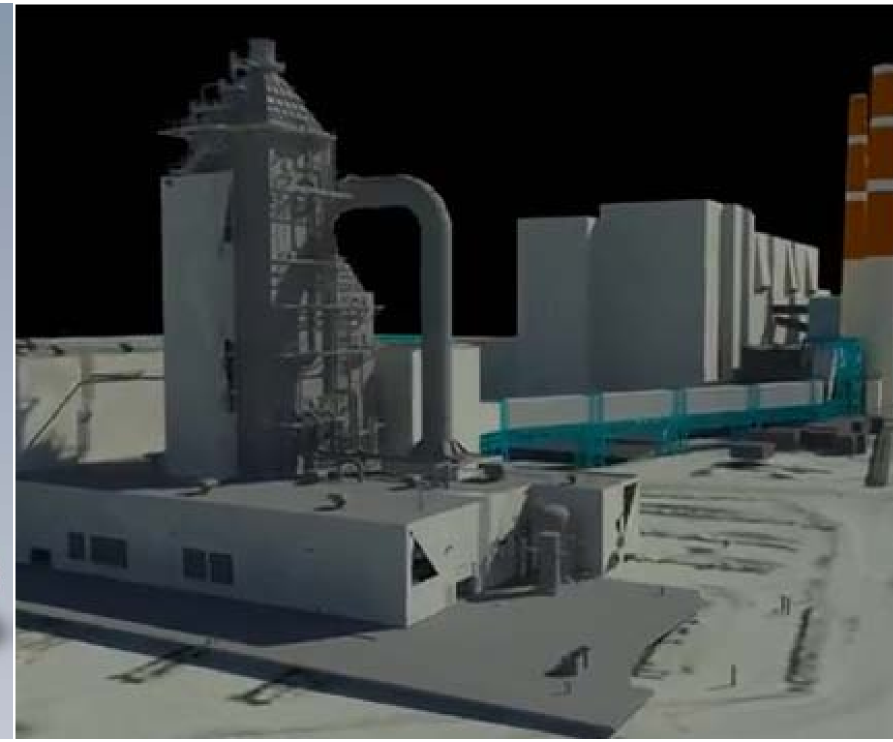


- Counter-current liquid/gas
- Horizontal arrangement requires **significantly less structural support**
- Contactor specific surface area of >**400 m^2/m^3** demonstrated
- Acceptable gas velocity **up to 7.5 m/s**
- Pressure drop of **1inWC per meter** of jets at 4 m/s gas velocity

Capture Subsystem

Traceability to Commercial Design

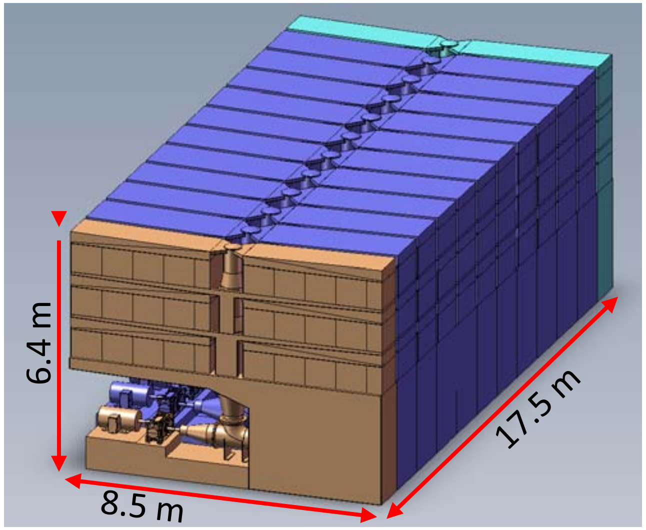




- BD3 project information:
  - BD3 is expected to gross approximately 165 MW after boiler upgrade
  - Carbon Capture System expected to operate at 21% parasitic power
  - Net power from BD3 will be approximately 110-115MW
- NeuStream™-C system:
  - Designed for 165 MW; utilizing 27x 5-MW cells
  - Estimated 26.5% parasitic power using current performance metrics:
    - Stripper = 16.5%; Compression = 4.3%; Absorber (including FD fan, FGD polish scrubber, CO_2 absorber and Amine wash) = 5.5%;

Energy Audit

Design Performance



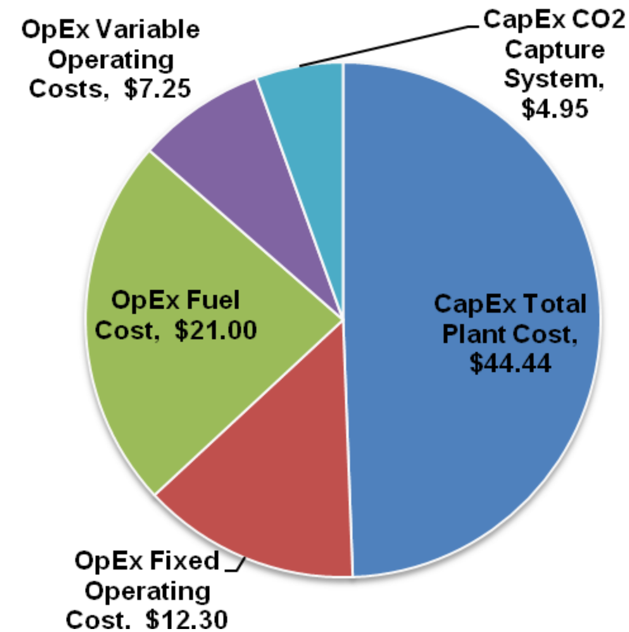
- Scrubber sized for NETL Case 9 power plant (1 atm, 2007 SCFM/MW)
- ULFT nozzles separated at 3mm on a tube; tube-to-tube separation of 3.5cm operated at 6 psi
- Amine Wash and FGD polishing scrubbers are included in Auxiliary equipment
  - AW and FGD each have 1m of reactor depth
  - 4mm nozzle-nozzle separation
  - ULFT nozzles with same 0.76 m jet length

				Equivalent power plant		135 MW
Equipment	**Flow (GPM)**	**TDH (ft)**	**Efficiency**	**Power (hp)**	**Power (kW)**	**%**
Absorber Recirc 1	66728.3	30	0.78	648.100	483.288	0.36%
Absorber Recirc 2	66728.3	30	0.78	648.100	483.288	0.36%
Absorber Recirc 3	66728.3	30	0.78	648.100	483.288	0.36%
Absorber Recirc 4	66728.3	30	0.78	648.100	483.288	0.36%
Absorber Recirc 5	66728.3	30	0.78	648.100	483.288	0.36%
Absorber Recirc 6	66728.3	30	0.78	648.100	483.288	0.36%
Absorber Recirc 7	66728.3	30	0.78	648.100	483.288	0.36%
Absorber Recirc 8	66728.3	30	0.78	648.100	483.288	0.36%
Absorber Recirc 9	66728.3	30	0.78	648.100	483.288	0.36%
Absorber Recirc 10	66728.3	30	0.78	648.100	483.288	0.36%
Amine Wash Recirc Pump	35747.3	30	0.75	361.084	269.260	0.20%
FGD Polish/DCC	35747.3	30	0.75	361.084	269.260	0.20%
Solvent Cooling Pump	7500	15	0.75	37.879	28.246	0.02%
Condenser Cooling Pump	7500	15	0.75	37.879	28.246	0.02%
Rich Pump	11150	380	0.75	1426.599	1063.815	0.79%
Equipment	**AFCM**	**Press Drop (in H2O)**	**Efficiency**	**Power (hp)**	**Power (kW)**	**%**
Blower Loss	293275	17	0.7	1120.58	835.614	0.62%
Heat Requirements	**Heat (kW)**	**Stripper Temp (C)**			**Equivalent Work**	**%**
Stripper 1	35100	150			8299.35	6.15%
Stripper 2	57857	150			13680.24	10.13%
Compression Requirements	**Flow Rate (mol/min)**	**Pressure (bar)**	**Avg. Press. (bar)**	**Equivalent Work (kJ/mol)**	**Equivalent Work (kW)**	**%**
Stripper 1	19093	11	9.3	8.33	6051.19	4.48%
Stripper 2	24493	8				
Totals	**CO2 Flow (mol/s)**			**Equivalent Work (kJ/mol)**	**Equivalent Work (kW)**	**%**
Stripper	726.429			30.26	21979.59	16.28%
Compression	726.429			8.33	6051.19	4.48%
Auxiliary	726.429			3.43	2494.44	1.85%
Absorber	799.071			6.65	4832.88	3.58%
Total				**48.67**	**35358.094**	**26.19%**

Levelized Cost of Electricity

CARE System - Preliminary

- All numbers are from EERC TEA Report for 550 MW plant
  - NSG supplied absorber cost
  - Did not include updated CARE energy audit
    - (**<u>used 30% from EERC</u>**)
  - 40% increase in LCOE
  - CO_2 Removal Cost = $28.50/ton
- **Needs Absorber Module Cost Updated Before New TEA Can Be Generated.**



Category	LCOE
CapEx Total Plant Cost	$ 44.44
OpEx Fixed Operating Cost	$ 12.30
OpEx Fuel Cost	$ 21.00
OpEx Variable Operating Costs	$ 7.25
CapEx CO_2 Capture System	$ 4.95
Total	$ 89.94

Schedule/Future Work

- Status/Plans
  - Critical design review (FEED) completed March ‘13
  - Procurement/Fabrication began May ‘13
  - Construction/Installation to begin in Sept ‘13
  - Testing begins Feb ’14
- Development Plan
  - **2014:** Demonstrate 0.5MW and gather data to support the 5MW system
  - **2016:** Demonstrate at 5MW, which represent base unit where scaling occurs by increasing the number of 5MW cells
  - **2020:** Demonstrate at commercial scale (>50MW)

Conclusions

- NeuStream™-C
  - High mass transfer G/L contactor
  - Up to 10x smaller volume than traditional CO_2 capture systems
  - Significantly reduced CapEx
    - < $30/ton CO_2 capture and compression costs
- Successfully proven at bench-scale (80kW)
- 0.5MW pilot demonstration in progress
  - NOx, SOx controls
  - Flue gas heat extraction
  - Innovative Stripper design

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