Carbon Absorber Retrofit Equipment (CARE)

primary project goals

Neumann Systems Group, Inc. (NSG) has designed, constructed, and tested a 0.5-MW scale patented NeuStream® absorber at the Colorado Springs Utilities (CSU) Martin Drake #7 power plant. The absorber employs nozzle technology proven during a previously completed 20-MW NeuStream-S flue gas desulfurization (FGD) pilot project, as well as a 6-m piperazine (PZ) solvent, which is an efficient solvent for capturing carbon dioxide (CO_2). The goal of the project is to show that the absorber system is capable of significantly reducing the process equipment footprint and the CO_2 capture system cost.

Due to an unrelated turbine fire at the Martin Drake plant in May of 2014, the project scope was revised to relocate the system to NSG's facility, where a natural gas steam boiler will provide the flue gas and stripping heat. Stripped CO_2 was recycled to increase the incoming CO_2 concentration to ≈13 percent to simulate flue gas from a coal-fired boiler.

technical goals

- Design a 0.5-MW_e slipstream CO_2 scrubber to minimize parasitic power through efficient design.
- Demonstrate a 2-month steady-state operation with a three-stage absorber and a multistage stripper.
- Demonstrate 90 percent CO_2 capture efficiency utilizing the best available solvent.
- Show unit traceability/scalability to commercial scale.

technical content

The NSG Carbon Absorber Retrofit Equipment (CARE) project includes design, construction, and testing of a 0.5-MW NeuStream® CO_2 capture system, based on NSG's patented flat jet, modular absorber technology. The NeuStream® absorber uses a proven technology with an array of flat jets and an advanced solvent (6 m PZ) to capture CO_2. The CARE absorber design is based on modeling (computational fluid dynamics [CFD] and Aspen Plus™) and analysis of carbon capture data from slipstream experiments, where experimental specific surface areas of 440 m^2/m^3 have been achieved. The CARE system slipstream test includes compact NeuStream® modules, as well as sulfur oxide (SO_x) scrubbing and amine washing equipment that also utilizes the NeuStream® flat jet technology.

The SO_x scrubbing equipment uses compact modular NeuStream® technology and can be adjusted to residual SO_x level (1–30 parts per million [ppm]) prior to CO_2 capture. The CARE project employs slipstream nitrogen oxide (NO_x) removal; a four-stage, 0.5-MW_e NeuStream® high-performance absorber unit for scrubbing; a novel stripper design that reduces heat waste; and a flue gas heat-recovery method to offset a portion of steam usage.

technology maturity:
Pilot-Scale, Actual Flue Gas Slipstream

project focus:
Carbon Absorber Retrofit Equipment

participant:
Nuemann Systems Group

project number:
FE0007528

predecessor projects:
N/A

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percent complete:
100%

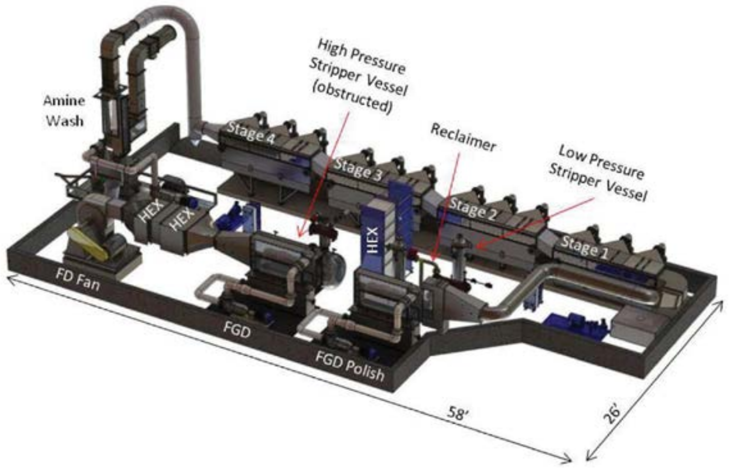

Figure 1: The system layout of the 0.5-MW NeuStream®-C demonstrator system

TABLE 1: SOLVENT PROCESS PARAMETERS

Pure Solvent	Units	Current R&D Value		Target R&D Value
Molecular Weight	mol^{-1}	86.14		86.14
Normal Boiling Point	°C	146		146
Normal Freezing Point	°C	106		106
Vapor Pressure @ 15 °C	bar	<0.001		<0.001
Manufacturing Cost for Solvent	$/kg	—		—
Working Solution				
Concentration	kg/kg	34%		34%
Specific Gravity (15 °C/15 °C)	—	0.99 (50 °C)		0.99 (50 °C)
Specific Heat Capacity @ STP	kJ/kg-K	3.6 (50 °C)		3.6 (50 °C)
Viscosity @ STP	cP	3.6 cP at 50 °C		3.6 cP at 50 °C
Absorption				
Pressure**	bar	0.101		0.101
Temperature	°C	40		40
Equilibrium CO_2 Loading	mol/mol	0.38		0.38
Heat of Absorption	kJ/mol CO_2	73		73
Solution Viscosity	cP	4.7		4.7
Desorption				
Pressure***	bar	2/4		2/4
Temperature	°C	150		150
Equilibrium CO_2 Loading	mol/mol	0.28		0.28
Heat of Desorption	kJ/mol CO_2	73		73
Proposed Module Design		*(for equipment developers)*		
Flue Gas Flowrate	kg/hr		2,370	
CO_2 Recovery, Purity, and Pressure	%/%/bar	90	>95	4/8
Absorber Pressure Drop	bar		—	
Estimated Absorber/Stripper Cost of Manufacturing and Installation	$\frac{\$}{kg/hr}$		—	

*unloaded PZ solution is a solid at 15 °C; **CO_2 partial pressure in the flue gas at Drake plant; ***CO_2 partial pressure exiting stripper

Definitions:

STP – Standard temperature and pressure (15 °C, 1 atmosphere [atm]).

Pure Solvent – Chemical agent(s), working alone or as a component of a working solution, responsible for enhanced CO_2 absorption (e.g., the amine monoethanolamine (MEA) in an aqueous solution).

Manufacturing Cost for Solvent – "Current" is market price of chemical, if applicable; "Target" is estimated manufacturing cost for new solvents, or the estimated cost of bulk manufacturing for existing solvents.

Working Solution – The solute-free (i.e., CO_2-free) liquid solution used as the working solvent in the absorption/desorption process (e.g., the liquid mixture of MEA and water).

Absorption – The conditions of interest for absorption are those that prevail at maximum solvent loading, which typically occurs at the bottom of the absorption column. These may be assumed to be 1 atm total flue-gas pressure (corresponding to a CO_2 partial pressure of 0.13 bar) and 40 °C; however, measured data at other conditions are preferable to estimated data.

Desorption – The conditions of interest for desorption are those that prevail at minimum solvent loading, which typically occurs at the bottom of the desorption column. Operating pressure and temperature for the desorber/stripper are process-dependent (e.g., an MEA-based absorption system has a typical CO_2 partial pressure of 1.8 bar and a reboiler temperature of 120 °C). Measured data at other conditions are preferable to estimated data.

Pressure – The pressure of CO_2 in equilibrium with the solution. If the vapor phase is pure CO_2, this is the total pressure; if it is a mixture of gases, this is the partial pressure of CO_2. Note that for a typical pulverized coal (PC) power plant, the total pressure of the flue gas is about 1 atm and the concentration of CO_2 is about 13.2 percent. Therefore, the partial pressure of CO_2 is roughly 0.132 atm or 0.130 bar.

Concentration – Mass fraction of pure solvent in working solution.

Loading – The basis for CO_2 loadings is moles of pure solvent.

Estimated Cost – Basis is kg/hr of CO_2 in CO_2-rich product gas; assuming targets are met.

Flue Gas Assumptions – Unless noted, flue gas pressure, temperature, and composition leaving the FGD (wet basis) should be assumed as:

		Composition						
		vol%					ppmv	
Pressure	Temperature	CO_2	H_2O	N_2	O_2	Ar	SO_x	NO_x
14.7 psia	135 °F	13.17	17.25	66.44	2.34	0.80	42	74

Provide brief description of the following items:

Chemical/Physical Solvent Mechanism – The absorption of CO_2 into concentrated PZ follows a carbamate mechanism, which is typical of primary and secondary amines. The overall chemical reaction of PZ with CO_2 is

$$2PZ + CO_2 \Leftrightarrow PZH^+ + PZCOO,$$

while the full aqueous reaction pathway is [3]

$$2H_2O \Leftrightarrow H_3O^+ + OH^-$$

$$2H_2O + CO_2 \Leftrightarrow HCO_3^- + H_3O^+$$

$$HCO_3^- + H_2O \Leftrightarrow CO_3^{2-} + H_3O^+$$

$$PZH^+ + H_2O \Leftrightarrow PZ + H_3O^+$$

$$PZ + HCO_3^- \Leftrightarrow PZCOO^- + H_2O$$

$$HPZCOO + H_2O \Leftrightarrow PZCOO^- + H_3O^+$$

$$PZCOO^- + HCO_3^- \Leftrightarrow PZ(COO)_2^{2-} + H_2O.$$

Solvent Contaminant Resistance – 6-m PZ is thermally stable at 150 °C with negligible oxidative degradation. The total amine loss is estimated to be 0.4 percent/week when stripping at 150 °C. At 135 °C, the reported thermal degradation of PZ is 0.07 percent as compared to 8.1 percent in the case of an MEA solvent.[4] The main degradation products of PZ are nitrates (0.13 mM/hr) and ethylenediamine (0.09 mM/hr).

Flue Gas Pretreatment Requirements – The flue gas is passed through a NeuStream® NO_x- and SO_x-removal system before being fed to the CARE system. The SO_x concentration is kept below 10 ppm using two stages of NeuStream® FGD absorbers. The polishing scrubber for SO_x removal has a high volumetric mass-transfer coefficient and 90 percent removal efficiency. The polishing scrubber also cools the flue gas from 57 °C to ≈32 °C by contacting the flue gas with cold sorbent. This helps maintain water balance while also reducing the volumetric flow rate through the CO_2 absorber and counteracting some of the heat from the exothermic CO_2 absorption reaction, reducing the PZ solvent temperature and decreasing the equilibrium vapor pressure, both of which help to reduce the size of the CO_2 absorber.

Waste Streams Generated ––Solid waste streams are generated by the reclaimer, which removes heat stable salts formed by NO_x and SO_2 absorption, and by the inline filters. Fugitive liquid amine emissions will be controlled by incorporating seamless valves, rupture disks, closed-loop ventilation systems, pumps with dual mechanical seals, minimum welds, and correct gasket material selection. Amine slip is minimized through the use of an amine water wash absorber unit, also based on NeuStream® technology. The FGD unit generates a gypsum by-product suitable for landfill.

Process Design Concept – Process flow diagram is shown in Figure 2 below.

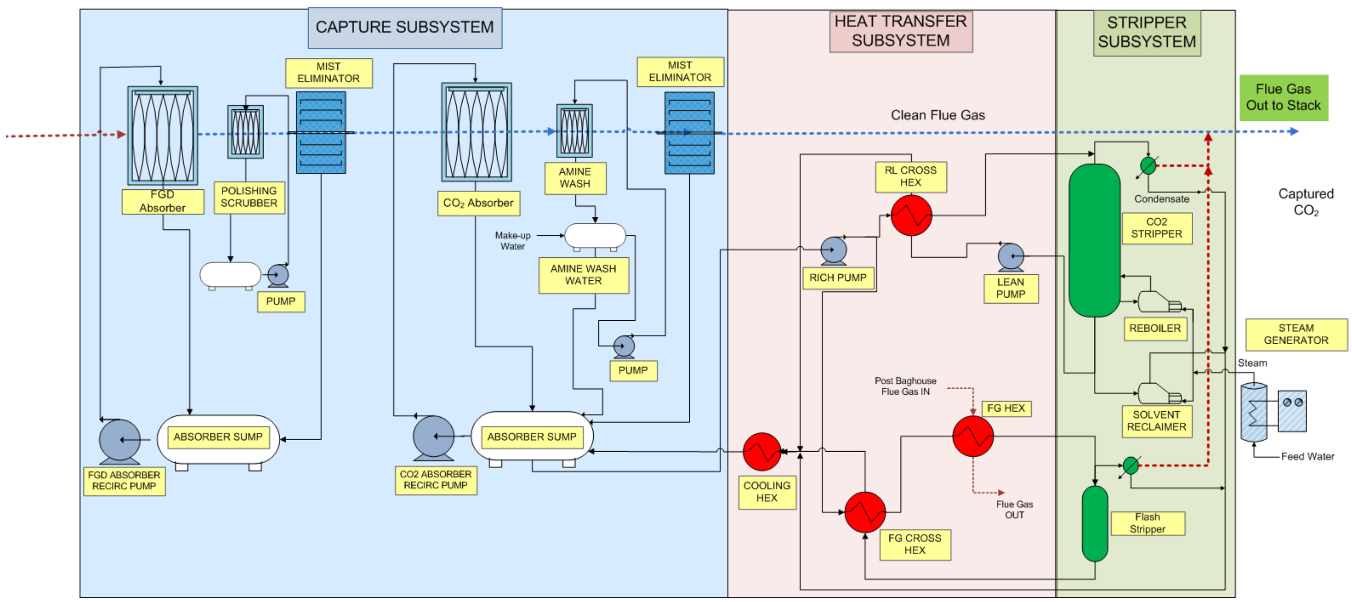

Figure 2: Process flow diagram of CARE system

Proposed Module Design – The heart of the NeuStream® system is NSG's patented, high specific surface area NeuStream® flat jet nozzle technology (shown in Figure 3) engineered into modular, scalable, and efficient cross-flow gas liquid contactor (absorber) units. The modular absorber units are arranged in parallel into full scale systems. Several areas of innovation make this gas-liquid contactor extremely effective for absorbing CO_2 from flue gas. First, a high specific surface area (400–800 m^{-1}) absorption zone is achieved over a large volume from an array of flat jets driven by low liquid-side pressure (<34 kPa). Secondly, the flat jets are aerodynamically shaped, which allows for a high gas flow parallel to the jets while maintaining a low gas-side pressure drop (0.25 kPa/m). Packaging of the NeuStream® absorber takes advantage of the high specific surface area and high gas velocities (typically 5 m/s for CO_2 capture) to reduce the footprint of the system by up to 90 percent and booster fan power requirements by up to 70 percent when compared to conventional packed towers.

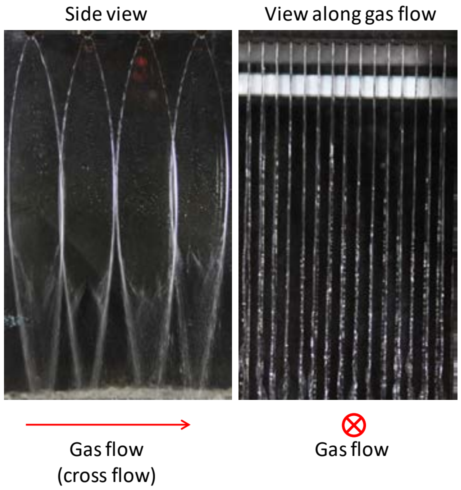

Figure 3: NeuStream® flat jet technology

The system layout is shown above in Figure 1 and the process flow diagram is shown above in Figure 2. Ozone is introduced upstream of a forced draft to oxidize NO_X to more soluble components. The fan moves the flue gas through a heat exchanger to heat the slipstream flow back up to a representative temperature (350 °F). The flue gas then passes through a second heat exchanger, which heats loaded solvent and reduces steam usage in the regeneration subsystem. The flue gas then passes through a NeuStream® FGD system to reduce the SO_x concentration to 15 ppm and the NO_x by 80–90 percent. A polishing/direct contact cooler (DCC) NeuStream® scrubber is used to further reduce the SO_x to 1 ppm, and to cool the flue gas to <35 °C. After the polishing/DDC scrubber, the gas passes through a four-unit NeuStream® CO_2 absorber (shown in Figure 4), where each unit has three stages. This 12-stage absorber reduces the CO_2 by 90 percent prior to contacting the flue gas with a NeuStream® amine wash, which cleans the amine slip from the gas before reintroducing it into the plants main flue gas stream. Due to space constraints, only 3 of the 4 absorber units were relocated to NSG's facility following the unrelated turbine fire at the Drake plant, such that the expected capture efficiency at design gas flow rates would decrease from 90 percent to ≈75 percent and the gas flow would need to be de-rated in order to realize 90 percent CO_2 capture.

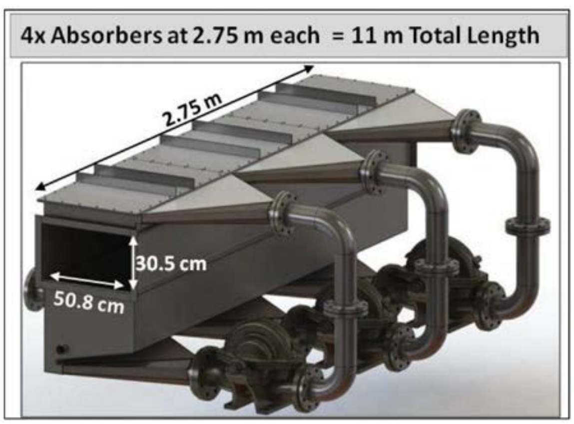

Figure 4: Solid model of one of four NeuStream® CO_2 absorber stages utilized in Project CARE (Cross-sectional area scales with system size, but length remains unchanged.)

The regeneration system contains all typical components, such as cross heat exchangers, solvent cooler exchanger, rich pump, reclaimer, and condenser. A custom-designed stripper vessel is utilized to lower steam usage during operation. Additionally, approximately 10 percent of the rich flow is directed to a lower-pressure flash vessel to desorb the CO_2 from the solvent using only heat provided by the flue gas.

technology advantages

- The NeuStream® CO_2 capture technology integrates a highly-efficient, compact absorber design with an advanced solvent, leading to substantial (≈90 percent) reduction in absorber volume as well as significant savings in both capital and operating costs compared to conventional systems.
- The high surface areas of the NeuStream® flat jets and low-pressure drop in the absorber lower the capital cost of the absorber considerably, leading to significant reductions in the increase in levelized cost of electricity (LCOE) over MEA.
- The NeuStream® technology is adaptable to a wide range of solvents encompassing a large spectrum of properties such as surface tension, viscosity and mass transfer rates.
- The NeuStream® flat jets are engineered into modular absorber units, which are arranged in parallel to meet the flue gas flow rate requirements for specific applications, facilitating rapid, low-risk scale-up of the technology.
- The NeuStream® technology incorporates PZ regeneration at high pressures, leading to lower CO_2 compression power requirements.
- The CARE system utilizes an alternative NO_x-removal strategy to demonstrate the viability of this option over selective catalytic reductions (SCRs).
- The CARE system utilizes a flue gas heat-recovery strategy to reduce the steam usage in the regeneration subsystem.
- A novel stripper design developed by NSG with Dr. Rochelle and Dr. Chen at the University of Texas is incorporated into the CARE system to minimize steam usage.

R&D challenges

- Ensuring optimal distribution of gas in the absorber and avoiding gas bypassing the jets in large-scale absorbers may be an issue, which is addressed via CFD modeling.
- Results from tests on the design verification stand indicate that the specific surface area is not fully preserved with increasing jet length; this may lead to larger absorbers, increasing capital costs. It is possible this decrease is due to the wall effects that become more prevalent at longer jet lengths in the design verification test stand.

status

NSG designed, built and tested a 0.5-MW NeuStream® CO_2 capture system using flue gas from a natural gas boiler. The system exhibited 90 percent capture at the CSU's Martin Drake PC power plant, regenerated CO_2 purity was measured to be 98.6 percent. The NeuStream® absorbers tested support a 90 percent reduction in absorber volume compared to packed towers and with an absorber parasitic power of less than 1 percent when configured for operation with a 550-MW coal plant. Figure 5 shows a size comparison between a 110-MW (net) NeuStream® CO_2 absorber and a commercial 110-MW (net) CO_2 absorber, which was recently commissioned at SaskPower's Boundary Dam Unit #3.[5] As can be seen, NeuStream® technology provides a significant size advantage over conventional CO_2 capture technology, resulting in a volume reduction of 82 percent for the 160-MW Boundary Dam application. The preliminary techno-economic analysis predicted a cost of CO_2 capture at $25.73/tonne, with a corresponding COE increase of 40 percent. Project complete as of December 31, 2015.

Figure 5: CO_2 absorber size comparison: 110 MW (net) NeuStream® vs. CanSolv's 110 MW (net) SaskPower Boundary Dam Unit #3 Project (Includes flue gas desulfurization, CO_2, and amine wash absorbers.)

available reports/technical papers/presentations

"Carbon Absorber Retrofit Equipment (CARE) Final Scientific/Technical Report," December 2015. https://netl.doe.gov/File%20Library/Research/Coal/carbon%20capture/post-combustion/FE0007528-Neumann-Final-Report.pdf.

"Progress Update on the Carbon Dioxide Absorber Retrofit Equipment (CARE) Program," 2014 NETL CO_2 Capture Technology Meeting, July 2014. *http://www.netl.doe.gov/File%20Library/Events/2014/2014%20NETL%20CO2%20Capture/A-Awtry-NSG-Progress-Update-On-NSGs-CARE.pdf*.

"Status of the Carbon Dioxide Absorber Retrofit Equipment (CARE) Program," 2013 NETL CO_2 Capture Technology Meeting, July 2013. *http://www.netl.doe.gov/File%20Library/Events/2013/CO2%20Capture/A-Awtry-NSG-Status-of-the-CARE-Program.pdf*

Brasseur, J., and Awtry, A., "Compact Absorber Retrofit Equipment (CARE)," presented at the 2012 NETL CO_2 Capture Technology Meeting, July 2012, Pittsburgh, PA. *http://www.netl.doe.gov/publications/proceedings/12/CO2capture/presentations/2-Tuesday/2-Brasseur-NeumannSG.pdf*.

Awtry, A., Klein, E., and Brasseur, J., "NeuStream®-C: Carbon Capture Progress Update," Air Quality IX, Arlington, VA, 2013.

Awtry, A., Klein, E., and Brasseur, J., "NeuStream®-C: Carbon Capture Progress Update," Power-Gen XXV, Orlando, FL, 2013.

references

[1]Dugas, Ross E., "CO_2 Absorption, Desorption, and Diffusion in Aqueous Piperazine and Monoethanolamine," PhD Thesis, University of Texas, 2009.

[2]Van Wagener, David H., "Stripper Modeling for CO_2 Removal Using Monoethanolamine and Piperazine Solvents," PhD Thesis, University of Texas, 2011.

[3]Bishnoi, S., and Rochelle, G. T., "Absorption of carbon dioxide into aqueous piperazine: reaction kinetics, mass transfer and solubility," Chemical Engineering Science 55 (2000) 5531-5543.

[4]Dombrowski, K, "Evaluation of Concentrated Piperazine for CO_2 Capture from Coal-Fired Flue Gas," DOE-NETL Contractor's Meeting, 2010.

[5]Couturier, Guy and DMello, Mark, (SNC-Lavalin), "From Engineering to Procurement to Construction of the Boundary Dam Carbon Capture System," SaskPower CCS Consortium, 2013 Information and Planning Symposium, May 21, 2013.