Carbon Absorber Retrofit Equipment (CARE)

Final Scientific/Technical Report

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I. ABSTRACT:

During Project DE-FE0007528, CARE (Carbon Absorber Retrofit Equipment), Neumann Systems Group (NSG) designed, installed and tested a 0.5MW NeuStream® carbon dioxide (CO_2) capture system using the patented NeuStream® absorber equipment and concentrated (6 molal) piperazine (PZ) as the solvent at Colorado Springs Utilities' (CSU's) Martin Drake pulverized coal (PC) power plant. The 36 month project included design, build and test phases. The 0.5MW NeuStream® CO_2 capture system was successfully tested on flue gas from both coal and natural gas combustion sources and was shown to meet project objectives. Ninety percent CO_2 removal was achieved with greater than 95% CO_2 product purity. The absorbers tested support a 90% reduction in absorber volume compared to packed towers and with an absorber parasitic power of less than 1% when configured for operation with a 550MW coal plant. The preliminary techno-economic analysis (TEA) performed by the Energy and Environmental Research Center (EERC) predicted an over-the-fence cost of $25.73/tonne of CO_2 captured from a sub-critical PC plant.

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III. EXECUTIVE SUMMARY:

During project CARE (Carbon Absorber Retrofit Equipment), Neumann Systems Group (NSG) designed, installed and tested a 0.5MW NeuStream® carbon dioxide (CO_2) capture system using concentrated (6 molal) piperazine (PZ) as the solvent at Colorado Springs Utilities' (CSU's) Martin Drake pulverized coal (PC) power plant. Prior to and during the CARE program, NSG piloted its NeuStream® system for CO_2 capture at the 70kW and 100kW scales using both PC and natural gas (NG) burning CO_2 sources.

The CARE program summarized herein was a 36 month project consisting of separate and distinct design, build and test phases. During the design phase, the CARE system was designed to meet program objectives including 90% CO_2 capture and 95% CO_2 product purity. Design verification testing (DVT) was performed to facilitate nozzle selection to minimize parasitic power associated with the absorber recirculation pumps. During the build phase, system components were procured and fabricated and the system was constructed at CSU's Martin Drake PC power plant and integrated with Unit 7's flue gas.

During the test phase, shakeout testing was completed and parametric testing started when an unrelated turbine fire at the Drake plant resulted in a long-term outage. As such, the CARE system was relocated to NSG's facility and integrated with flue gas supplied by a natural gas boiler, and captured CO_2 was recycled to the absorber inlet to simulate coal flue gas (~13% CO_2). Due to space constraints at the NSG location, only 3 of the 4 absorber units were relocated, such that the expected capture efficiency at design gas flow rates would decrease from 90% to ~80% and the gas flow would need to be de-rated in order to realize 90% CO_2 capture. The testing of the 0.5MW CARE system at NSG culminated in a one week continuous 24x7 extended run. During this extended run, CO_2 capture efficiency and specific surface area were characterized as a function of gas velocity.

Capture efficiencies were demonstrated to match expected values during testing using both coal and natural gas as the flue gas source. CO_2 capture efficiency was determined to be 90% at the Drake site (coal flue gas source) with 4 absorber units in operation during a parametric test at 0.44MW equivalent gas flow. CO_2 capture efficiency was determined to be 80% at the NSG location (natural gas flue gas source) with 3 absorber units in operation at the design 0.5MW gas flow. Regenerated CO_2 purity was measured to be 98.6%, exceeding the 95% project goal.

The NeuStream® absorbers tested support a 90% reduction in absorber volume compared to packed towers and with an absorber parasitic power of less than 1% when configured for operation with a 550MW coal plant. Figure 1 shows a size comparison between a 110MW (net) NeuStream® CO_2 absorber and a commercial 110MW (net) CO_2 absorber which was recently commissioned at SaskPower's Boundary Dam Unit #3.[1] As can be seen, NeuStream® technology provides a significant size advantage over conventional CO_2 capture technology, resulting in a volume reduction of 82% for the 160MW Boundary Dam application.

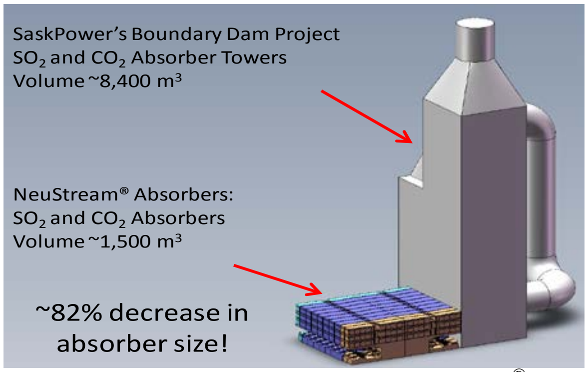

Figure 1: CO_2 absorber size comparison: 110MW (net) NeuStream® vs. CanSolv's 110MW (net) SaskPower Boundary Dam Unit #3 project. Includes flue gas desulfurization (FGD), CO_2 and amine wash absorbers.

Furthermore, the reduced size of NeuStream® technology also results in significant cost reduction. The preliminary techno-economic analysis (TEA) performed by the Energy and Environmental Research Center (EERC) predicted an over-the-fence cost of $25.73/tonne of CO_2 captured from a subcritical PC plant, significantly below NETL's current 2025 goal of $40/tonne.[2,3]

IV. EXPERIMENTAL METHODS

NSG's NeuStream® systems are based on NSG's patented, ultra-efficient NeuStream® flat jet gas-liquid contacting technology (see Figure 2).[4-22] The aerodynamic flat jets exhibit high specific surface area (a_s) which reduces absorber gas-liquid contact time requirements, and also are able to operate at high gas cross-flow velocities which reduces absorber cross-sectional area requirements. NeuStream® absorbers typically operate at gas velocities ranging from 5 to 10 m/s and demonstrate a_s ranging from 400 to 800 m^{-1}. The 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. Packaging of the NeuStream® absorber takes advantage of the high specific surface area and high gas velocities to reduce the volumetric footprint of the absorber by up to 90% when compared to conventional packed towers.

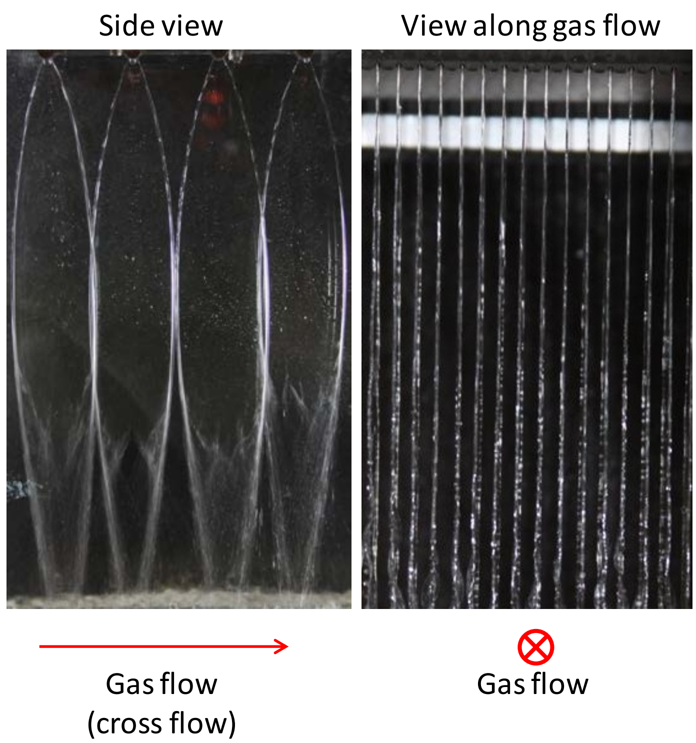

Figure 2: NeuStream® flat jet technology

The CARE system design included a multitude of sensors and control elements interfaced via National Instruments' CompactRIO control and monitoring platform. Examples of sensor types include pressure gauges, differential pressure gauges, thermocouples, flow meters and density meters while examples of control elements include control valves, pump variable frequency drives (VFDs) and mass flow controllers (MFCs). Gas composition measurements were performed using a portable Fourier transform infrared (FTIR) gas analyzer while solvent composition measurements were performed using a total inorganic carbon / total organic carbon analyzer (TIC/TOC). By measuring both organic carbon (i.e.

PZ) and inorganic carbon (i.e. CO_2) in the solvent samples, both PZ concentration and CO_2 loading were determined.

V. RESULTS AND DISCUSSIONS

A. DESIGN PHASE

The main focus of budget period 1 (BP1) was design of the CARE system, including design verification testing (DVT) to support key design decisions. Key design requirements to meet the program objectives included 0.5MW capacity, 90% CO_2 capture efficiency, 95% CO_2 product purity, reduced absorber parasitic power through increased jet length and nozzle optimization, traceability to commercial scale units and a maximum cost of electricity (COE) increase of 35%.

The critical design review (CDR) system layout is shown below in Figure 3 and the process flow diagram (PFD) is shown below in Figure 4. Ozone is introduced upstream of a forced draft fan 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 of 176°C (350 °F). The flue gas then passes through a second heat exchanger, which heats rich 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/DCC scrubber, the gas passes through a four-unit NeuStream® CO_2 absorber (shown in Figure 5), 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. The CO_2 absorbers, FGD absorbers, amine wash absorber and stripper are all based on NSG's patented NeuStream® flat jet technology.

The state-point data table is shown below in Table 1. The solvent was specified to be 6 molal PZ at lean and rich loadings of 0.28 mol CO_2 / mol alkalinity and 0.38 mol CO_2 / mol alkalinity respectively.

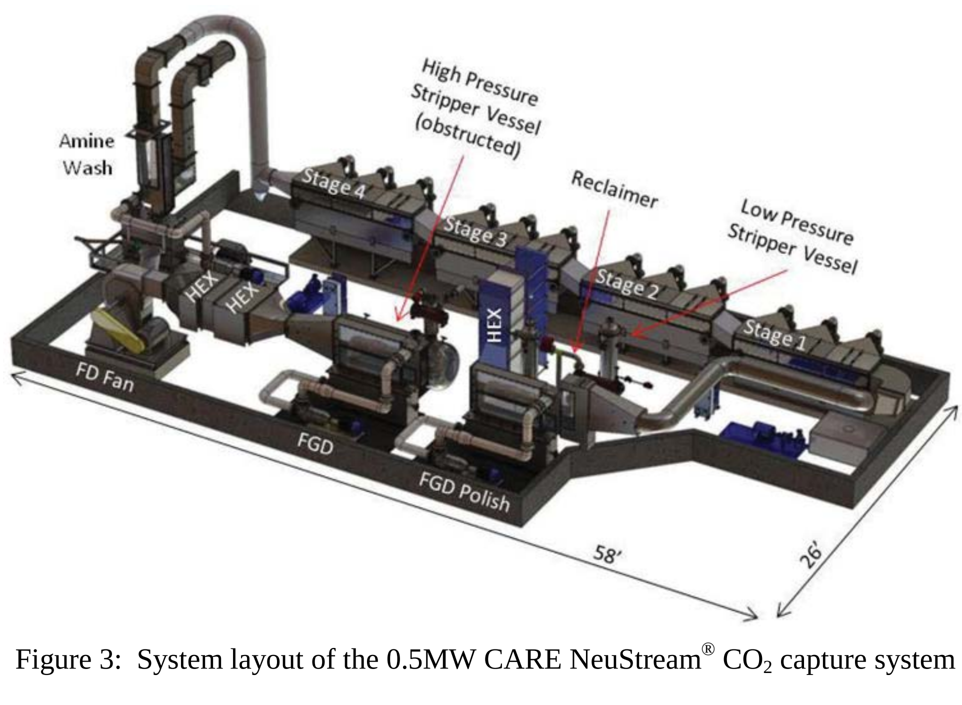

Figure 3: System layout of the 0.5MW CARE NeuStream® CO_2 capture system

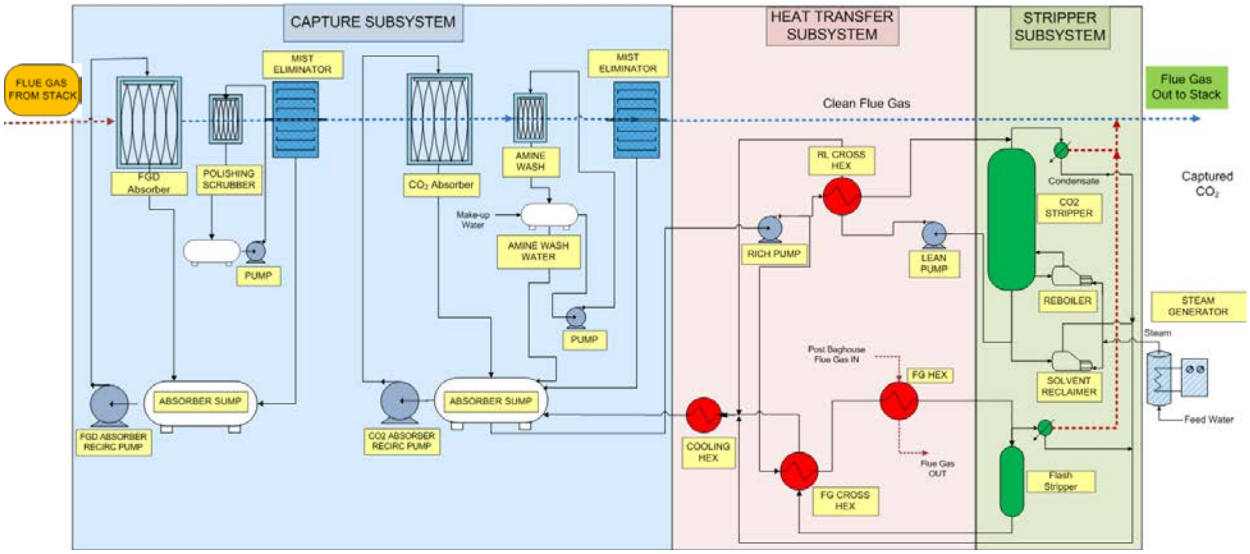

Figure 4: CARE NeuStream® CO_2 system process flow diagram (PFD)

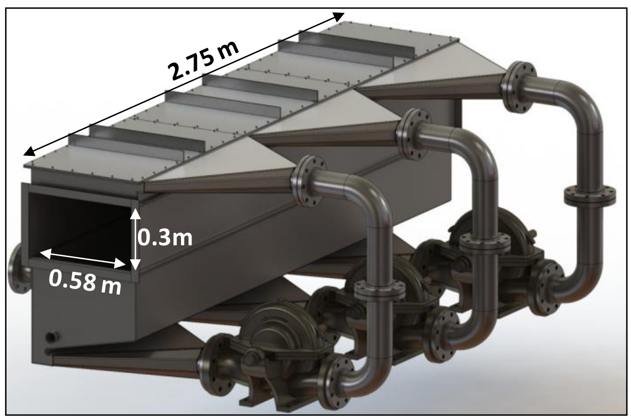

Figure 5: Solid model of one of four NeuStream® CO_2 absorber stages utilized in project CARE

Table 1: CARE NeuStream® CO_2 capture system state-point data

	Units	Current Value[23,24]
Pure Solvent (Piperazine)		
Molecular Weight	mol^{-1}	86.14
Normal Boiling Point	°C	146
Normal Freezing Point	°C	106
Vapor Pressure at 15 °C	bar	<0.001
Manufacturing Cost for Solvent	$/kg	—
Working Solution*		
Concentration	kg/kg	34%
Specific Gravity (15 °C/15 °C)	—	0.99 (50°C)

	Units	Current Value[23,24]
Specific Heat Capacity at STP	kJ/kg-K	3.6 (50 °C)
Viscosity at STP	cP	3.6 cP (50 °C)
Absorption		
Pressure**	bar	0.101
Temperature	°C	40
Equilibrium CO_2 Loading	mol/mol alk	0.38
Heat of Absorption	kJ/mol CO_2	73
Solution Viscosity	cP	4.7
Desorption		
Pressure***	Bar	2/4
Temperature	°C	150
Equilibrium CO_2 Loading	mol/mol alk	0.28
Heat of Desorption	kJ/mol CO_2	73

*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

During the design phase, the preliminary environmental health and safety (EH&S) assessment and the preliminary techno-economic analysis (TEA) were completed by the EERC. The EH&S assessment highlighted risks and hazards associated with the PZ solvent and the system was designed accordingly to minimize risk, including the inclusion of a containment berm surrounding the processing equipment. The basis of the preliminary TEA was a 550 MW net sub-critical PC fired power plant. The TEA predicted an over-the-fence capture cost of $25.73 / tonne of CO_2, significantly below NETL's 2025 goal of $40/tonne.[2,3]

Design verification testing (DVT) was performed on a test skid that was set up at CSU's Martin Drake power plant. The results of this testing had a maximum specific surface area achieved of 438 m^{-1} with jets that averaged 0.28m (11”) in length. Part of the program was to evaluate performance of longer jets, up to 0.76m (30”) in length, in order to reduce parasitic power requirements. With the DVT test skid NSG determined that increasing jet length reduced performance and resulted in an experimental surface area around 200 m^{-1} (see Figure 6). It was noted during the testing that at least a portion of the performance degradation associated with longer jets was caused by the increase in wall effects. In addition to the standard nozzle configuration, several other configurations were tested including variations on scrubber geometry as well as nozzle geometry, and the absorber design was configured for successful demonstration using the highest possible surface area configuration (about 450 m^{-1}) and the most economical option (lower surface area, but significant drop in energy demand).

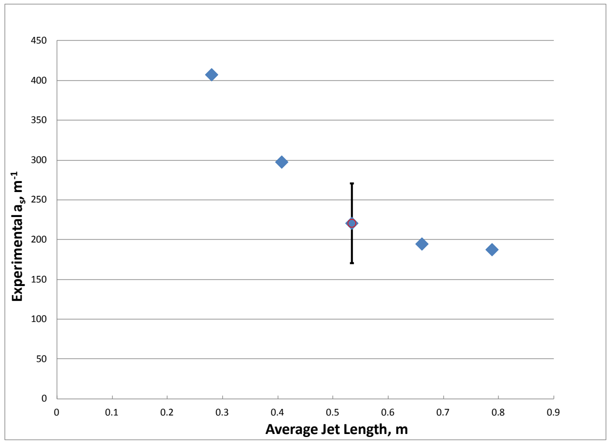

Figure 6: Experimental surface area as a function of jet length

B. CONSTRUCTION PHASE

The main focus of budget period 2 (BP2) was the procurement, fabrication, construction and installation of the system at CSU's Martin Drake PC power plant and integration with Unit 7's flue gas. NSG relied on its past experience constructing emissions control systems at coal plants and on its excellent working relationship with CSU to successfully drive the system construction to completion. Proper safety protocol was followed throughout the construction, and the project was completed without incident. Figure 7 through Figure 10 below detail the construction and the major pieces of equipment installed at the Martin Drake power plant.

Figure 7: CARE system enclosure with containment berm at CSU's Martin Drake power plant

Figure 8: CARE NeuStream® FGD absorbers installed at the Drake plant

Figure 9: CARE NeuStream® CO_2 absorbers installed at the Drake plant

Figure 10: CARE stripper unit installed at the Drake plant

C. TESTING PHASE

During budget period 3 (BP3), the NeuStream® 0.5MW CARE slipstream demonstration was commissioned at CSU's Martin Drake PC plant in early 2014 (see Figure 11). Acceptance testing, parametric testing and a 2 month extended 24x7 test were planned. NSG had completed check-out testing and had started parametric testing when an unrelated turbine fire broke out at the host site.

Before the turbine fire, NSG did briefly operate the 0.5MW CARE system at steady state conditions. Lean and rich loadings were measured to be 0.282 and 0.365 mol CO_2 / mol alkalinity respectively compared to the design point of 0.28 and 0.38. CO_2 capture efficiency was determined to be 89.9% at a gas flow rate equivalent to 0.44MW.

The turbine fire at the Martin Drake plant prevented planned long duration testing. Because initial CSU estimates were that the plant would remain offline for up to one year, the project scope was revised to relocate the 0.5MW CARE system from the Drake plant to NSG's facility, also in Colorado Springs (see Figure 11). A natural gas steam boiler was installed at NSG's facility to provide the stripping heat and also served as the flue gas source. Stripped CO_2 was recycled back to the front of the absorber to increase the incoming CO_2 concentration in the flue gas to ~13% to simulate flue gas from a coal-fired boiler. With the CO_2 recycle, the flue gas at NSG's facility was identical to that at the Drake plant with respect to flow rate, temperature, and concentration of major constituents. While coal-fired flue gas contains trace contaminants not typically present in natural gas-fired flue gas, NSG expects that the majority of the water-soluble trace contaminants would be removed in the FGD absorber, upstream of the CO_2 absorber.

Due to space constraints, only 3 of the 4 absorber units were relocated to NSG's facility, such that the expected capture efficiency at design gas flow rates would decrease from 90% to ~80% and the gas flow would need to be de-rated in order to realize 90% CO_2 capture. The FGD (not required with natural gas flue gas) and NO_X removal systems as well as the secondary stripper were also not relocated to NSG's facility.

The testing of the 0.5MW CARE system at NSG included acceptance testing and parametric testing and culminated in a one week continuous 24x7 extended run. Parametric testing varied process parameters such as gas velocity, flat jet nozzle pressure and stripper pressure to characterize the process and determine optimal operating conditions for the extended run. During the extended run, removal efficiency was characterized as a function of gas velocity, as shown in Figure 12. At the design gas velocity, CO_2 capture efficiency was about 80% (as expected due to 3 vs. 4 absorber units). As expected, a 25% reduction in gas velocity increased the capture efficiency back to the 90% design point. Specific surface area was measured to be 450 m^{-1} at the design gas velocity, slightly higher than the 425 m^{-1} design value. Regenerated CO_2 purity was measured to be 98.6%, exceeding the 95% project goal. Total run time on the CARE NeuStream® CO_2 capture system while installed at NSG's facility exceeded 320 hours.

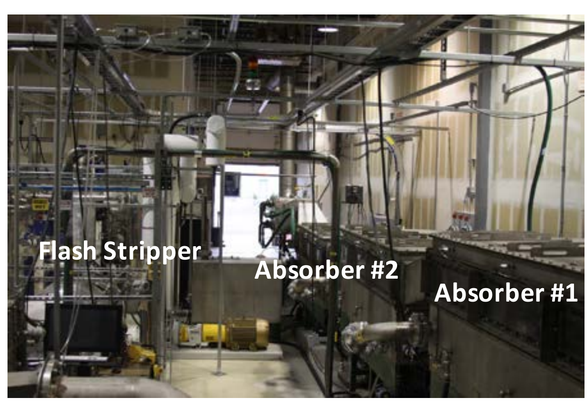

Figure 11: NeuStream® 0.5MW CARE at CSU's Martin Drake plant (left) and NSG's facility (right)

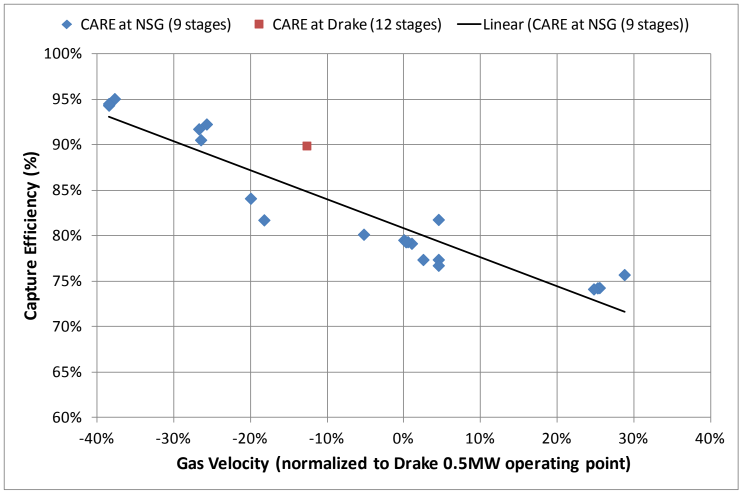

Figure 12: NeuStream® 0.5MW CARE capture efficiency

As discussed above, increased jet length is an important design parameter in order to minimize the liquid to gas ratio (L/G) and therefore the parasitic power associated with the absorber recirculation pumps. In addition to the parametric and extended testing, NSG also reconfigured the amine wash reactor which supports jet lengths up to 0.76m (30") to facilitate testing of the optimal jet configuration employed in the nominal NeuStream® CARE absorbers, which utilize 0.3m (12") jets, at longer jet lengths.

Figure 13 below shows the results of these runs at longer jet length. As can be seen by comparing to Figure 12 above, specific surface area decreased significantly when the jets were extended from 0.3m (12") to 0.38m (15") and then to 0.76m (30"), indicating that more work was required to realize jet lengths longer than 0.3m (12") at acceptable parasitic power requirements.

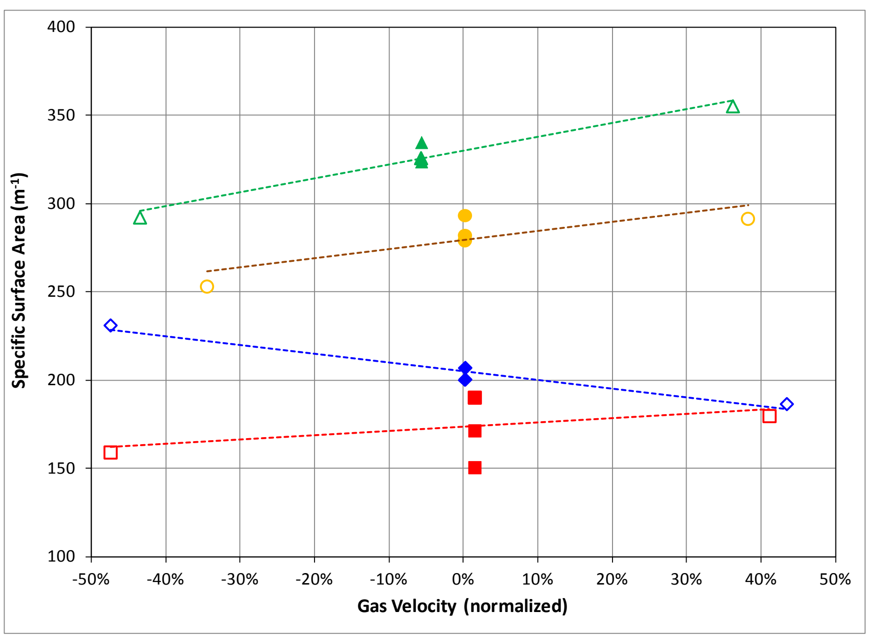

Figure 13: Experimental specific surface area for two nozzle configurations at 0.38m (15") jet length (green and orange) and 0.76m (30") jet length (blue and red) vs. gas velocity.

While the CARE CDR design achieved the program objectives, it did not fully meet our scaling objectives as laid out in our original proposal with respect to parasitic power requirements for the absorber recirculation pumps. Therefore, in parallel with the CARE program, NSG conducted a major, internally funded, internal research and development (IR&D) effort that directly supported the CARE statement of project objectives (SOPO) to decrease the parasitic power associated with the absorber recirculation pumps. Through this IR&D effort, NSG successfully engineered optimized jet nozzles coupled with a jet stabilization technique that reduces liquid flow per nozzle by a factor of 3, reduces nozzle driving pressure by a factor of 7 and increases jet length by a factor of 3.

The sum of these improvements results in an advanced NeuStream® absorber configuration that demonstrates a specific surface area of 400 m^{-1}, while reducing parasitic power requirements associated with the recirculation pumps by a factor of 10 when compared to the technology demonstrated during the 0.5MW CARE project. Table 2 contains performance specifications for the nominal CARE vs. stabilized jets for the 0.5MW CARE system and a conceptual 550MW NeuStream® design featuring eight vertical levels.

Table 2: Performance specifications for NeuStream® nominal CARE jets vs. stabilized jets

	0.5MW CARE 1 absorber level	0.5MW CARE 1 absorber level	550MW NeuStream® 8 absorber levels
Jet Type	nominal	stabilized	stabilized
Jet Length (m)	0.3	0.76	0.91
Total recirculation pump power (kW)	82	18	3129
Absorber Capacity (effective MW(net))*	1	2	563
Parasitic power (% of net)	8.17%	0.84%	0.56%
*NETL case 11 conditions[25]. CARE is oversized due to CSU altitude and flow/MW compared to NETL basecase			

The advanced, stabilized jet configuration was thoroughly tested on NSG's large bench scale test stand, which features a 0.25m (10") jet length, with PZ solvent. Figure 14 contains a comparison of the a_s attained with the CARE nozzle configuration vs. the advanced stabilized jets. Note that the slightly lower a_s attained with the advanced jets is tolerable due to the significant decrease in parasitic power.

NSG recently converted the amine wash reactor of the 0.5MW CARE test stand into a single stage for CO_2 absorption to facilitate testing of the advanced, stabilized jets with a jet length of 0.76m (30"). As shown in Figure 14, a preliminary test resulted in a measured a_s of 360m^{-1}, significantly higher a_s than was determined for 0.76m jet lengths during the CARE design verification testing in BP1 and BP2 as well as the more recent testing summarized in Figure 13.

When compared to traditional packed tower absorber technology, the NeuStream® CO_2 absorber with advanced stabilized jets exhibits higher effective a_s (400-500m^{-1} vs. 100-200m^{-1})[26,27] and also operates at higher gas velocity, reducing absorber size by up to 90% and system cost by 50% or greater.[1,2] The higher a_s also reduces contact length in the absorber, which at NeuStream®'s low gas-side pressure drop of 0.25kPa/m equates to a significant decrease in booster fan power requirements (~70% decrease when compared to Boundary Dam).[28] Even though packed towers typically have no internal recycle of liquid, NSG estimates that NeuStream® CO_2 capture parasitic power requirements for the fan and solvent pumps are 35% less than those associated with a packed tower application. Moreover, NSG performed tests with multiple solvents to demonstrate that the benefits of the NeuStream® technology are independent of the solvent employed.

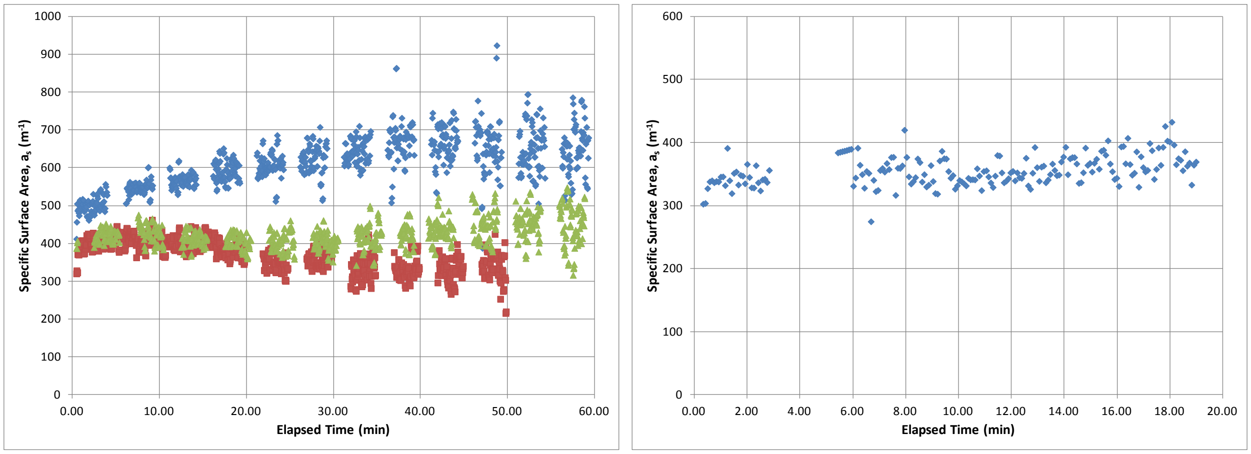

Figure 14: Performance comparison between 0.5MW CARE jets (blue) and stabilized jets (red and green), 0.25m (10”) jet length (left); Stabilized jets in 0.5MW CARE system, 0.76m (30”) jet length, steady-state test (right).

In addition to the testing performed with concentrated PZ described above, NSG investigated the performance of several other solvents to show that the NeuStream® absorber technology is widely applicable to a variety of common CO_2 capture solvents. Additional solvents tested included a monoethanolamine (MEA) / triethylene glycol (TEG) blend, a PZ / potassium carbonate blend, and Akermin’s proprietary solvent.

NSG tested a solvent blend of MEA and TEG in water in the NeuStream® 0.5MW CARE system. Testing was stopped almost immediately due to the formation of a significant aerosol cloud in the absorber that was not being captured by the amine wash. This aerosol was not observed during preliminary testing of the MEA/TEG solvent blend on NSG’s large bench-scale NeuStream® test stand (0.1 Nm^3/s, 200 scfm).

The main difference between the large bench scale system and the 0.5MW CARE system is the source of the flue gas supply. The large bench scale system flue gas is provided by a diesel generator which is fitted with an inline combustion filter to eliminate particulate emissions, while the natural gas boiler used to generate the flue gas for the CARE system does not have any particulate control. The formation of aerosols when using MEA solvent in the presence of very small particulates in the flue gas is well documented in the literature.

NSG also tested a blend of 2.6m PZ and potassium carbonate (4.25m K^+) in the NeuStream® 0.5MW CARE system. To facilitate determination of the mass transfer coefficients, specific surface area was assumed to be equivalent to that measured during PZ testing. In general, mass transfer coefficients agreed with those published by Rochelle for a 2.5m PZ / 5.0m K^+ solvent blend as shown in Figure 15. [29]

Finally, NSG worked with Akermin, Inc. to test their proprietary solvent in NSG’s large bench scale (0.1 Nm^3/s, 200 scfm) NeuStream® test stand. Prior to the start of the testing, minor modifications were made to the test stand to facilitate the testing of Akermin’s solvent. No compatibility issues between Akermin’s solvent and the NeuStream® absorber were observed. The data is considered proprietary to Akermin.

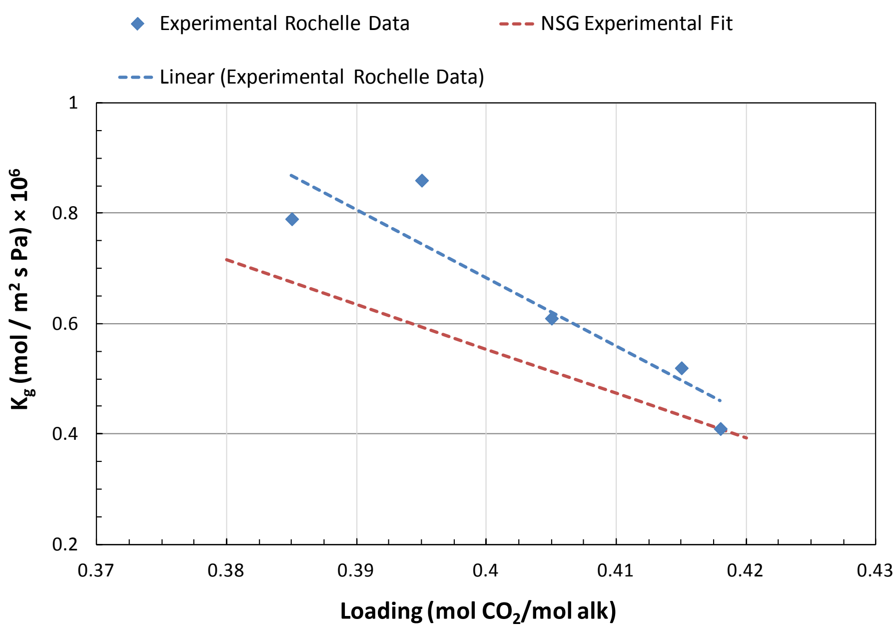

Figure 15: Mass transfer coefficients for ~2.5m PZ / ~5.0m K+ solvent blend measured on the 0.5MW CARE system vs. literature values [29]

VI. CONCLUSIONS:

In conclusion, NSG designed, built and tested a 0.5MW NeuStream® CO_2 capture system for project CARE. The system was tested both at CSU's Martin Drake PC power plant and at NSG's facility using flue gas from a natural gas boiler. The system performed as designed, exhibiting 90% capture at the Drake facility with all four absorber units in operation and ~80% capture at the NSG facility with three of the four absorber units in operation. Regenerated CO_2 purity was measured to be 98.6%, exceeding the 95% goal. The preliminary TEA performed by EERC predicted an over-the-fence cost of CO_2 capture at \$25.73/tonne, significantly below NETL's current 2025 goal of \$40/tonne. The corresponding COE increase is 40%, closely approaching the CARE program objective of 35% and significantly lower than the base case COE increase of 69%.

Additionally, as part of an internally funded IR&D project in direct support of the program objectives, NSG has successfully engineered improvements to the NeuStream® CO_2 absorber technology that reduces parasitic power associated with the absorber recirculation pumps by a factor of 10. This improvement in the technology will significantly decrease NeuStream® CO_2 capture system operating costs and the COE. Finally, a direct comparison of NeuStream® technology to conventional packed tower absorber technology predicts significant savings in volumetric footprint (up to 90% size reduction), cost (50% or greater) and electrical parasitic power (up to 35% less power required for pumps and fans).

Given the above results and NSG's successful track history of scaling NeuStream® technology to commercial scale as demonstrated by the commercialization of its NeuStream® FGD technology, it is clear that NSG's NeuStream® technology is relevant to the successful development of future commercial-scale CO_2 capture systems. The modularity of NeuStream® technology significantly reduces the risk involved in scaling NeuStream® CO_2 capture systems to larger pilots and ultimately to commercial scale.

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VIII. LIST OF ACRONYMS AND ABBREVIATIONS

a_s:	Specific surface area
BP:	Budget period
CARE:	Carbon Absorber Retrofit Equipment
CDR:	Critical design review
CO_2:	Carbon dioxide
COE:	Cost of electricity
CSU:	Colorado Springs Utilities
DCC:	Direct contact cooler
DVT:	Design verification testing
EERC:	Energy & Environmental Research Center (University of North Dakota)
EH&S:	Environmental health and safety
FGD:	Flue gas desulfurization
FTIR:	Fourier transform infrared spectroscopy
IR&D:	Internal research & development
L/G:	Liquid to gas ratio
MFC:	Mass flow controller

NG:	Natural gas
NSG:	Neumann Systems' Group, Inc.
PC:	Pulverized coal
PFD:	Process flow diagram
PZ:	Piperazine
SOPO:	Statement of project objectives
TEA:	Techno-economic analysis
TIC/TOC:	Total inorganic carbon / total organic carbon analyzer
VFD:	Variable frequency drive