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Demonstration of ION's Novel CO_2 Capture Solvent (ICE-31) with High Performance and Exceptional Stability through Field Testing at NCCC's PSTU with Coal and NGCC Gas

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Abstract

ION Clean Energy, Inc (ION) plans to decarbonize the electrical grid and carbon intensive industries by deploying its 3rd generation CO_2 capture solvent, ICE-31. After demonstrating the unique physical and chemical properties of ICE-31 at lab-scale, ION performed parametric and long-term steady state testing with ICE-31 as a drop-in solvent at the 0.6 MWe scale using the Pilot Solvent Test Unit (PSTU) located at the National Carbon Capture Center (NCCC) in Wilsonville, Alabama.

The testing was performed over 4,000 operational hours where ION captured 750 tonnes of CO_2 from natural gas combined-cycle (NGCC) type flue gas (4.4% CO_2), real gas-fired boiler-gas (7.8% CO_2), and real coal-fired flue gas (13% CO_2). Using a simple stripper configuration at the PSTU, ION demonstrated 95% CO_2 capture on the three flue gases setting respective baselines. With NGCC-type flue gas, ION increased to 98% capture and observed an increase in the Specific Reboiler Duty (SRD) by 2-3%. Using a heat-integrated stripper at the PSTU, ION demonstrated a minimum SRD of 2.6 GJ/tCO_2 at 91% CO_2 capture for NGCC-type flue gas with a slight increase to 2.7 GJ/tCO_2 at 97% capture. Under coal-fired flue gas conditions, ION achieved an SRD of 2.5 GJ/tCO_2 at 91% CO_2 capture.

After parametric testing, ION executed a long-term test on NGCC-type gas at 95% CO_2 capture for 1,500 hours. PSTU operation was stable and reliable with over 99% uptime and no solvent addition or reclamation. The overall mass balance for original solvent components was 99 ± 1% for the entire long-term test. Heat stable salts, mainly originating from flue gas NO_x, increased at 3.7 ppmw/day. Extractive sampling after the water wash for NH_3 and solvent were below 1 ppm and 40 ppb, respectively.

ION modeled the PSTU simple stripper results in Optimized Gas Treating's (OGT) ProTreat® process simulator utilizing default parameters for all heat and mass-transfer equipment. The model predicted SRDs with an average error of 0.4% ± 1.7%. ProTreat® modeling indicated that when utilizing ION's advanced heat-integrated stripper and ICE-31, typical U.S. facilities could expect SRDs of 2.6 GJ/tCO_2 for NGCC and 2.4 GJ/tCO_2 for coal-fired flue gas at 95% CO_2 capture.

Keywords: Solvent Carbon Capture; Specific Reboiler Duty; Heat Integrated Stripper; Natural-Gas Combined Cycle

1. Introduction

Carbon Capture Utilization and Storage (CCUS) technologies continue to be of great interest to point-source emitters as mechanisms to reduce their carbon footprint. ION Clean Energy, Inc. (ION) is developing and deploying solvent-based CO_2 capture technologies to decarbonize the electrical grid and carbon-intensive industries. As part of its continuous development of solvent-based capture systems, ION completed a six-month testing campaign for its third-generation solvent technology, ICE-31, at the National Carbon Capture Center (NCCC) in Wilsonville, Alabama, as part of U.S. Department of Energy project DE-FE0031727 "Validation of Transformational CO_2 Capture Solvent Technology with Revolutionary Stability." The objective for the project was to scale up ICE-31 from the bench scale to the pilot scale in an industrially relevant environment.

At NCCC, ION was afforded the opportunity to be the first technology developer to test at NCCC's Pilot Solvent Test Unit (PSTU) using ICE-31 as a drop-in solvent on the test facility's newly configured natural gas-fired boiler. ION commenced the campaign with parametric testing to determine Key Performance Indicators. This was followed by an extended, steady-state run to observe solvent performance and degradation rates using natural gas-fired flue gas. ION's results from this test program demonstrated a reduction in both capital and operating expenses to support large-scale carbon capture deployment within the next decade.

Nomenclature

AFS	Advanced Flash Stripper
CCUS	Carbon Capture Utilization and Storage
CRB	Cold Rich Bypass
ICE-31	ION's proprietary carbon capture solvent
NCCC	National Carbon Capture Center
NGCC	Natural Gas Combined Cycle
LWW	Lower Water Wash
OGT	Optimized Gas Treating
PSTU	Pilot Solvent Test Unit
SRD	Specific Reboiler Duty
UWW	Upper Water Wash

2. Methodology

2.1 PSTU Overview

The PSTU is a 0.6 MWe CO_2 capture pilot unit at NCCC. The primary flue gas utilized for the test campaign was provided from a natural gas packaged boiler and has a concentration of roughly 7-8% CO_2. The flue gas can then be cooled and diluted with air to natural gas combined-cycle (NGCC) type flue gas CO_2 content (4.4% CO_2) prior to introduction to the PSTU absorber. Pre-treated, coal-fired flue gas was also used for tests at about 12% CO_2 supplied by the host site E.C. Gaston coal-fired power station. The CO_2 absorption section contains three 6-meter beds of Sulzer Mellapak^{TM} 252.Y structured packing. Due to the exothermic reaction, the flue gas at the top of the column is significantly warmer than the inlet flue gas. Thus, a water wash vessel cools the flue gas to within a few degrees of inlet flue gas temperatures and restores water balance via recirculating, cooled wash water. The CO_2-lean flue gas exits the PSTU through an NCCC or Gaston stack for release to atmosphere, depending on the source of flue gas used.

Exiting the bottom of the absorber, the CO_2-rich solvent gravity-flows into a buffer tank. The rich solvent is then pumped through the lean-rich cross exchanger where it exchanges heat with the lean solvent and enters the top of the regenerator. The rich solvent flows down the regenerator, releasing CO_2 and absorbing water vapor while CO_2 and water vapor from the reboiler flow up the column. The semi-lean solvent falls to the stripper sump and recirculates through a forced-convection reboiler, which utilizes steam to heat the solvent and removes CO_2 to achieve lean loading. The lean solvent is then recirculated back to the absorber through the lean-rich heat exchanger for further CO_2 capture. The CO_2 out of the top of the stripper is cooled and then released to the atmosphere via the stack (Figure 1).

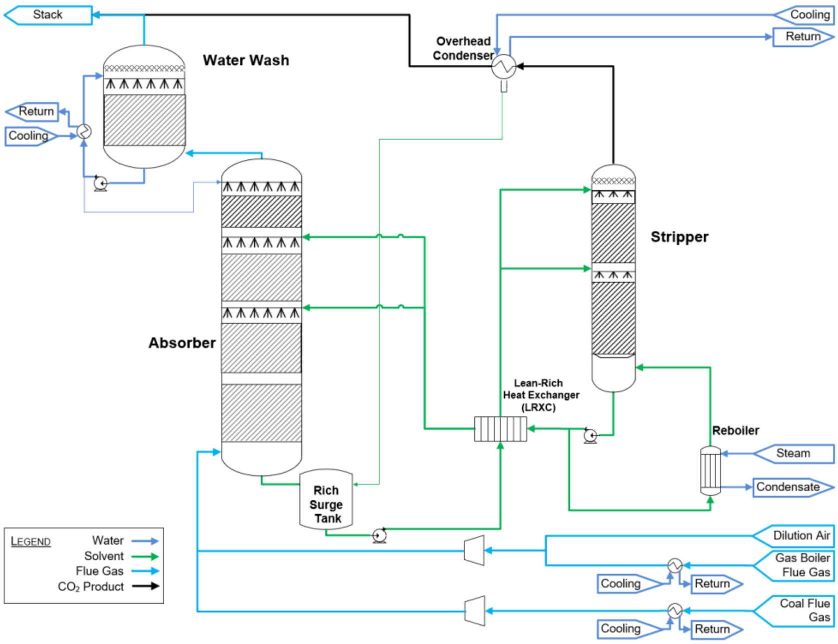

Figure 1: Process Flow Diagram for ICE-31 operation at the PSTU

2.2 PSTU Modifications

Prior to testing, ION requested modifications to the PSTU. The most impactful was the installation of a fourth bed containing a distributor and packing system (both Sulzer) designed specifically for solvent absorption in carbon capture water washes. This allowed for counter current gas-liquid mass transfer of solvent vapours into the water wash solution which significantly reduces solvent emissions.

In some of the work packages, ION also utilized an alternative configuration at the PSTU where the existing Advanced Flash Stripper (AFS) was incorporated into the regeneration process. The AFS is similar to the simple regenerator but with an incorporated heat exchange system [1, 2]. The rich solvent from the buffer tank is first split so a portion goes to a gas/liquid heat exchanger to exchange heat from the hot CO_2 out of the stripper. Similarly, after the first lean-rich heat exchanger, the other portion of warm-rich solvent bypasses the heat exchanger and enters directly in the top of the stripper. Lean solvent exchanges heat with the remaining portion of rich solvent. Finally, the hot-rich solvent passes through a once-through forced convection steam heater and then flashes into the bottom of the stripper.

2.3 Measuring Specific Reboiler Duty

Over the first two months of testing, ION focused on parametric data collection where 70 individual setpoints were measured. Each data point was recorded once both the Specific Reboiler Duty (SRD) and capture efficiency were constant within 1% over the course of 30 minutes. The most important output from the parametric data was SRD, defined by Equation 1.

$$SRD[=]\frac{GJ}{tonne\ CO_2} = \frac{Reboiler\ Heat\ Duty - Ambient\ Heat\ Loss}{CO_2\ Captured} \quad (1)$$

The reboiler heat duty was calculated from the overall flow of steam ($\dot{m}_{steam}$) into the reboiler multiplied by the enthalpy differential between the steam conditions into the reboiler and the condensate conditions coming out (Equation 2).

$$Reboiler\ Heat\ Duty[=]\frac{GJ}{hr} = \dot{m}_{Steam}(H_{steam} - H_{condensate}) \quad (2)$$

The captured CO_2 was measured on the absorber side of the process as the difference between CO_2 going in and coming out of the absorber (Equation 3).

$$CO_2\ Captured[=]\frac{tonnes}{hr} = \dot{m}_{Flue\ Gas\ in}C_{CO_2\ in} - \dot{m}_{Flue\ Gas\ Out}C_{CO_2\ out} \quad (3)$$

During the campaign ION measured the heat loss for the simple stripper configuration to estimate the ambient heat losses for the PSTU. For this measurement, the simple stripper was operated at standard gas and liquid flows but at a very low steam input. Under these operating conditions, most of the heat is lost to the atmosphere and only a small portion of the reboiler heat goes towards regenerating the solvent. To isolate the effects of temperature swings throughout the day, the data was analyzed and averaged over two days. Ambient heat loss was calculated at 60 MJ/hr under heat loss conditions, which extrapolates to 80 ± 10 MJ/hr at the standard reboiler temperature. Ambient heat loss accounts for a significant amount of overall heat duty for NGCC-type flue gases and must be properly considered in Equation 1 above to improve the accuracy of the modeling results. The same heat loss test was performed for the AFS configuration with the determined average heat loss of 70 MJ/hr.

2.4 Solvent Analysis

Solvent samples on both the lean and rich side were taken during each test condition throughout the parametric testing and at least three times a week during the long-term, steady-state testing. These samples were analyzed at NCCC's laboratories as well as in ION's laboratory in Boulder, CO. The water concentration was determined by Karl Fisher titration, CO_2 by Total Inorganic Carbon, and solvent components by Gas Chromatography. Heat stable salts and other anions were determined by Ion Chromatography, whereas Gas Chromatography in conjunction with Mass Spectrography was used to identify potential organic degradation products.

2.5 Emissions Analysis

The flue gas outlet of the PSTU was equipped with a Gasmet DX4000 hot-gas FTIR for continuous emissions monitoring. The sample was pulled through a heated line into the FTIR where the spectra was then analyzed for main solvent components as well as degradation products. Both the outlet of the lower water wash (LWW) and the upper water wash (UWW) were tested during the campaign. Table 1 provides the spectra range for the components analyzed along with the approximate limit of detection in the process gas. Residuals for the spectra were very low ranging from 0.001 to 0.003 for the analyzed species. Extractive samples for Ammonia (NH_3) were significantly lower than the reported FTIR results, showing that NH_3 was typically below the limit of detection throughout long-term testing.

Table 1: Emissions Analysis on Outlet Flue Gas

Component	Wavenumber [cm^{-1}]	Lowest Calibration Standard [ppm]	Limit of Detection [ppm]
Solvent Component(s)	3150-2700	30	~3
NH_3	1650-1550	10	~2
CH_2O	n.d.	25	~3
NO_2	n.d.	20	~1
NO	2000-1800	20	~1
H_2O	3450-3200	1000	-

3. Parametric Testing

3.1 Parametric Testing with Natural Gas Combined-Cycle (NGCC) type Flue Gas

ION analyzed ICE-31 performance over a range of operating conditions with NGCC-type flue gas by diluting the on-site boiler flue gas with air by approximately 50%. Table 2 gives the range of conditions and baseline condition for select operating parameters.

Table 2: Operating conditions for parametric testing with NGCC-type flue gas

Operating Condition for Parametric Testing: NGCC-type Flue Gas		
Condition	Range	Baseline
Inlet CO_2 [vol%]	4.3-4.5	4.4
Capture Efficiency [%]	78-98	95
Absorber Packing Height [m]	12-18	18
L/G [kg/kg]	0.7-1.1	0.8

3.1.1 Optimal Liquid to Gas Ratio at 95% CO_2 Capture

ION varied the L/G ratio at 95% ± 1% CO_2 capture to determine optimal performance of the solvent at the PSTU using an absorber packing height of 18 m. For each setpoint, ION modeled the steam duty needed for 95% capture prior to changing operating conditions. The steam load was then set at a determined flow rate, and the capture efficiency was allowed to reach steady state. The optimal lean loading is a balance between increasing carrying capacity of the solvent to limit sensible heat loss in the lean/rich cross exchanger and increasing lean loading in the stripper bottoms to better utilize stripping steam. Under these conditions, there was a wide optimal L/G range where these two effects balanced the SRD within 1% of the minimum (Figure 2). The wide range for optimal performance allows a more robust design of a large-scale facility without concern that solvent energy performance will be significantly different than the guarantees.

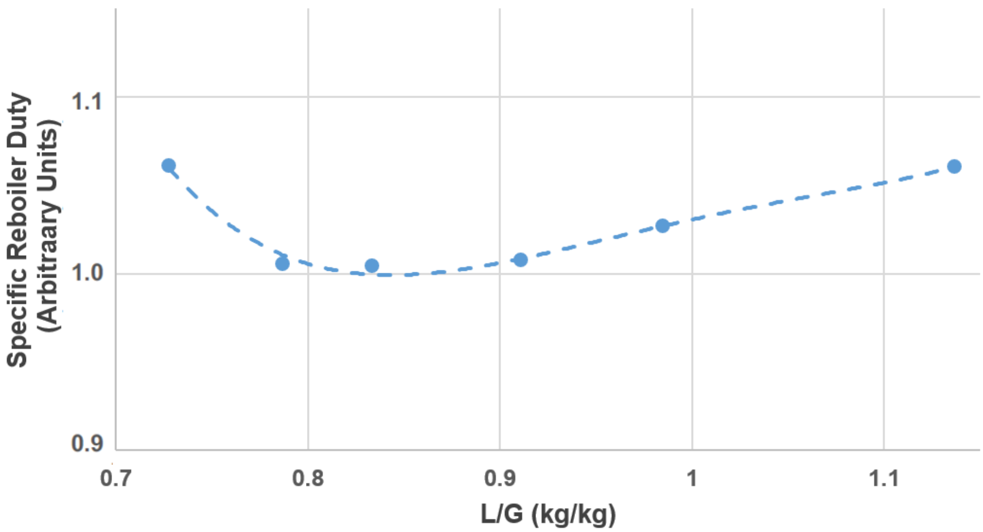

Figure 2: Optimal SRD at PSTU: 95% CO_2 capture with 4.4% inlet CO_2, 18m of MP252Y absorber packing

3.1.2 SRD versus Capture Efficiency

Another work package focused on varying the capture efficiency of the PSTU while simultaneously choosing optimal L/G ranges to determine minimum SRD performance at each capture efficiency. Both 12 m and 18 m absorber heights were tested for each capture efficiency; a 24 m absorber height was also modeled in ProTreat® after parametric testing (Figure 3). With 18 m of packing, the CO_2 mass transfer into the solvent was fast enough to reach a similar rich loading across the entire capture efficiency range. The modeled 24 m absorber only significantly outperformed the measured performance in the 18 m absorber at very high capture efficiencies above 97%. The lean loading became leaner as CO_2 capture efficiency increased, but due to the high heat of absorption of the ICE-31 solvent, the stripper sump temperature increased only 5 °C going from 78 % to 98 % CO_2 capture efficiency. There were no difficulties operating at the higher capture efficiencies.

The overall impact of the fast kinetics and favorable thermodynamics of ION's ICE-31 solvent demonstrate that there is only a 4% SRD penalty when increasing capture from 90% to 98%, even when using a simple stripper. Further optimization with cold-rich bypass allows even leaner optimal lean loadings and a smaller penalty when increasing capture efficiency. When utilizing 12 m of packing in the absorber, the rich loading approached equilibrium for the 80% and 87% carbon capture data points. However, the solvent could not reach its optimal rich loading at higher capture efficiencies, leading to an SRD penalty of 14% when increasing capture from 87% to 95%. The large energy penalty for high capture with 12 m of packing demonstrates the importance of optimizing packing height along with capture efficiency when designing for higher capture rates. However, there is little benefit to additional absorber packing above 18 m until the facility approaches carbon-neutral capture efficiencies.

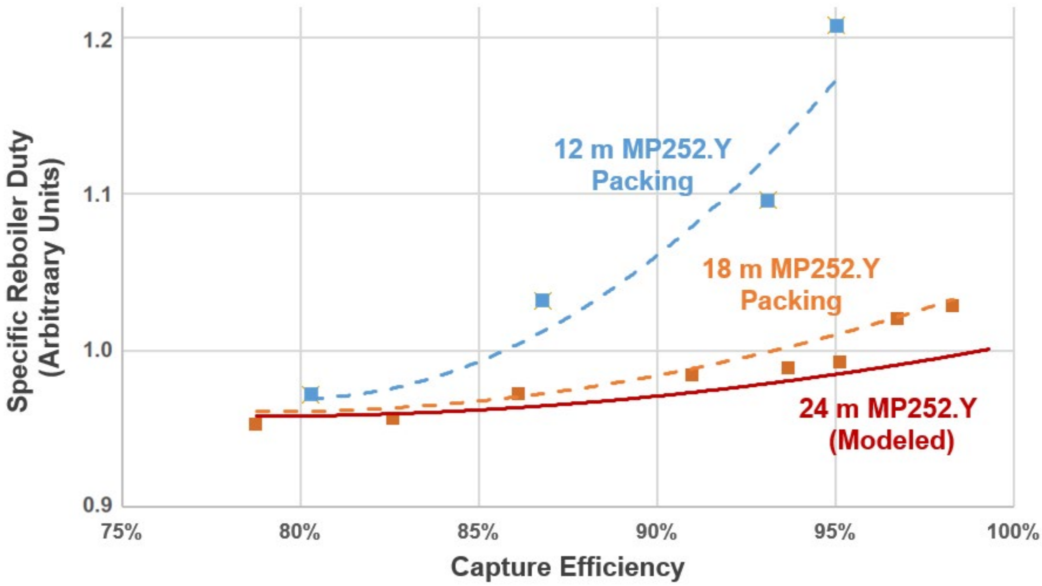

Figure 3: SRD at Optimal L/G for varying capture efficiencies with 4.4% inlet CO_2 measured at 12 m MP252.Y and 18 m MP252.Y absorber packing height and modeled at 24 m MP252.Y absorber packing height

3.1.3 Optimal SRD Using the Advanced Flash Stripper (AFS)

Similar to the simple stripper tests, ION ran a series of advanced stripper tests with varying capture efficiencies at optimal solvent flow and ratios for both the cold-rich and warm-rich bypasses. The AFS outperformed the simple stripper by 12-14% across all capture efficiencies (Figure 4). The lower SRD was possible due to the lower overhead stripper temperature, which fell about 40 °C when utilizing the optimal cold-rich and warm-rich ratios. Because of the heat capacity differences between the lean and rich solvents, the bypasses shift the temperature pinch to the hot-side of the lean-rich heat exchanger but do not significantly impact the total heat exchanged. The AFS operation empirically demonstrated an SRD of 2.7 GJ/tonne CO_2 at 95% CO_2 capture from an

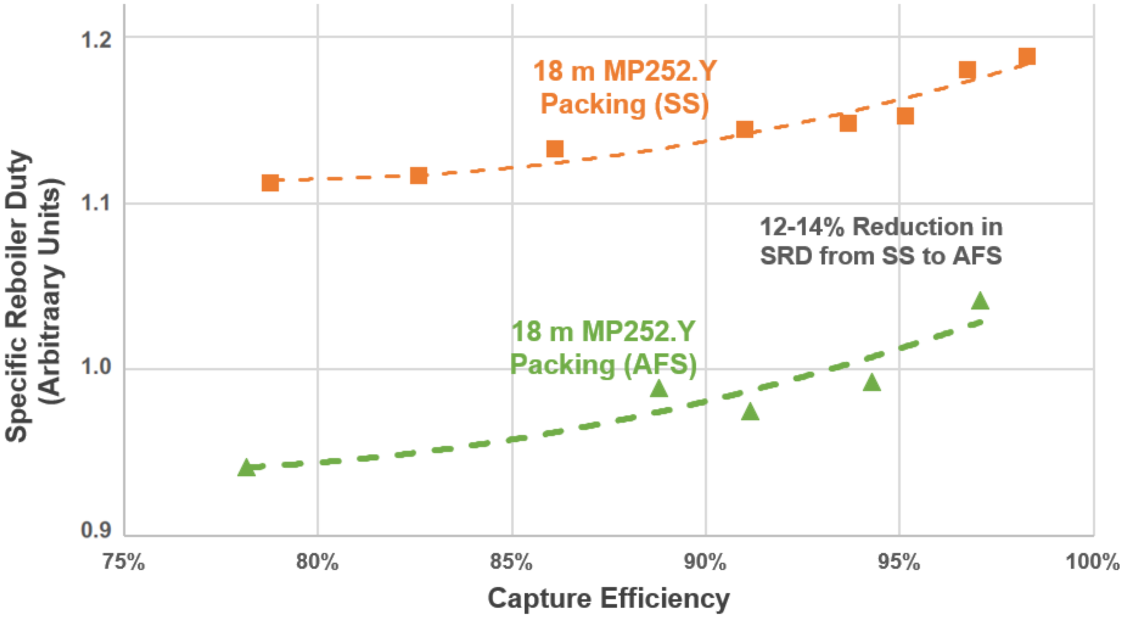

Figure 4: SRD at Optimal process conditions for varying capture efficiencies utilizing both the simple stripper (squares) and Advanced Flash Stripper (triangles) with 4.4% inlet CO_2

NGCC-type flue gas. With optimized equipment and ION's substantially similar heat-integrated process, ICE-31 will provide an SRD of 2.6 GJ/tonne CO_2 at 95% CO_2 capture from an NGCC flue gas.

3.2 Parametric Testing with Undiluted Natural Gas-Fired Boiler Flue Gas

ION analyzed ICE-31 performance over a range of operating conditions with undiluted boiler flue gas using the PSTU simple stripper to determine optimum performance both on PSTU equipment and for large-scale applications. Table 3 gives the range of conditions and baseline condition for select operating parameters.

Table 3: Operating conditions for parametric testing with undiluted boiler flue gas

Operating Conditions for Parametric Testing: Undiluted Boiler Flue Gas		
Condition	Range	Baseline
Inlet CO_2 [vol%]	7.2-7.4	7.2
Capture Efficiency [%]	74-98	95
Absorber Packing Height [m]	12-18	18
L/G [kg/kg]	1.3-1.8	1.5

3.2.1 Optimal L/G at 95% Capture

Similar to the NGCC-type flue gas, ION varied the L/G ratio at 95% ± 1% CO_2 capture to determine optimal performance with boiler flue gas using the simple stripper and an absorber packing height of 18 m. Under these conditions, there was a wide optimal L/G range of 1.5 ± 0.1 kg/kg where the SRD was within 1% of the minimum (Figure 5). Two points at 1.4 and 1.5 kg/kg showed significant error compared to the trend, likely due to changes in inlet flue gas temperatures, which varied by 15 °C and were not controlled during this testing.

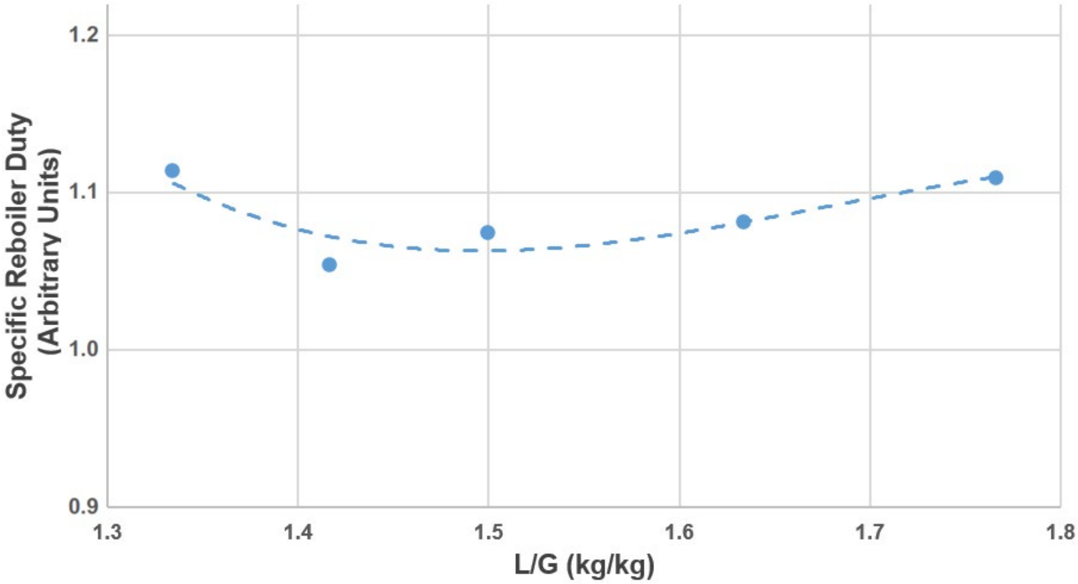

Figure 5: Optimal SRD at PSTU: 95% CO_2 capture with 7.2% inlet CO_2, 18 m of MP252.Y absorber packing

3.2.2 SRD Increase with Capture Efficiency

ION also varied the capture efficiency for the undiluted boiler flue gas while simultaneously choosing optimal L/G ranges for minimum SRDs. Both 12 m and 18 m absorber heights were tested for each capture efficiency (Figure 6). The overall impact of the fast kinetics and favorable thermodynamics demonstrate that there is only a 6% energy penalty in SRD when increasing capture from 90% to 98%, even when using a simple stripper. When utilizing 12 m of packing in the absorber, the rich loading approached equilibrium for the 73% and 86% capture data points. However, the solvent could not reach its optimal rich loading at higher capture efficiencies, leading to an SRD penalty of 11% when increasing capture from 86% to 93%.

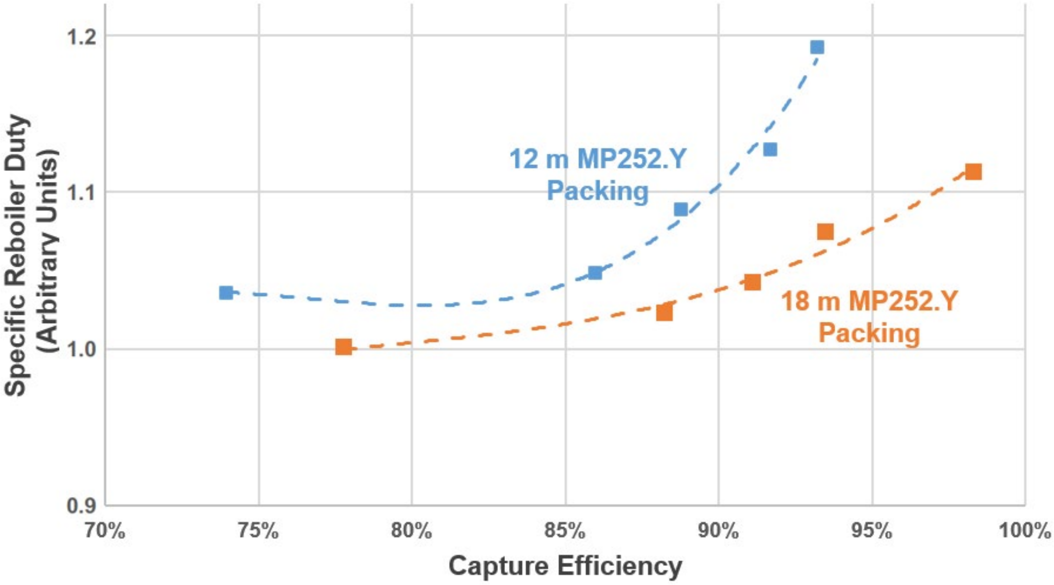

Figure 6: SRD at optimal L/G for varying capture efficiencies with 7.2% inlet CO_2 measured at 12 m MP252.Y and 18 m MP252.Y absorber packing height

3.3 Parametric Testing with Coal Flue Gas

ION analyzed ICE-31 performance over a range of operating conditions with coal flue gas from Plant E.C. Gaston using the PSTU simple stripper. Table 4 gives the range of conditions and baseline condition for select operating parameters.

Table 4: Operating conditions for parametric testing with Coal flue gas

Operating Conditions for Parametric Testing: Coal Flue Gas		
Condition	Range	Baseline
Inlet CO_2 [vol%]	12.2-11.7	11
Capture Efficiency [%]	94-96	95
Absorber Packing Height [m]	18	18

3.3.1 Optimal L/G at 95% Capture

ION again varied the L/G ratio at 95% ± 1% CO_2 capture to determine optimal performance with coal flue gas using the simple stripper and an absorber packing height of 18 m. Under these conditions, the optimal L/G was 1.9 kg/kg at an SRD of 2.9 GJ/tCO_2 (Figure 7). The coal flue gas had the lowest SRD of all flue gases due to its high CO_2 partial pressure at the absorber bottom. Whereas there was only a small increase in SRD over the NGCC-type and boiler flue gas cases because the solvent achieves a high rich loading with all three flue gas types.

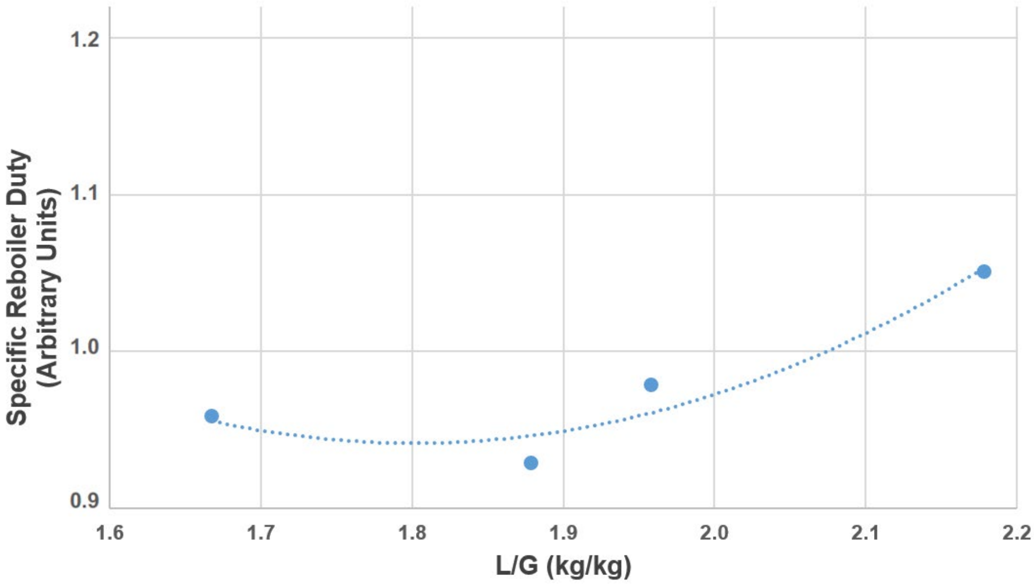

Figure 7: Optimal SRD at PSTU: 95% CO_2 capture with 11% inlet CO_2, 18 m of MP252.Y absorber packing

4. Long Term Steady State Testing

A critical test during the campaign was long term steady-state testing to determine the overall stability of the ICE-31 solvent. For this test, ION maintained an optimal plant performance with NGCC-type flue gas for 1,500 hours. The conditions for the long-term operation are shown below (Table 6).

Table 5: Operating conditions for long-term steady state

Operating Conditions: Long-Term Steady State	
Condition	Value
Inlet CO_2 [vol%]	4.4
Capture Efficiency [%]	95
Absorber Packing Height [m of MP252Y]	18
L/G [kg/kg]	0.8-0.9

PSTU on-time during the long-term operation was very high with only minor operational upsets. With almost a constant steam input, ION was able to maintain 100% of expected CO_2 capture output throughout the test. ION compensated for minor shutdowns due to boiler performance by operating at slightly higher than 95% average capture efficiency (Figure 8 & Figure 9).

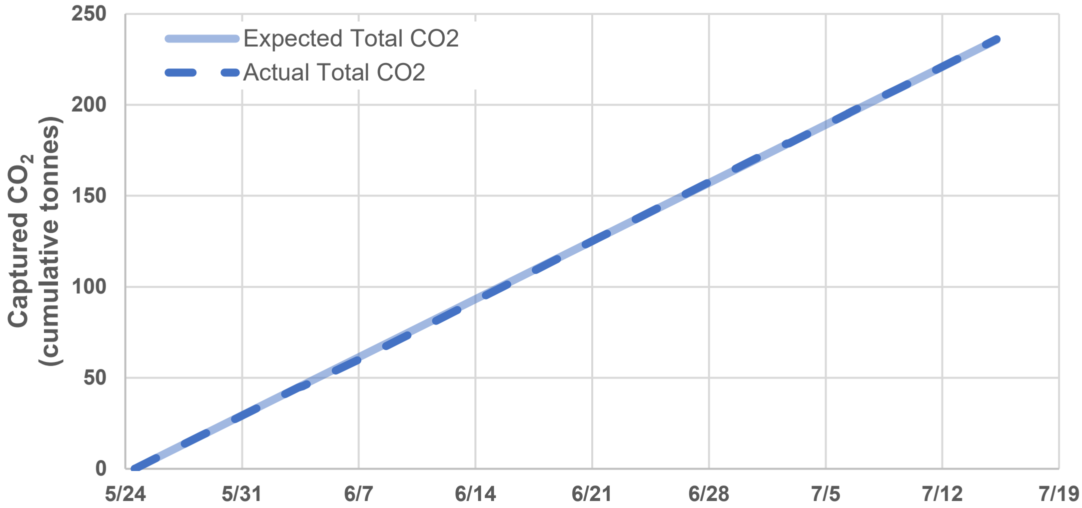

Figure 8: Total CO_2 captured during long-term steady-state operation

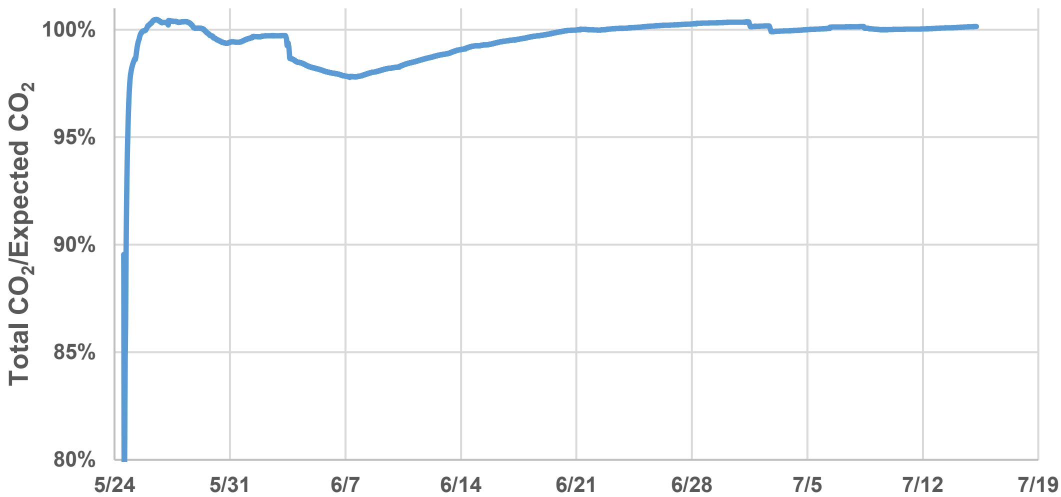

Figure 9: Comparison of Total Captured CO_2 over Expected Captured CO_2

4.1 Capture Efficiency and SRD

Since the steam rate was almost entirely constant throughout the long-term test campaign, the overall SRD at the expected capture efficiency was close to constant over the 1,500 hours of operations (Figure 10). The capture efficiency was also maintained with only minor drops. Each drop was attributed to a change in the steam flowmeter calibration that tended to drift on occasions during testing. After recorrecting the steam flowmeter, capture efficiency always returned to its previous point (Figure 11).

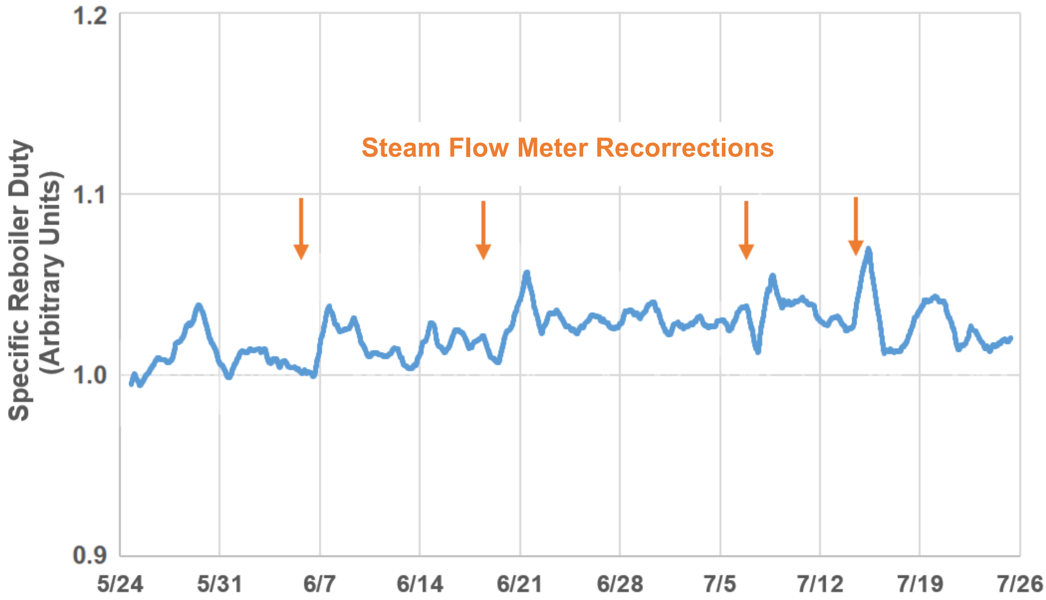

Figure 10: SRD during long-term operations; spikes in SRD correspond to suspected steam flowmeter miscalibration

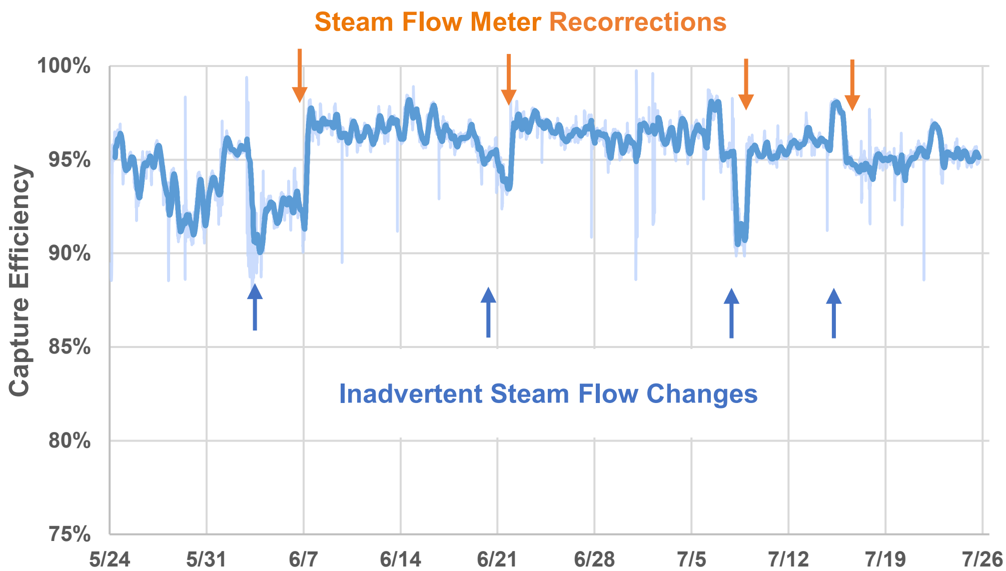

Figure 11: Capture efficiency for long-term operation (6-hr average)

4.2 Long-Term Emissions

The PSTU emissions were continuously monitored out of the water wash via a GASMET FTIR. NH_3 was the only emitted species detected by the FTIR with the overall spectra showing extremely low residuals. The FTIR typically reported NH_3 at 3-4 ppm outlet. The extractive sampling result showed NH_3 at 0.76 ppm when the FTIR reported 3.5 ppm, suggesting that the FTIR can only qualitatively determine NH_3 at low ppm levels.

Solvent components were also analyzed through both the FTIR and the extractive sampling. Components were below the quantitation limit of the FTIR throughout long-term testing and below the 40 ppb quantitation limit from RJ Lee, a third-party emissions analysis lab. Since ION could not analyze the flue gas outlet from the UWW, the focus shifted to LWW outlet. Once again, solvent components were at the FTIR detection limit after the lower water wash. To determine the impact of the LWW, ION stopped wash water flow to the LWW for approximately an hour and then restarted flow. The FTIR showed a lag of approximately 40 minutes while the LWW packing saturated with solvent vapors. Solvent concentration in the flue gas then increased to 430 ppm before the LWW wash water flow was re-activated. Immediately, the wash water absorbed solvent emissions until they were once again below quantification (Figure 12). The LWW absorbed over 99% solvent vapors during the test, demonstrating the low volatility of the ION solvent when utilizing the dual-stage water wash.

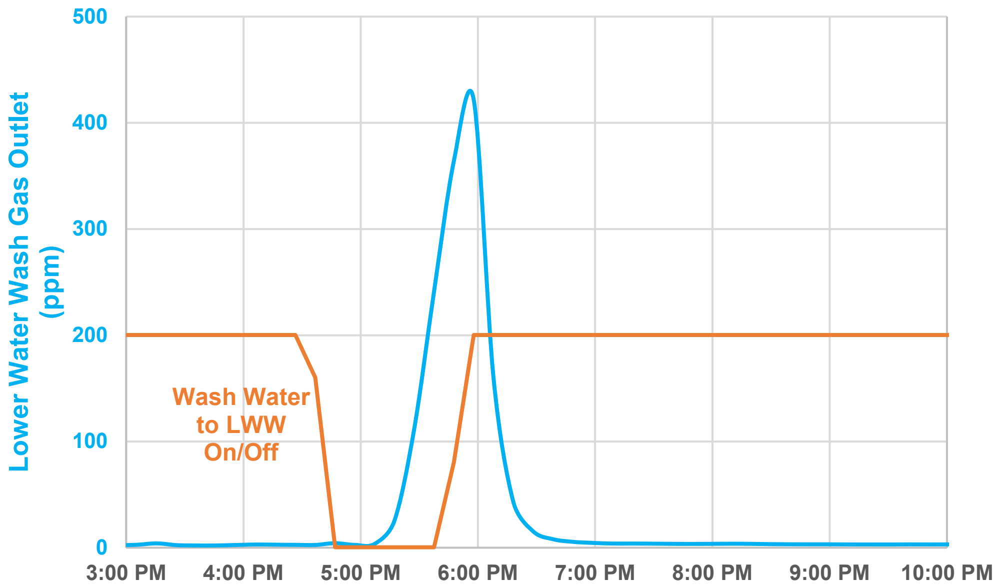

Figure 12: Solvent emissions response to LWW operation

Furthermore, the UWW circulating solvent was analyzed for solvent components to understand the amount of carryover from the LWW. During parametric operation, the wash water flow to the LWW turned off 1-5 times a day for up to half an hour at a time to maintain water balance. However, during long-term operations, the operators had a much better understanding of the wash water rate and were able to maintain continuous wash water flow for almost the entire 1,500-hour month test. When the LWW was in continuous operation, solvent component concentration in the UWW recirculating loop dropped over 50-fold (Figure 13). During coal testing and AFS parametric testing, the operators were able to maintain continuous wash water flow and extremely low solvent concentrations in the UWW circulating loop.

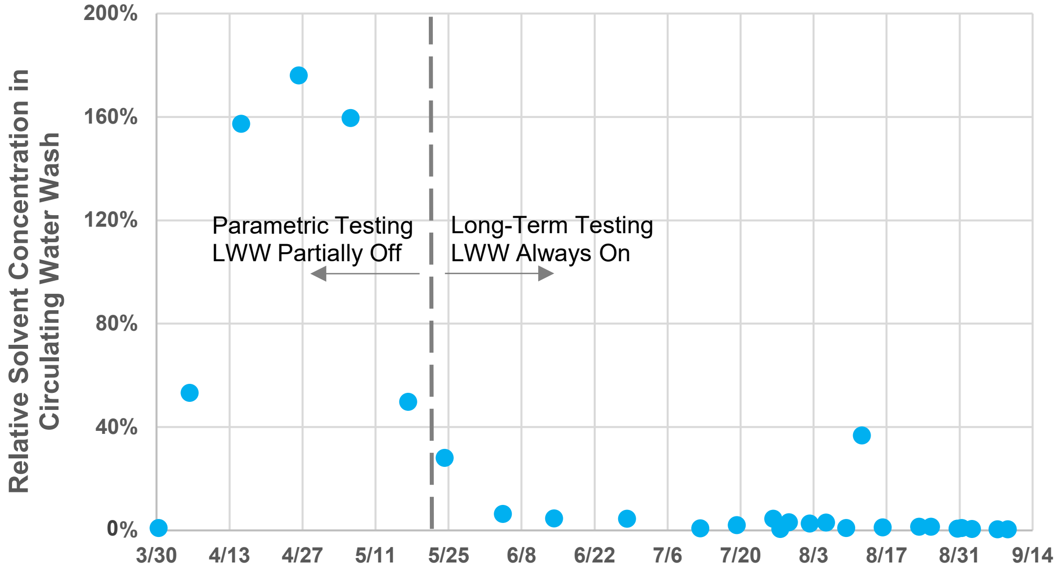

Figure 13: Solvent concentration in circulating upper wash water with different lower water wash operating conditions

4.3 Active Component Analysis

Lean samples from the long-term campaign were analyzed for all active components, CO_2, and water to determine the degradation rate of active components. Since total system inventory was constant throughout the testing, water content remained within a narrow range. However, to account for any minor difference in water content between samples, all solvent analyses were normalized by water content. A linear regression was applied to the loss rate for the total active components and then normalized to the total CO_2 captured using Equation 6. Since the loss rate is calculated from changes in the total solvent inventory, it encompasses all forms of solvent losses at the facility such as oxidative degradation, thermal degradation, flue gas emissions, and solvent spills.

$$\text{Solvent } Loss[=]\frac{kg\ Active}{tonne\ CO_2} = \frac{\Delta C_{Active}}{\Delta\text{time}} * \frac{m_{Inventory}}{\dot{m}_{CO_2 captured}} = \text{slope} * \frac{4200\ kg\ Solvent}{4.5\ tonnes\ CO_2/day} \qquad \text{Eq 6}$$

The loss rate for the sum of active components was statistically insignificant with total active concentration varying randomly at 99 ± 1% of the starting composition (Figure 14). Since longer-term testing is necessary to determine loss-rates for active components via the liquid-side mass balance, ION is building and testing its ICE-31 solvent in a purpose-built pilot at Los Medanos Energy Center in Pittsburg, California (Project Enterprise; DOE-FE0031950). The pilot will be installed on the commercially dispatched NGCC facility in Q1 of 2023 and operate throughout 2024. Results will be used to fine-tune emissions and degradation models for ICE-31 as well as develop reclaiming strategies necessary for multi-year operations.

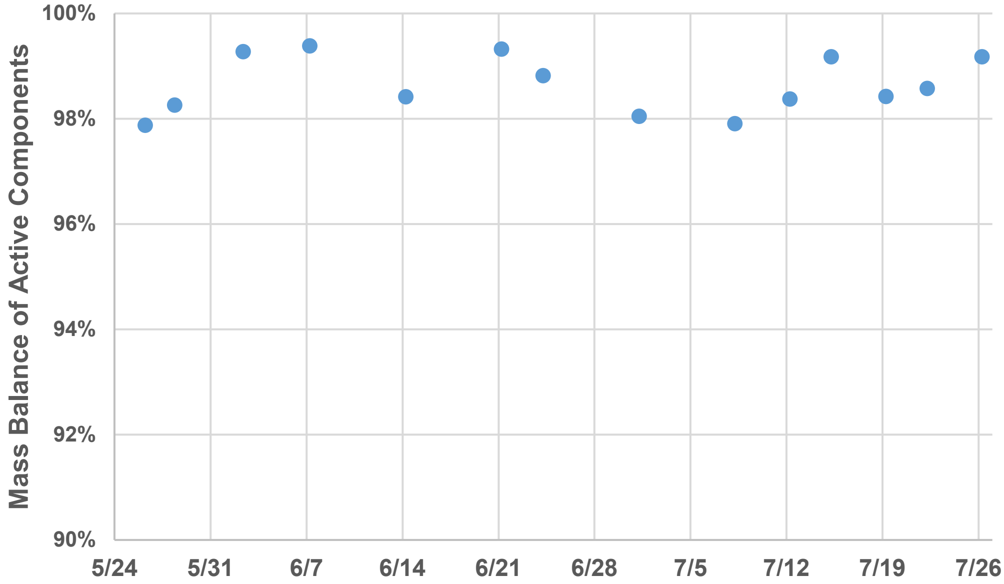

Figure 14: Total solvent component mass balance over the 1,500-hour long-term campaign including active components, water, and CO_2

5. Heat-Stable Salt Analysis

Heat-Stable Salts (HSS) are introduced either by flue gas impurities or are the result of amine oxidation. The major HSS observed during this campaign were sulfate, Degradation Product A, nitrate, nitrite, and Degradation Product B (in order of abundance). Figure 15 shows the HSS content during the entire campaign; the dips in concentration on 7/28 are due to taking a significant sample after the long-term testing on natural gas-derived flue gas and replacement of that solvent with fresh solvent in preparation for testing on coal-derived flue gas.

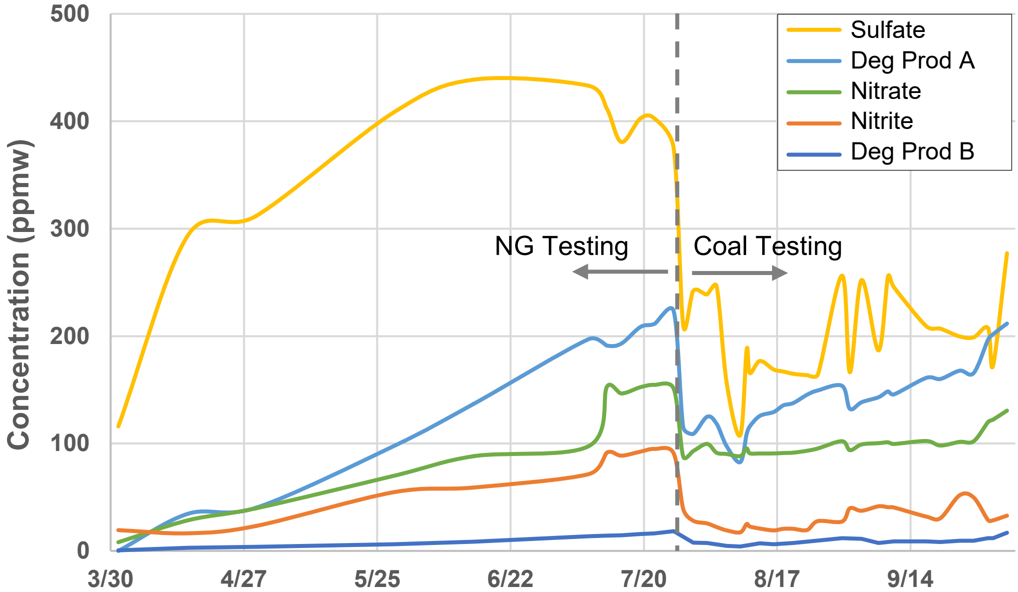

Figure 15: HSS accumulation throughout test campaign; the variation on 7/28 was due to solvent replacement upon changing from natural gas-focused to coal-focused flue gas testing

Sulfate (SO_4^{2-}) was the major HSS accumulating in the solvent. It derives from capture of SO_x (mostly SO_2) in the flue gas stream and subsequent oxidation of the intermediary sulfite (SO_3^{2-}) to sulfate. Nitrites (NO_2^-) and nitrates (NO_3^-) are the other major HSS introduced by flue gas NO_x, a mixture of gases primarily containing NO and NO_2. NO_2 is an acid gas which readily dissolves in alkaline solvents to form a mixture of nitrite and nitrate. The maximum combined nitrite/nitrate concentration was about 250 ppm at the end of the boiler gas testing (end of July) and the accumulation rate decreased thereafter.

Degradation Product A and Degradation Product B are the only HSS that were found in the solvent resulting from solvent oxidation at a maximum concentration of about 200 ppm and 20 ppm, respectively. Low heat stable salt formation demonstrates that ICE-31 does not need continuous reclaiming for flue gases with proper pre-treatment.

6. ProTreat ® Model Validation

The results for the simple stripper cases were thermodynamically and kinetically validated in the Optimized Gas Treating's (OGT) ProTreat® process modeling tool. These validated results were then used to build a process model with stripper heat integration. The benefits of heat integration were empirically tested on both coal and natural gas using the AFS equipment at the PSTU. These empirically show the 12-14% reduction in SRD compared to the simple stripper operation that the ProTreat® model predicts.

ProTreat® was validated against the simple stripper data using a process model that matches the PSTU mass and heat transfer equipment (Figure 16). Packing heights and packing types used the default values built into the ProTreat® model, which have been validated directly with Sulzer's test facilities. The lean-rich heat exchanger (LRXC) is significantly over-sized for the lower solvent flows needed for the high-capacity ICE-31. Thus, the pressure drop across the LRXC was less than 1 psi and flow was laminar. Instead of attempting to model the heat transfer coefficient so far from the LRXC design point, the shortcut heat transfer method was used with the measured temperature approach on the cold side as an input. The overall model was iteratively solved for reboiler heat duty necessary to achieve the experimental CO_2 capture as determined by the flue gas outlet mole fraction. For simple stripper and lower water wash operation, streams 202 and 304 were modeled at 1% of streams 209 and 303 respectively. Table 5 gives the other main inputs and outputs from the ProTreat® validation models. All parametric test conditions reported above were validated and reported in the ProTreat® process models.

Table 6: Select inputs and outputs for ProTreat® process model validation

Stream #	Input	Output
101 (Dilution Air In)	Flow, Pressure, Temperature, Composition	-
100 (Flue Gas In)	Flow, Pressure, Temperature, Composition	-
301 (Absorber Rich Outlet)	Flow	Temperature, CO_2 Loading
205 (Water Wash Recirculation)	Flow	-
208 (Water Wash Recirculation)	Temperature	-
104 (CO_2 Out)	CO_2 Mole Fraction	Solvent Mole Fraction, Temperature
501 (Stripper CO_2 Outlet)	Pressure	Temperature, Water Content
Absorber	-	Max Temperature
Stripper	-	Specific Reboiler Duty (SRD)
403 (Stripper Lean Outlet)	-	Temperature. CO_2 Loading

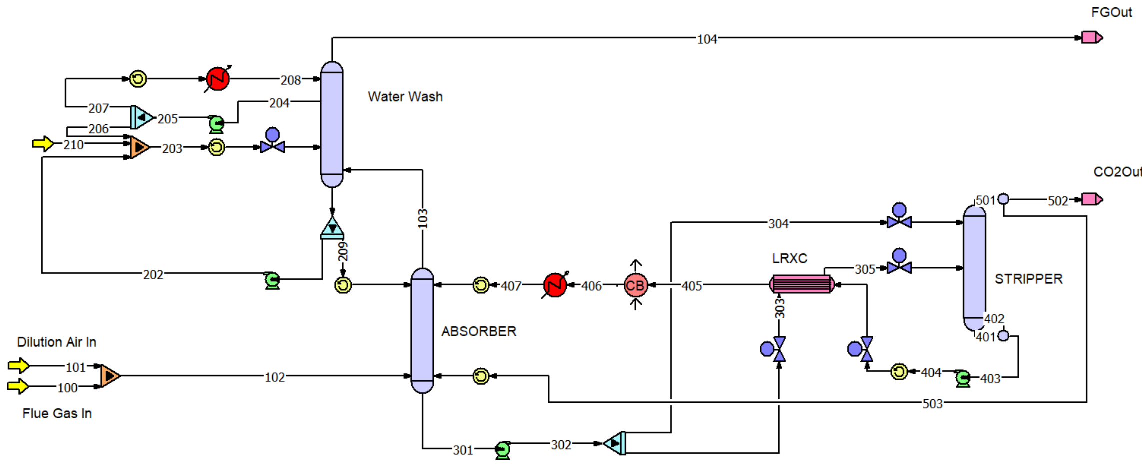

Figure 16: ProTreat® process model for simple stripper validation

6.1 Process Model Fit for SRD

ProTreat® models closely validated the NCCC results for SRD over the wide range of flue gas, capture efficiency, and flow rate parametric test conditions. The average error for SRD was only 0.4% with a standard deviation of 1.7% (Figure 17). The very close fit proves the robust nature of the thermodynamic and kinetic framework with the ICE-31 module inside OGT's ProTreat® software. This imparts strong confidence in ION's ability to model energy performance for large-scale systems and minimizes the risk in utility costs associated with those projects. The maximum error was 3% and was associated with the two outliers at high SRD's. These two points were run at the highest capture efficiency with only two absorber beds and consequently had significantly lower rich loading than the other points. These points are far away from standard operating conditions for ICE-31 and can be avoided in large-scale applications by optimizing absorber height along with capture efficiency.

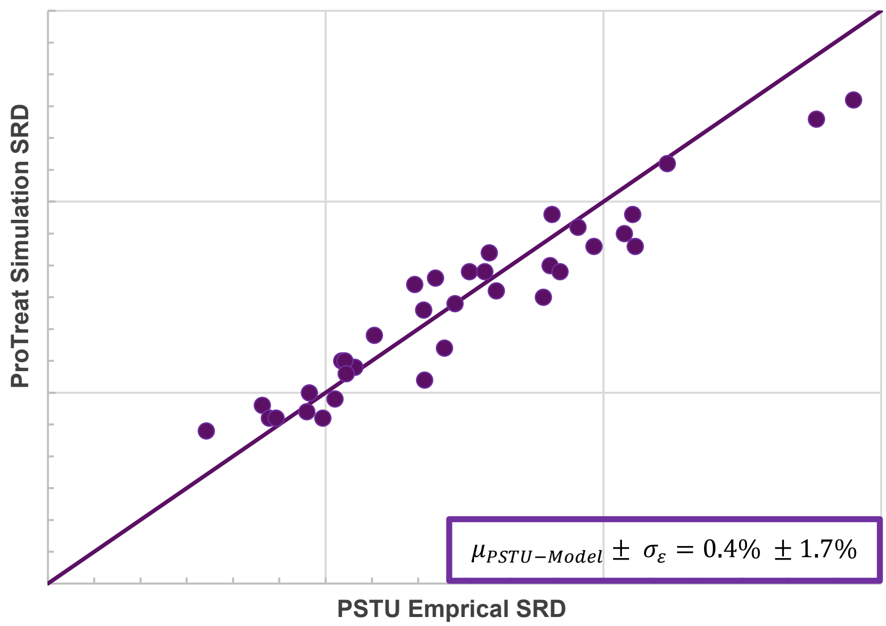

Figure 17: ProTreat® process model validation versus empirical results for SRD

6.2 ProTreat® Process Model Fit for Other Key Performance Indicators

Results from the process model were also used to validate the cooling and pumping loads for a large-scale facility. To determine this, model temperatures and solvent CO_2 capacity at key process points were compared to empirical results. ProTreat® was able to simulate process conditions at all points in the process model with extremely good fit similar to ICE-21 validated at NCCC and TCM [3, 4]. In all cases, the PSTU empirical results are not statistically different than the ProTreat® simulated results (Figure 18).

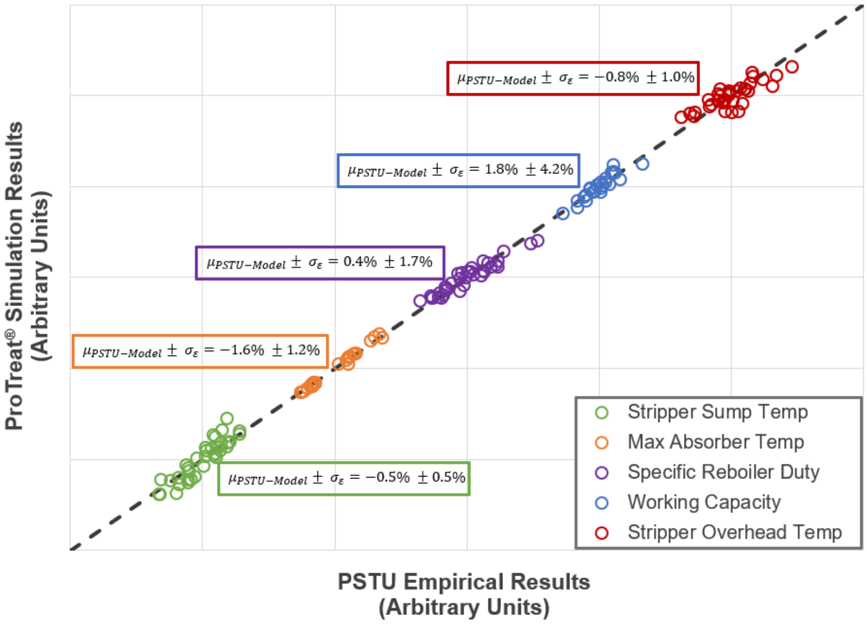

Figure 18: ProTreat® process model validation for other empirical results

7. Outlook

ION has partnered with Calpine California CCUS Holdings and Sargent & Lundy to present a Front-End Engineering Design (FEED) for the installation of a Carbon Capture System retrofitted to Calpine's Delta Energy Center (DEC) removing 2.4 million tonnes of CO_2 per annum (mtpa). DEC is an 857 MW natural gas-fired combined cycle (NGCC) power plant located in Pittsburg, California, USA [5]. Additionally, ION is partnering with Tampa Electric Company to conduct a FEED study for retrofitting ION's post-combustion CO_2 capture technology at Polk Power Station – an existing 1,190-MW NGCC power station in Mulberry, Florida, USA. The Polk site can capture nearly 3.7 mtpa and has many features that make it an ideal candidate for post-combustion carbon capture including favorable geology for large-scale CO_2 storage onsite.

In parallel to FEED studies, ION will fine-tune and operate ICE-31 solvent in an end-to-end fashion focusing on minimization of pre-treatment, reclamation and emissions in a custom-built pilot plant capable of capturing 10 tonnes per day during a long-term operation (~10,000 h). This pilot will take a 1 MWe slipstream from Calpine's NGCC at Los Medanos Energy Center in Pittsburg, California, USA.

8. Conclusion

ION confirmed the strong performance of its ICE-31 solvent over 4000 hours of parametric and long-term steady state testing using NGCC-type flue gas (4.4% CO_2), real gas-fired boiler gas (7.8% CO_2), and real coal-fired flue gas (13% CO_2) on the PSTU at NCCC. ION demonstrated 95% CO_2 capture on all three flue gases, achieved steady-state capture efficiencies of up to 98% capture with NGCC-type flue gas, and reached over 99% capture during dynamic operations. Using the PSTU Advanced Flash Stripper configuration, ION demonstrated a minimum SRD of 2.6 GJ/tCO_2 at 91% CO_2 capture for NGCC-type flue gas with an increase to 2.7 GJ/tCO_2 at 97% capture.

During the 1,500 hour long-term test on NGCC-type gas at 95% CO_2 capture without reclamation or solvent make-up, the overall mass balance for original solvent components was 99 ± 1%. These results further substantiate the environmentally advantageous characteristics of the ICE-31 solvent, including extremely low solvent replacement rates in high oxygen environments. Lastly, ICE-31's stability is further demonstrated through the emissions monitoring and extractive sampling – with NH_3 emissions below 1 ppm and solvent below 40 ppb.

Utilizing OGT's ProTreat®, which was further validated with the empirical data from this test campaign, ION's process model predicted SRDs with an average error ± standard deviation of 0.4% ± 1.7%. The modeled performance indicates that typical U.S. facilities, where processes are optimized for capital costs due to relatively low fuel costs, ION's technology could provide SRDs of 2.6 GJ/tCO_2 for NGCC-type and 2.4 GJ/tCO_2 for coal-fired flue gas at 95% CO_2 capture. In high fuel-cost cases, ION could further reduce SRD values.

The process performance results confirm ION's expectations that ICE-31 is an exceptional solvent for post-combustion carbon capture in general, but more specifically is extremely well suited for high oxygen environments such as NGCC facilities. ION is commercializing this technology through multiple projects with large-scale utilities such as Calpine and Tampa Electric.

Acknowledgments

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