17th International Conference on Greenhouse Gas Control Technologies, GHGT-17

20th -24th October 2024 Calgary, Canada

Demonstration of ION's Novel CO_2 Capture Solvent (ICE-31) at TCM's Amine Plant with Transformational Deep Decarbonization and CO_2 Capture Co-Benefit Results

N.A. Fine*, M.A. Lynch, A.R. Awtry, R. Kupfer, K.L. Gray,
D.H. Shierstone, J.S. Atcheson, N.S. Brown, A.E. Brown, E.E.B. Meuleman

ION Clean Energy, Inc., 2995 Center Green Ct, Boulder, CO 80301, USA

Abstract

ION Clean Energy (ION) recently demonstrated their novel amine-based solvent system (ICE-31) in the Amine Plant at the Technology Centre Mongstad (TCM) in Norway. Various flue gases from the adjacent Equinor refinery were utilized during this campaign; coal-type flue gas from the Residue Fluid Catalytic Cracker (RFCC) and combined-cycle gas-turbine (CCGT)-type gas from the newly operational Mongstad Heat Plant (MHP). ION's objectives while testing at TCM were to evaluate ICE-31's operability window, revalidate ProTreat® for process simulations, achieve deep decarbonization on a large-scale pilot facility, and verify co-benefits of post-combustion CO_2 capture. These were accomplished through comprehensive parametric testing with both flue gas types, followed by performance testing via long-term stability operations, and completed with extensive isokinetic testing. The resulting data demonstrates ICE-31's low energy consumption, transformational low emissions, deep decarbonization capture efficiencies, and exceptional solvent stability with over 2,500 hours contacting flue gas.

The test campaign validated ION's ProTreat ® simulation tool at large scale (over 10 MWe flue gas; 100 to 200 tpd) and prepares ICE-31 for a Technology Readiness Level of 7 when deployed for commercial applications.

ION has conducted a comprehensive and successful program in close collaboration with all project partners including TCM, Lawerence Livermore National Laboratory (LLNL), Lawrence Berkeley National Laboratory (LBNL), FORCE Technology (FORCE), SINTEF, and University of Oslo (UiO). Various configurations of the two flue gases were leveraged throughout this campaign including MHP undiluted, MHP diluted, RFCC diluted with Brownian Demister Unit (BDU), RFCC undiluted with BDU, RFCC diluted with BDU bypass, and MHP diluted with CO_2 product recycle. The resulting data from each of these configurations strengthens the development of ION's transformational solvent (ICE-31) and provides confidence to operate as a drop-in solvent for large point sources including both power generation and industrial flue gas types. In addition to the work package goals, the resulting data was used to validate the process model which is critical to developing large-scale engineering designs with confidence.

ION has worked with their project partners at LLNL to evaluate the techno-economic analysis of deep decarbonization and the additional CO_2 reduction usually only reached by Direct Air Capture technologies. Results indicate that even as a stand-alone technology, ION's ICE-31 solvent is highly competitive with state-of-the-art

DAC technologies for incremental capture costs from air.

Throughout the pilot campaign at TCM, ION proved their 3rd generation transformational solvent successfully operated as a drop-in solvent with significantly lower liquid circulation rates, specific reboiler duties (SRD), and higher capture rates compared to MEA. ION reached new limits of steady-state high capture efficiencies, resulting in the depleted flue gas out of the absorber containing less CO_2 than the surrounding air. ION will leverage these results to inform commercial facility design and operations as the company continues to grow its project portfolio.

Acknowledgment: Technology Centre Mongstad team in Mongstad, Norway; Lawrence Livermore National Laboratory team in Livermore, California, USA; FORCE Technology team in Denmark, University of Oslo team in Oslo, Norway

Keywords: Water-lean solvent; Costing; Post-combustion capture of CO_2; Large-scale pilot operations; Carbon capture scale-up; Deep decarbonization; CO_2 capture co-benefits; Enhanced emissions mitigation from carbon capture

---

1. Introduction

Many research organizations and companies are developing and investigating carbon capture technologies to remove or reduce the quantity of CO_2 emitted into the atmosphere from flue gas emissions. The increased levels of atmospheric CO_2, since the industrial revolution, are largely attributed to emissions from industrial facilities and the combustion of fossil-fuel for power generation. Solvent-based technologies that interact with flue gas to selectively remove CO_2 are most common for post-combustion processes and represent the most promising technology for retrofitting carbon capture systems to existing power plants.

ION's proprietary ICE-31 solvent is a leading third-generation solvent system currently under development for post-combustion CO_2 capture. ION has consistently demonstrated significant reductions in regeneration energy requirements in comparison to traditional aqueous mono-ethanolamine (MEA) throughout bench-scale and laboratory testing, small-scale pilot testing with coal, and large-scale pilot testing with natural gas-fired and residue fluid catalytic cracker flue gases. This reduction is directly correlated to ION's physiochemical solvent characteristics, which include higher carrying capacity and a lower specific heat capacity, as well as an advanced process design.

TCM is the world's largest and most flexible amine facility for testing and improving technologies for point source carbon capture[1]. TCM is owned by the Norwegian State, through Gassnova (34%), together with the industrial partners Equinor (22%), Shell (22%), and TotalEnergies (22%). Equinor operates the amine facility and the adjacent refinery. Planning for TCM began in 2007, and the plant was operational starting in 2012. TCM has hosted many open-source and private customers throughout its twelve years of operations.

The amine plant at TCM has multiple components that allow for vast testing flexibility to TCM's customers (Figure 1). Customers can utilize two differing flue gases while operating: Mongstad Heat Plant (MHP) flue gas and Residue Fluid Catalytic Cracker (RFCC) flue gas. The MHP flue gas is fueled by refinery off-gas and results in 8 – 9% CO_2 compared to 3.5 – 4% CO_2 in a typical natural gas derived combined heat and power flue gas. The MHP flue gas has caustic injection into the DCC as a form of pretreatment and has the ability to recycle CO_2 from the product stream to the absorber inlet flue gas, up to 20%. The RFCC flue gas has a composition of 14% inlet CO_2 concentration and uses a Brownian Demister Unit (BDU) to reduce the aerosols entering the DCC and absorber. The facility has a rectangular absorber constructed with cement; a polypropylene plastic liner separates the concrete walls from the solvent. The absorber has five sections of packing: two dedicated to solvent contacting, two dedicated to water wash sections, and one flexible bed to be used for either configuration. There are two strippers available for operations: CHP and RFCC. These differ in diameter and reboiler type. The CHP stripper has a diameter of 1.25 meters while the RFCC stripper has a diameter of 2.17 meters. The CHP stripper utilizes a plate & frame reboiler while the RFCC stripper uses a shell & tube reboiler. The facility also has the capabilities of intercooling before the bottom bed of absorber packing, a cold-rich bypass stream around the Lean Rich Heat Exchanger (LRHX), and a trim cooler for additional lean solvent cooling before re-entering the absorber.

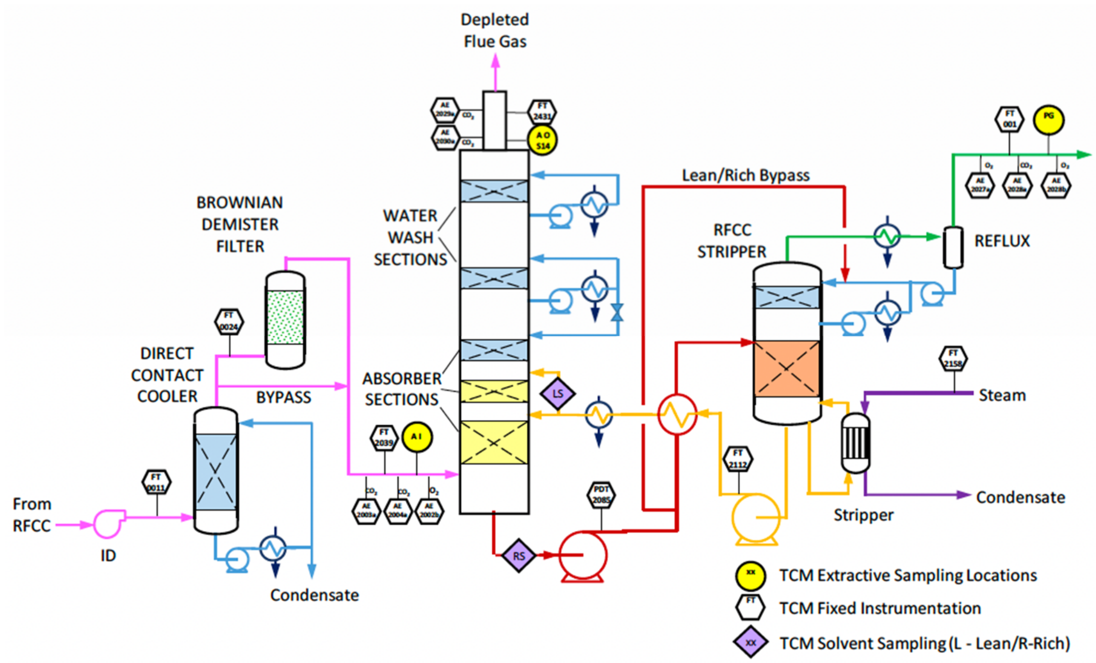

Figure 1: RFCC Stripper Configuration Process Flow Diagram[1]

While the RFCC process flow diagram (PFD) is shown above, the Table 1 & Table 2 outline the differences between the flue gas and stripper potential configurations.

Table 1: TCM Flue Gas Differences

MHP Flue Gas	RFCC Flue Gas
Caustic Injection	Caustic Injection and BDU Filter
CO_2 Recycle	No CO_2 Recycle

Table 2: TCM Stripper Differences

CHP Stripper	RFCC Stripper
Plate & Frame	Shell & Tube
Small Stripper	Large Stripper

2. Test Plan

ION Clean Energy (ION) began their campaign with ICE-31 at Technology Centre Mongstad (TCM) the first week of October 2023. During the first month, ION completed commissioning and the first parametric testing setpoints on the CHP stripper.

In November, ION performed initial deep decarbonization testing and coal-equivalent parametric baselining, studied the impacts of aerosols, and assessed the energy savings from optimizing RFCC stripper operating pressure. ION was required to switch to the RFCC flue gas from Nov 8th through Nov 23rd due to a planned maintenance shutdown of the MHP flue gas.

ION began the month of December optimizing pilot performance for deep decarbonization testing. Additionally, December kicked off the start of long-term stability testing which included a week at three solvent-contacting beds in the absorber, targeting 98% capture, and a week with two solvent-contacting beds in the absorber, targeting 87% capture. These tests were all performed on the CHP stripper using MHP flue gas.

In January, ION ran two additional long-term steady state tests: one week of 4% MHP flue gas followed by one week of 6% MHP flue gas with three solvent contacting beds. FORCE, a 3rd party emissions monitoring company, then came onsite to sample the flue gas inlet and outlet of the absorber for emissions verification. The first week of FORCE sampling included steady state operations with MHP flue gas. The second week included two days of BDU bypass testing and two days of steady state RFCC flue gas operations. After completion of FORCE testing, ION ran the high-CO_2 inlet flue gas commercial applicability work package with inlet CO_2 concentrations at 6% – 20% using RFCC flue gas (6% – 12% CO_2) and MHP flue gas (12% – 20% CO_2) using both CO_2 product recycle and absorber intercooling.

ION assessed each setpoint by extracting the raw data from IP21, TCM's data historian interface, for the timespan that the test was run and selecting a 30-minute average, representative steady state point for the results. Most setpoints were held for 6 – 8 hours to ensure steady state conditions were reached, however some setpoints required less or more time depending on the setpoint goal and process conditions.

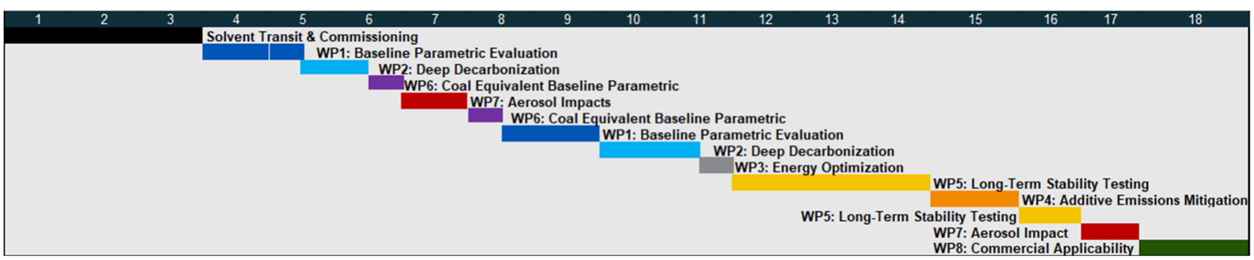

Figure 2: Weekly ION Test Plan at Technology Centre Mongstad

3. Results & Discussion

3.1 Parametric Baselining

As a drop-in solvent at TCM, it was imperative to baseline the facilities process conditions with ICE-31. Parametric baselining was performed to compare the performance of MEA at TCM vs ICE-31 at TCM, evaluate the optimal liquid flow rates with both strippers, and assess energy consumption at standard conditions early in the campaign.

3.1.1 MEA Baseline

ION evaluated the ICE-31 solvent against results that TCM has previously published using MEA. The inlet process parameters were mimicked from the MEA campaign run in 2015; including the inlet flue gas CO_2 concentration and the inlet flue gas flow rate. The resulting required liquid solvent flow rate for ICE-31 was 77% of the liquid solvent flow rate with MEA, indicating a higher capacity solvent requiring less inventory, lower circulation rates, and therefore less pump power. In addition, the improvement to the capture efficiency of the system was greater than 10% from MEA to ICE-31. This resulted in a depleted flue gas CO_2 reduction of 3.6-fold, from 6,500 ppm with MEA to 1,800 ppm with ICE-31. Additionally, the heat loss corrected energy required to achieve 10% greater capture with ICE-31, using the same process conditions, was 9% less than the non-heat loss corrected MEA setpoint. Overall, these results indicate a tremendous improvement in solvent performance between 1st and 3rd generation amine point-source carbon capture solvents for drop-in systems.

Table 3: MEA vs ICE-31 Baseline Parametric Comparison[3]

	MEA - 2015	ICE31 - 2023
Inlet CO_2 Concentration (%)	3.5	3.5
Flue Gas Flow Rate (Sm^3/hr)	59,000	59,000
L/G (kg/Sm^3)	0.97	0.75
Capture Efficiency (%)	83.4	95.6
Depleted Flue Gas CO_2 (ppm)	5,810	1,540

3.1.2 CHP Stripper Baseline

To understand the optimal operating condition for ICE-31 on the CHP stripper at TCM, parametric baseline setpoints were run to generate a "U-curve" for liquid flow requirements and the associated specific reboiler duty. These baseline setpoints were operated with 4% inlet CO_2 concentration from the MHP flue gas with 24 meters of packing in the absorber. The optimal L/G for the CHP stripper with ICE-31 at TCM was 0.7 kg/Sm^3, at an SRD of 1.03 (arbitrary units) as shown in Figure 3. ION designed NGCC facilities usually operate at lower liquid flow rates, due to its high working capacity, fast solvent kinetics and optimal mass transfer properties of the column internals. The results at TCM, however, indicate an optimal liquid flow rate of 35,000 kg/hr, which corresponds to the minimum distributor turndown in the CHP stripper. An increase in SRD is seen for the lower liquid flow rate setpoints, indicating poor performance outside of the distributor range.

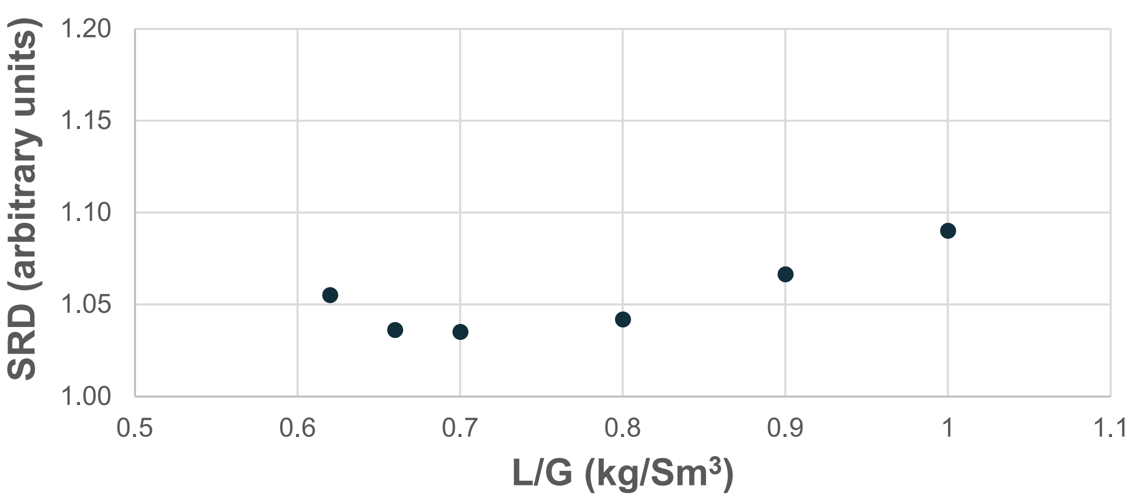

Figure 3: CHP Stripper ICE-31 Parametric Baseline

3.1.3 RFCC Stripper Baseline

To understand the optimal operating condition for ICE-31 on the RFCC stripper at TCM, ION ran parametric baseline setpoints to evaluate liquid flow requirements and the associated SRD. These baseline setpoints were operated with 14% inlet CO_2 concentration from the RFCC flue gas using 18 meters of packing in the absorber and the RFCC WW configuration. The RFCC WW is the 3rd bed within the absorber that can be either a solvent contacting bed or a water wash bed, depending on the objectives of the test. Figure 4 shows the results on the RFCC stripper where an optimum (low point) was not obtained due to the operational limitations caused by satisfying the flow requirements for the oversized distributor. The OEM-specified lower design limit on the RFCC stripper liquid distributor is 91,000 kg/hr and the L/G of 3.3 kg/Sm^3 corresponds to a liquid solvent flow rate of 104,000 kg/hr.

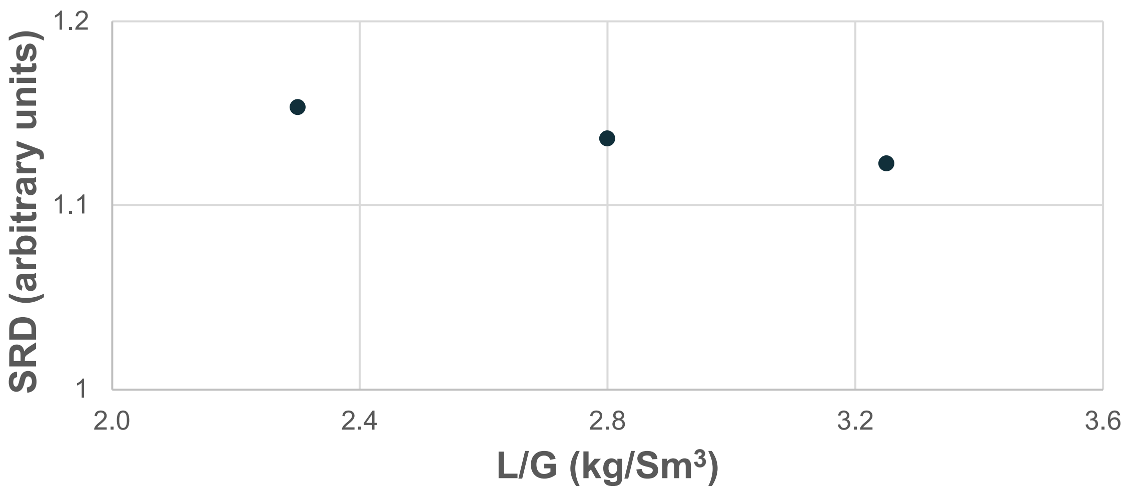

Figure 4: RFCC Stripper ICE-31 Parametric Baseline

3.2 Energy Optimization

Energy optimization at TCM was studied by understanding the correlation between SRD and stripper sump pressure. A higher column pressure may be associated with improved energy performance as the partial pressure ratio for CO_2:H_2O increases. This reduces heat loss to condensing water vapor at the top of the stripper, requiring less reboiler duty at the same capture efficiency. This energy optimization study was performed on the CHP stripper with 4% inlet CO_2 concentration from the MHP flue gas and 24 meters of packing in the absorber. Additionally, the L/G was held constant at 0.99 kg/Sm^3 and the cold rich bypass was operated at 15% of total rich flow. Emissions were monitored throughout this time period to ensure there was no degradation-associated emissions with these high-pressure operating points.

Results indicated an inverse correlation between SRD and stripper sump pressure; a stripper sump pressure of 1.9 barg yielded an SRD of 1.11 arbitrary units, while a stripper sump pressure of 2.7 barg yielded an SRD of 1.07 arbitrary units (Figure 5).

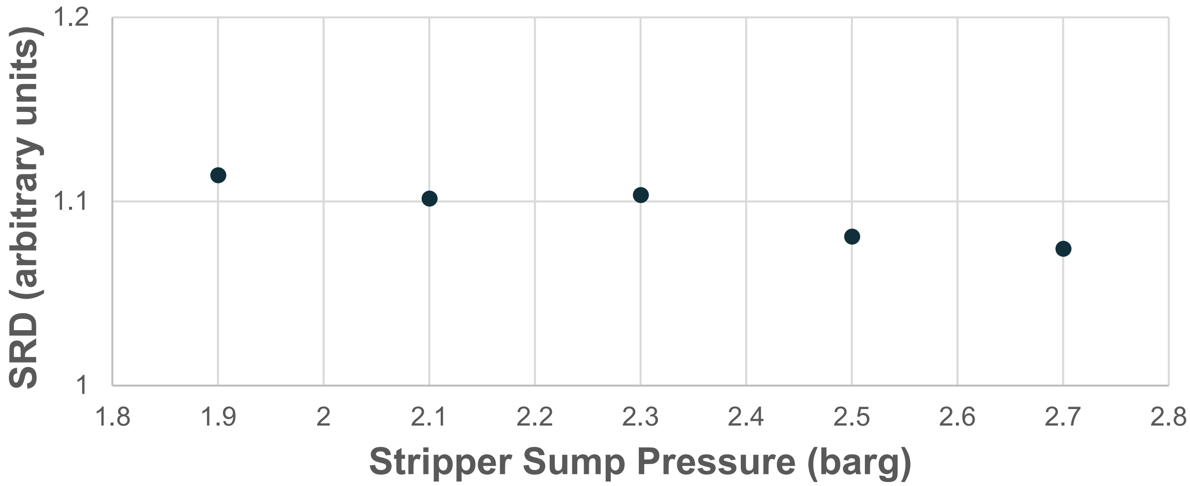

Figure 5: Energy Optimization with CHP Stripper

Furthermore, ICE-31's transformational solvent stability allows for higher stripper pressures and temperatures with no trend to emissions (Figure 6). The normalized emissions are based on the resulting emissions from baseline pressure conditions during normal operations. Further long-term testing at these operating conditions will be performed at other ION pilots, but these initial results indicate the possibility to run higher column pressures and lower energy consumption with ICE-31.

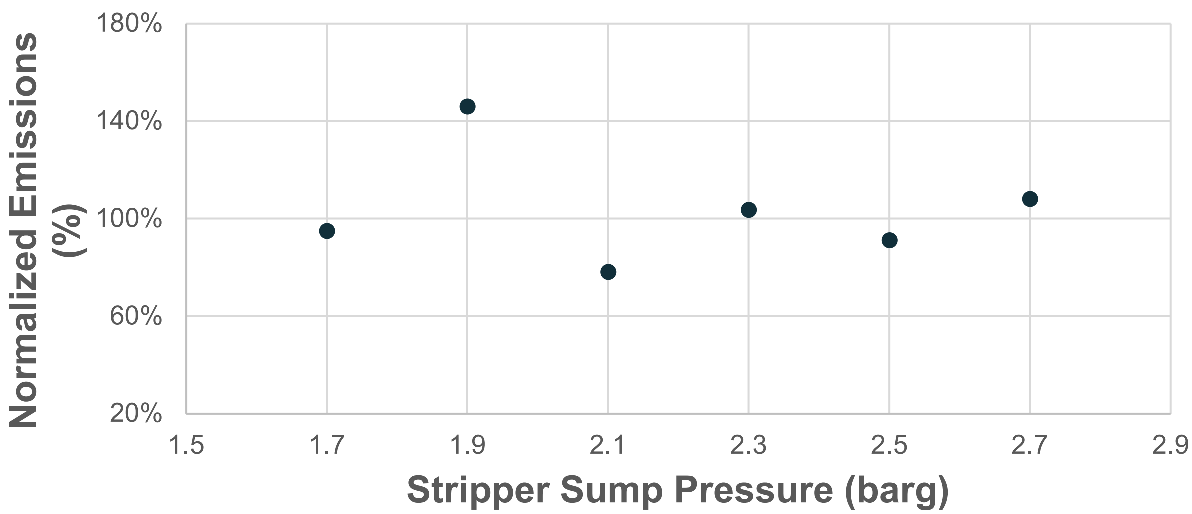

Figure 6: Amine Emissions from Energy Optimization Study

3.3 Deep Decarbonization

Following the completion of baseline parametric studies with the CHP and RFCC strippers, the optimal process conditions were built upon to evaluate the potential of deep decarbonization levels greater than 99% CO_2 capture efficiency.

For the deep decarbonization setpoint, ION utilized the CHP stripper with 3.9% inlet CO_2 concentration from the MHP flue gas and 24 meters of packing in the absorber. The L/G conditions were run at 0.99 kg/Sm^3 with a stripper sump pressure of 1.7 barg.

ICE-31 achieved greater than 99% capture efficiency for roughly 24 hours of operations, ranging from 99.1% - 99.4% based on the steam flow control from the TCM operations team (Figure 7). Steady state setpoints were achieved for both 99.4%, roughly 8 hours, and for 99.1%, roughly 14 hours, with an hour of changing setpoint conditions before and after the deep decarbonization setpoint. These elevated levels of deep decarbonization are associated with very low levels of CO_2 in the depleted flue gas leaving the top of the absorber. When 99% capture efficiency was achieved, the accompanying outlet concentration of CO_2 was 420 ppm, which aligns with the current atmospheric concentration of CO_2. Once ICE-31 reached 99.4% capture efficiency, the accompanying outlet concentration of CO_2 was 160 ppm, well below pre-industrial CO_2 levels in the atmosphere. This means that the flue gas leaving the absorber has less CO_2 than the atmosphere currently, and even below CO_2 levels from over 200 years ago. ION has worked with their project partners at LLNL to evaluate the techno-economic analysis of deep decarbonization and the additional CO_2 reduction usually only reached by Direct Air Capture technologies. Results indicate that even as a stand-alone technology, ION's ICE-31 solvent is highly competitive with state-of-the-art DAC technologies for incremental capture costs from air[4].

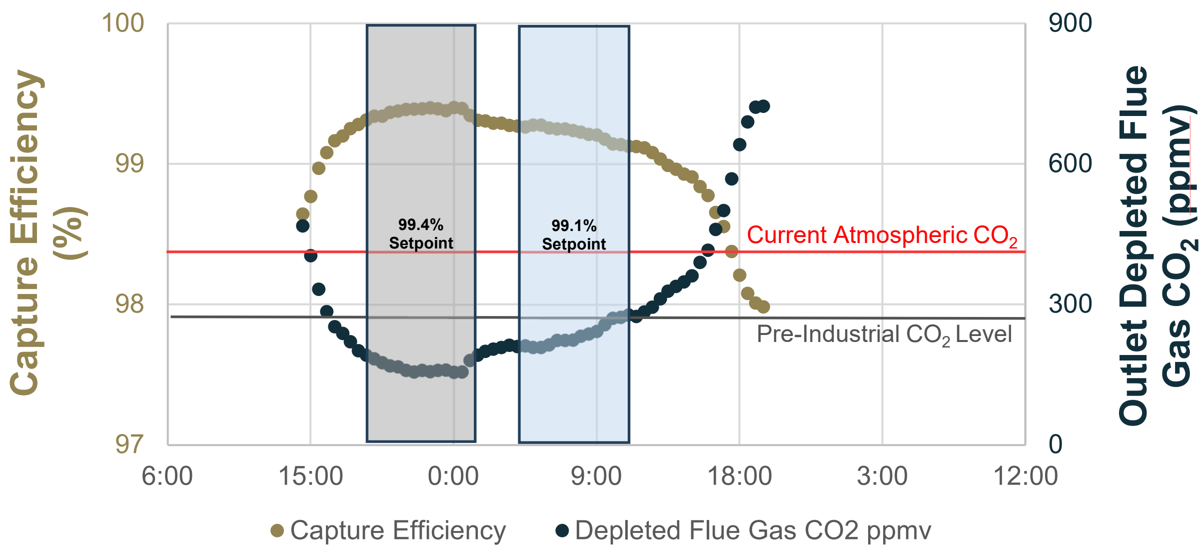

Figure 7: Deep Decarbonization and Depleted Flue Gas Corresponding CO_2 Concentration Reaching Pre-Industrial Ambient Levels of Outlet CO_2

After completion of the deep decarbonization study, ION incrementally decreased the steam to evaluate the additional energy associated with the levels of deep decarbonization achieved. No adjustments were made to the process conditions or column configurations during these setpoints, only the steam supply was varied (Figure 8).

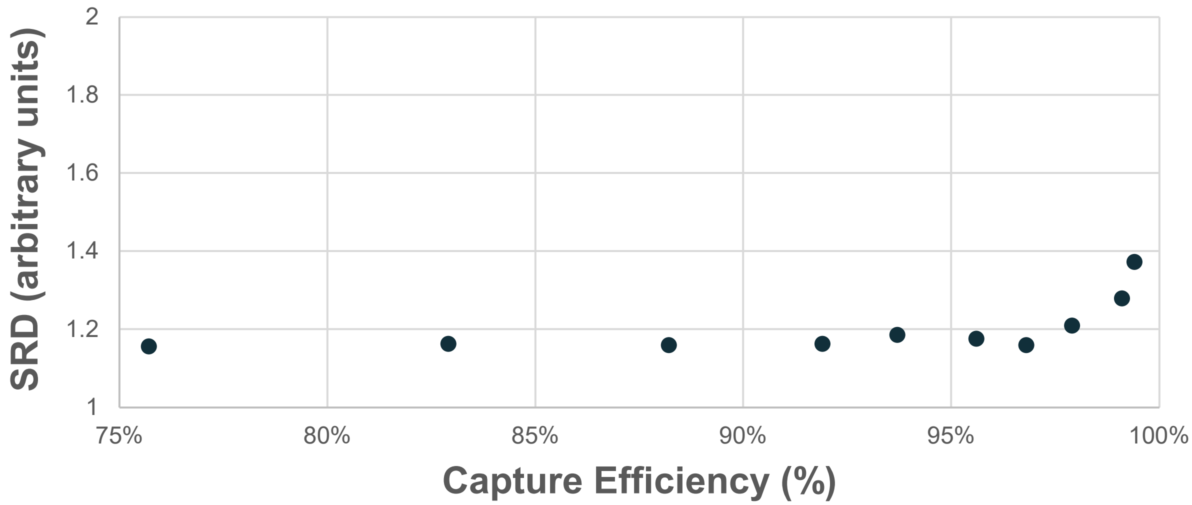

Figure 8: SRD Sensitivity to Capture Efficiency, Additional Incremental Energy Requirement

3.4 Emissions

Emissions were monitored continuously throughout the campaign on multiple online analytical instruments, as well as isokinetic sampling. The TCM air emissions permit had a campaign limit of 6 ppm amine emission and an hourly limit of 12 ppm amine emissions. Each analytical instrument had a differing operating window, so each component being analyzed had a specific instrument to report the concentration. The analytical instruments included Ion Molecule Reaction – Mass Spectrometry (IMR-MS), Fourier Transform Infrared (FTIR), and Proton Transfer Reaction – Time of Flight (PTR-ToF).

3.4.1 NGCC – Type Baseline Emissions (MHP Flue Gas)

To evaluate the amine emissions associated for parametric and standard operating conditions with MHP flue gas, emissions were monitored continuously with no additive emissions mitigation configurations for the 35 setpoints outlined below. While the 4% inlet CO_2 MHP flue gas is not directly comparable to NGCC typical flue gas, due to the elevated NO_2 levels, it was used for all parametric and baseline NGCC testing. Throughout the campaign, ION and TCM noticed a wide variation in the MHP flue gas quality, due to the type of fuel and refinery load day to day. With TCM's close relationship to the refinery, TCM was able to gather information about process upsets, outages, and variations in the load that explained results at the amine plant.

The average amine emissions for steady state setpoints were below 1 ppm with NGCC-type flue gas for standard and parametric setpoints. The majority of these setpoints were at or below 500 ppb, with the highest emissions corresponding to non-optimal L/G and high capture rate setpoints (Figure 9). These setpoints describe a wide range of process conditions and work package objectives with ICE-31 as a drop-in solvent and were not optimized for low emissions, so they are conservatively representative of the low emissions associated with ION's ICE-31 solvent.

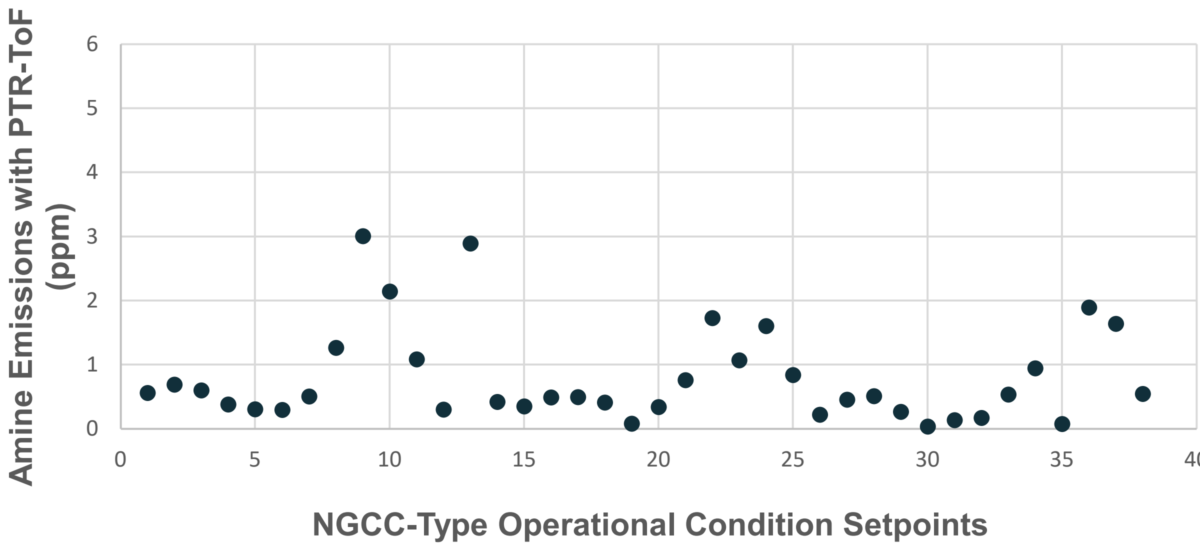

Figure 9: NGCC-Type Gas Amine Emissions

3.5 Solvent Analysis

3.5.1 Heat Stable Salts

Formation of Heat Stable Salts (HSS) from flue gas contaminates and oxidative degradation was analyzed and reported by TCM throughout the campaign. Solvent degradation and HSS formation can develop from constituents such as NO_x and SO_x in the flue gas or from oxidation within the system. The results collected at TCM with ION's ICE-31 solvent indicate minimal HSS formation. With the observed rate of formation, ionic reclamation to remove HSS would not be required for multiple years with a TCM-like flue gas (Figure 10). With ION's design and operated pilot facility in California, ION is anticipating even lower rates of formation of HSS due to the lower levels of contaminates in the incoming flue gas.

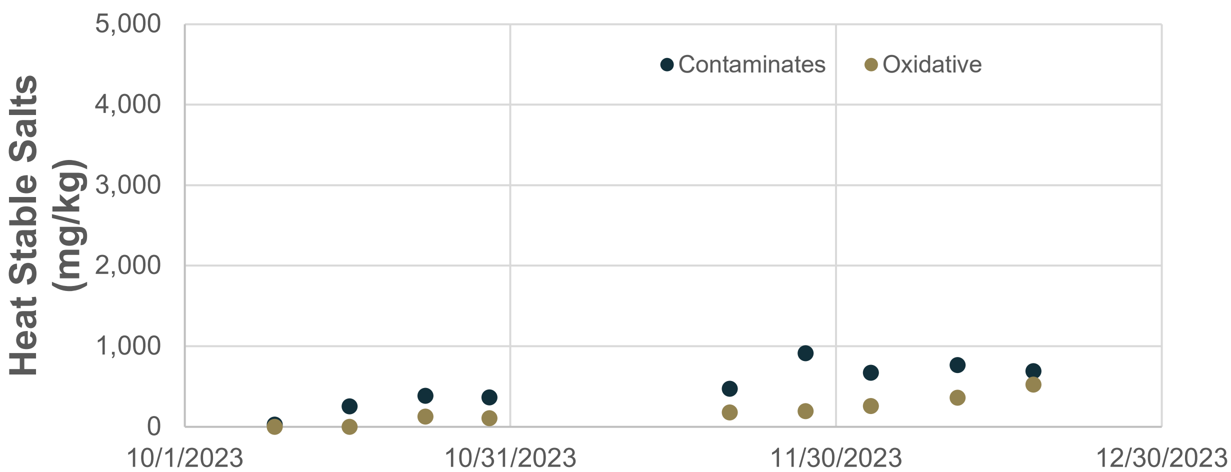

Figure 10: *Heat Stable Salt Formation from Oxidative Degradation and the Reaction with Flue Gas Minor Constituents*

3.5.2 Metals

Metals that are derived from the corrosion of Stainless Steel include Iron (Fe), Chromium (Cr), Nickle (Ni), and Molybdenum (Mo). All these metals were found close to or below the limit of quantification (LOQ) for the entirety of the campaign. Copper (Cu), Vanadium (V), and Zinc (Zn) were under the limit of detection for the entire campaign. Mo and Ni were found at the limit of detection but are not anticipated in the solvent. Iron is usually the most abundant metal found in the solvent after corrosion, which was not found throughout this campaign.

Table 4: Liquid Metals Analysis

Date	Cr (mg/kg)	Fe (mg/kg)	Mo (mg/kg)	Ni (mg/kg)
10/09/23	<0.1	0.1	0.2	0.3
10/16/23	0.1	0.1	0.2	0.3
10/23/23	0.1	0.1	0.2	0.3
10/29/23	<0.1	<0.1	0.2	0.3
11/06/23	0.1	0.1	0.1	0.3
11/20/23	0.1	0.1	0.2	0.4
12/03/23	0.2	0.1	0.2	0.5
12/18/23	0.2	<0.1	0.2	0.5
01/03/24	0.3	0.2	0.2	0.6
01/15/24	0.3	0.1	0.2	0.6
01/29/24	0.3	0.2	0.2	0.6
02/02/24	0.2	0.3	0.2	0.5

The liquid metals analysis results indicate extremely low corrosivity with ION's ICE-31 solvent. In addition to the liquid analysis, corrosion coupons were placed within the system prior to solvent introduction to evaluate the associated corrosion rate with stainless steel and carbon steel.

3.5.3 Corrosion Coupons

The stainless steel and carbon steel corrosion coupons were placed in five locations throughout the amine facility: hot lean solvent line (SP-86112096), hot rich solvent line (SP-86112095), cold lean solvent line (SP-86112099), cold rich solvent line (SP-86112100), stripper overhead vapor line (SP-86152001). When the campaign was completed, the coupons were removed after the system was drained. The coupons were then washed, weighed, visually analyzed, and catalogued for further analysis. The corrosion rate can be determined by weight loss, density, exposed area, and exposure time. The following equation was used:

$$Corrosion\ Rate\ \left(\frac{mm}{year}\right) = \frac{Weight\ loss\ (g)\ x\ 365\ x\ 24\ \left(\frac{hours}{year}\right) x\ 10\ \left(\frac{mm}{cm}\right)}{Density\ \left(\frac{g}{cm^3}\right) x\ Exposed\ Area\ (cm^2)\ x\ Exposure\ Time\ (hours)}$$

Corrosion rates for 316L and 304L stainless steels were negligible (Table 5) while corrosion rates for C1010 carbon steel were extremely low (Table 6).

Table 5: Stainless Steel Coupons Corrosion Rate

Material	Location	mm/year
316L	Hot Lean Solvent (8" Line)	$1.26*10^{-7}$
304L	Hot Lean Solvent (8" Line)	$6.33*10^{-8}$
304L	Hot Rich Solvent (6" Line)	$4.48*10^{-8}$
316L	Hot Rich Solvent (6" Line)	$4.18*10^{-8}$
304L	Hot Rich Solvent (6" Line)	0
316L	Cold Rich Solvent (6" Line)	$2.52*10^{-7}$
304L	Cold Rich Solvent (6" Line)	0
316L	Cold Lean Solvent (8" Line)	$1.62*10^{-7}$
304L	Cold Lean Solvent (8" Line)	$6.52*10^{-8}$
316L	Stripper Overhead (12" Line)	$1.29*10^{-7}$
304L	Stripper Overhead (12" Line)	$6.49*10^{-8}$
	Average	**$4.37*10^{-8}$**

Table 6: Carbon Steel Coupons Corrosion Rate

Material	Location	mm/year
C1010	Hot Lean Solvent (8" Line)	0.006
C1010	Hot Rich Solvent (6" Line)	0.003
C1010	Hot Rich Solvent (6" Line)	0.003
C1010	Cold Rich Solvent (6" Line)	0.003
C1010	Cold Lean Solvent (8" Line)	0.004
C1010	Stripper Overhead (12" Line)	0.001
	Average	**0.004**

These results indicate low corrosivity of ICE-31 and accompany the metals content liquid analysis outlined above. Visual inspection also showed no change to the stainless-steel coupons (Figure 11) and minimal discoloration on the carbon steel coupons (Figure 12). These initial results indicate that carbon steel may be an option for vessel fabrication. Using these corrosion rates, a carbon steel vessel would easily outlast typical lifetimes of industrial facilities and would provide a major cost benefit for the project.

Figure 11: Before (left) & After (right) Stainless Steel Corrosion Coupons - Hot Rich Solvent Line

Figure 12: Before (left) & After (right) Carbon Steel Corrosion Coupons – Hot Lean Solvent Line

3.6 Process Model Validation

A critical component of any pilot campaign for ION is the process model validation that accompanies the setpoint evaluation. The simulation validation provides insight into the ability to predict the performance of the facility and confidence for modeling commercial plants. Simulation development occurred before, during and after the campaign to assess how well the model fit the empirical data from TCM.

ION leverages Optimized Gas Treating's (OGT's) simulation software, ProTreat®. OGT has regressed the thermodynamic and kinetic properties for ICE-31 into their ProTreat® software, which was provided by ION and extracted from earlier bench-scale and pilot data. The simulation is a rigorous rate-based, first principles model that is thermodynamically consistent. Additionally, the Koch-Glitsch packings found within the TCM test facility have been previously regressed into ProTreat® for hydraulics and mass transfer performance. ION made no updates to either the mass transfer equipment nor the ICE-31 solvent parameters for the TCM campaign. Figure 13 shows the ProTreat® process model of the TCM facility layout with the same major units; absorber (ABS), water wash (WW), lean rich heat exchange (LRHX), and the stripper (STR).

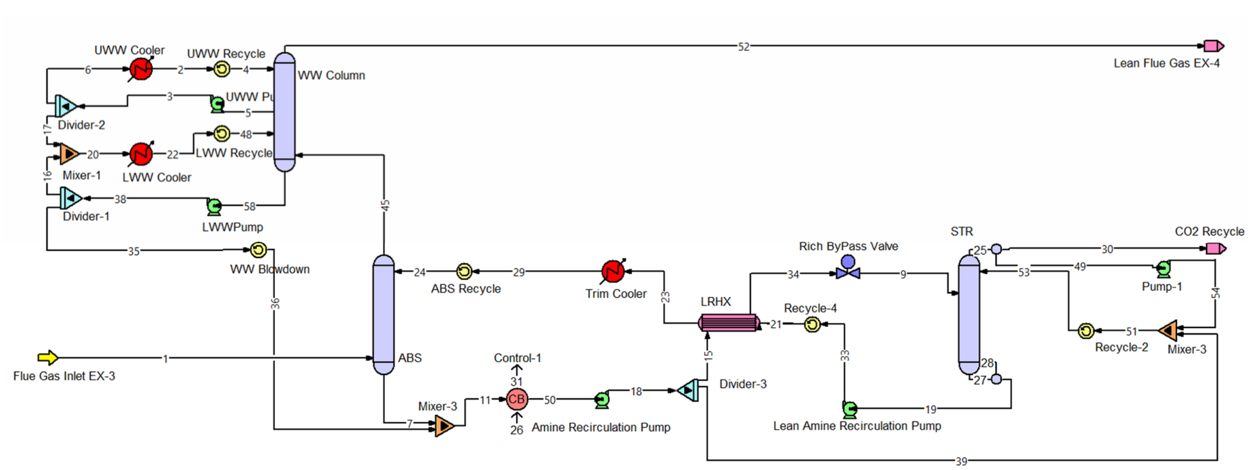

Figure 13: ProTreat® Process Model Simulation

After completion of the modeling efforts for this campaign, a parity plot was created between the empirical and simulated results (Figure 14 14). The parity plot focused on five major variables for comparison: stripper sump temperature (SST), maximum absorber temperature, specific reboiler duty (SRD), working capacity, and stripper overhead temperature. The working capacity can be defined as the difference between the rich and lean loading, indicating the solvents carrying capacity for CO_2. The parity plot below depicts the average and error associated with each variable grouping of setpoints. The results indicate an overall consistent match between the empirical results and the simulation results.

The working capacity has a higher error associated with the comparison due to the nature of offline measurements and the compounded error from sampling procedure: time of sample, time of analysis, and the lab technician taking the sample. Additionally, the working capacity has fewer datapoints due to the timing of samples occurring unaligned with the timing of setpoint changes throughout the campaign.

The SRD match between empirical and simulated results also indicated a higher error than other variables due to the wide variety of process conditions tested at non-optimal operating conditions. As discussed previously, due to the drop-in nature of the TCM facility, many of the column distributors are oversized for ICE-31 and therefore operate outside of their design parameters, limiting the optimization of solvent flow rates. The distributors within the ABS column are 1.3x oversized for the optimal ICE-31 performance leading to maldistribution and less than optimal energy consumption. The error associated with the SRD parity plot indicates this non-optimal energy requirement when operating outside of the design limitations of the facility.

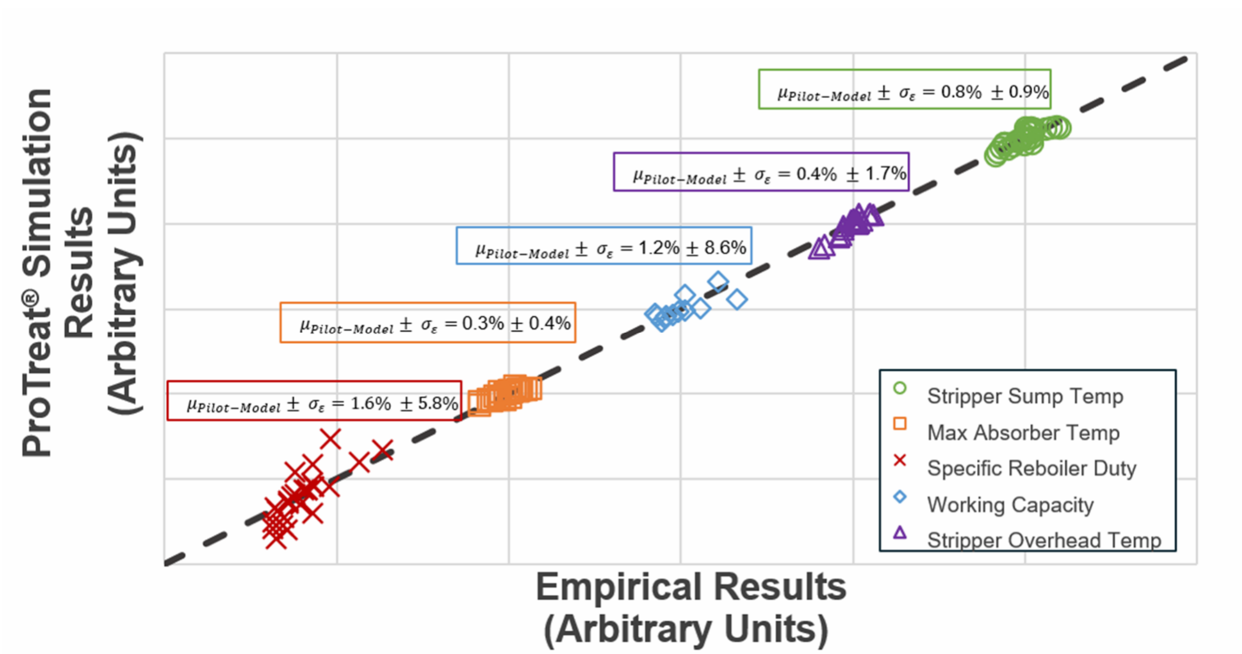

Figure 14: ICE-31 Parity Plot with ProTreat® Simulation Results

4. Conclusion

ION conducted an extremely successful campaign with their ICE-31 CO_2 capture solvent as a drop-in at TCM. The campaign at TCM resulted in 2,520 operational hours where 9,854 tonnes of CO_2 were captured from a combination of the Mongstad Heat Plant (MHP) and the Residue Fluid Catalytic Cracker (RFCC) flue gases. The campaign evaluated parametric baselining, energy optimization, deep decarbonization, aerosol impacts, and long-term stability testing.

ION was able to optimize the CHP stripper at an L/G of 0.7 kg/Sm^3 and unable to optimize the RFCC stripper L/G due to the OEM design flow limitations of the distributor. ION performed ambient heat loss studies on both strippers resulting in 10% heat loss with the CHP stripper and 6% heat loss with the RFCC stripper. ICE-31 was directly compared to the MEA baseline case run at TCM in 2015 and resulted in a 1.3x lower L/G, 10% higher capture efficiency and 3.6-fold reduction in depleted flue gas CO_2 concentration. When evaluating energy optimization, ION was able to operate the stripper at elevated pressures with no trend in increasing VOC emissions and improved energy requirements.

ICE-31 achieved steady state deep decarbonization at 99.4% capture efficiency, corresponding to a depleted flue gas CO_2 concentration of 160 ppm, which is lower than pre-industrial levels of atmospheric CO_2.

ION developed a parity plot using the piloted and simulated results that indicated a constant match with high alignment for energy consumption, capture efficiency, column temperature profiles, and solvent capacity. This validation of the ProTreat® process model allows ION to model commercial plants with great confidence.

ION worked with their project partners at LLNL to evaluate the techno-economic analysis of deep decarbonization and the additional CO_2 reduction usually only reached by Direct Air Capture technologies. Results indicate that even as a stand-alone technology, ION's ICE-31 solvent is highly competitive with state-of-the-art DAC technologies for incremental capture costs from air[4]

5. Acknowledgements

ION Clean Energy would like to thank LLNL for their partnership throughout the TCM campaign. ION worked with LLNL to provide insightful data to develop a Techno-Economic Analysis (TEA) and Life Cycle Assessment (LCA). ION would also like to thank the Department of Energy (DOE) for their continued support of ION advancement in technology development. This testing was funded in part through FWP-LLNL-23-FEW0290, with funding provided by DOE NETL/FECM.

ION Clean Energy would like to thank TCM for their partnership and experience operating point-source carbon capture test campaigns. ION would like to thank the owners of TCM as well including Gassnova, Equinor, Shell, and TotalEnergies.

6. References

1) Technology Centre Mongstad, About Us. Technology Centre Mongstad | Test centre for CO2 capture (tcmda.com)
2) Mongstad, Results from CESAR-1 testing at the CO2 Technology Centre Mongstad. Verification of Residual Fluid Catalytic Cracker (RFCC) baseline results, 2022. Collection 03: TCM Verified Baseline Results - TCM (tcmda.com)
3) Leila Faramarzi, David Thimsen, Scott Hume, Andrew Maxon, Guillaume Watson, S. Pedersen, Erik Gjernes, Berit F. Fostås, Gerard Lombardo, Toine Cents, Anne Kolstad Morken, Muhammad Ismail Shah, Thomas de Cazenove, Espen Steinseth Hamborg. Results from MEA Testing at the CO2 Technology Centre Mongstad: Verification of Baseline Results in 2015, (https://www.sciencedirect.com/science/article/pii/S1876610217314522)
4) NETL, 2024 FECM / NETL Carbon Management Research Project Review Meeting Proceedings. Techno-Economic Assessment (TEA) of High-Rate Post Combustion Carbon Capture from Natural Gas (2024 FECM / NETL Carbon Management Research Project Review Meeting - PROCEEDING | netl.doe.gov)
5) Yang Du, Tianyu Gao, Gary T. Rochelle, Abhoyjit S. Bhown. Zero- and negative-emissions fossil-fired power plants using CO2 capture by conventional aqueous amines. International Journal of Greenhouse Gas Control, Volume 111, 2021. Zero- and negative-emissions fossil-fired power plants using CO2 capture by conventional aqueous amines - ScienceDirect