ION Advanced Solvent CO_2 Capture Pilot Project

Final Scientific/Technical Report

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Principal Investigator: Alfred “Buz” Brown

Principal Authors: Andrew Awtry, Erik Meuleman

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ION Engineering LLC

3052 Sterling Circle, Suite 200

Boulder, CO, USA 80301

Abstract

This final report to DOE/NETL presents all the work and tests performed during ION Engineering's (ION) carbon dioxide (CO_2) capture pilot test campaign: "*ION Advanced Solvent CO_2 Capture Project*". This project is comprised of three budget periods (BP): BP1 – Design of a 0.6 MWe system, BP2 – 0.5 MWe National Carbon Capture Center (NCCC) Testing Campaign, and BP3 – 12 MWe Technology Center at Mongstad (TCM) Testing Campaign.

The program began in October 2013 and continued until December 2017. The campaign at NCCC, which took place from June to August of 2015, resulted in 1,116 operational hours where ~350 tonnes of CO_2 were captured from the 0.5 MWe coal-fired flue gas slipstream. The follow-up campaign at TCM took place from Oct 2016 to April 2017, where 2,775 hours of operation resulted in the capture of 14,820 tonnes of CO_2, which is a cumulative of capturing CO_2 from the natural gas-fired Combined Heat and Power (CHP) plant, and a residue fluid catalytic cracker gas (RFCC) from Statoil at Mongstad.

ION has conducted a thoughtful, comprehensive, and successful program in close collaboration with all its partners. CO_2 was successfully removed and captured for extended periods of time using three gas sources (NCCC Coal-fired Power plant, TCM CHP flue gas with and without CO_2 recycle, and TCM RFCC flue gas with air dilution) at various slipstream flows ranging from 0.5 MWe to 12 MWe. The data gathered on its solvent continues to strengthen the development of ION's advanced solvent and positive track record in executing on-site test campaigns in highly industrialized settings. These existing pilot plants do not include the necessary process modifications that ION requires to obtain the lowest possible regeneration energy; processes such as a cold-rich bypass and intercooling, would allow for lowering the demonstrated specific reboiler duty. The resulting data was also used to validate the process model, and, in the absence of testing on a custom test rig specifically designed for ION's advanced solvent, the results of the process model have shown specific reboiler duties under 2.5 MJ/kg CO_2 (1075 BTU/lb CO_2). When these regeneration energies are factored into the Techno-Economic Analysis (TEA), where ION's technology is compared to the DOE/NETL BBS Case 12, which integrates a highly optimized and commercially available CO_2 capture technology, ION's technology shows:

- 38% incremental reduction in capital cost of CO_2 capture;
- 28% incremental reduction in annual operating and maintenance costs of CO_2 capture; and
- $35-44 per tonne of CO_2 capture, which is a 20% to 40% reduction in cost of CO_2 capture.

Throughout pilot testing, ION has confirmed its understanding of process improvements and analytics that will enable successful operation of its advanced solvent at significantly lower L/G circulation rates, packing heights and regeneration energies than MEA. ION has identified routes to further develop its technology and is looking forward to testing a fully optimized solvent and capture system in the near future.

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Executive Summary

This final report to DOE/NETL presents all the work and tests performed during ION Engineering's (ION) carbon dioxide (CO_2) capture pilot test campaign: "*ION Advanced Solvent CO_2 Capture Project*". The objective of the report is to summarize the findings that have been obtained under the ION Slipstream project. This project is comprised of three budget periods (BP): BP1 – Design of a 0.6 MWe system, BP2 – 0.5 MWe National Carbon Capture Center (NCCC) Campaign, and BP3 – 12 MWe Technology Center at Mongstad (TCM) Campaign.

The program began in October 2013 and continued until December 2017. As is shown in Table 1, the campaign at NCCC, which took place from June to August of 2015, resulted in 1,116 operational hours where 380 tons of CO_2 were captured from the 0.5 MWe coal-fired flue gas slipstream. The follow-up campaign at TCM took place from Oct 2016 to April 2017, where 2,775 hours of operation resulted in the capture of 14,820 tonnes of CO_2, which is a cumulative of capturing CO_2 from the natural gas-fired Combined Heat and Power (CHP) plant, and a residue fluid catalytic cracker (RFCC) from the Statoil Mongstad refinery.

Table 1 - Top-level campaign information.

Test Campaign	Start Date	End Date	Op. Hours	Tonnes of CO_2
NCCC (0.5 MWe)	June 2015	Aug 2015	1,116	380
TCM (12 MWe)	Oct 2016	April 2017	2,775	14,820

This final report will highlight the key findings of each budget period in relation to project objectives, which include:

1. Demonstration of DOE's goal for second generation solvents of 90% CO_2 capture rate with 95% CO_2 purity at a cost of $40/tonne CO_2 captured by 2025.
2. Upscaling of capture process to 0.5 MWe and subsequently to 12 MWe including process optimization and control
3. Confirmation of ION ProTreat® model used as input values for techno-economic analysis (TEA)
4. Validation of process modelling tool for plant design at commercial scale.

The following are the main findings from the project based on parametric and continuous long-term testing of ION's proprietary, low-aqueous, advanced solvent whereby solvent performance, degradation, and air emissions under various steady-state and dynamic operational conditions were evaluated.

Testing on pilot systems designed for aqueous mono-ethanolamine (MEA):

The NCCC and TCM were designed for MEA and not for ION's advanced solvent, hence, ION could not operate its solvent at optimum operating conditions, which would include intercooling or a cold-rich solvent by-pass of the lean/rich cross exchanger.

Specific Reboiler Duty:

The TCM test campaign on CHP flue gas included optimization testing with aged solvent, and found that under optimal operating conditions the best achieved specific reboiler duty (SRD) was 3.37 MJ/kg CO_2 (1449 BTU/lb CO_2) for scrubbing 4.0 vol-% CO_2 flue gas. This represents a reduction of 15% in steam energy compared to the base case of MEA without anti-foam at TCM (3.9 MJ/kgCO_2 or 1677 BTU/lb CO_2) and approximately 10% when compared to the base case of MEA with anti-foam (3.62 MJ/kgCO_2 or 1557 BTU/lb CO_2), and was achieved without the need for additives to control foaming (Figure 1). The results of this testing are shown in the figure below. Important to note, during this comparison ION's advanced solvent was tested at a lower stripper pressure than what was used for the MEA (0.9 barg) runs, which was at the expense of an additional 10% in reductions of SRD. Operating at a lower stripper temperature and pressure protect the solvent by reducing thermal degradation effects.

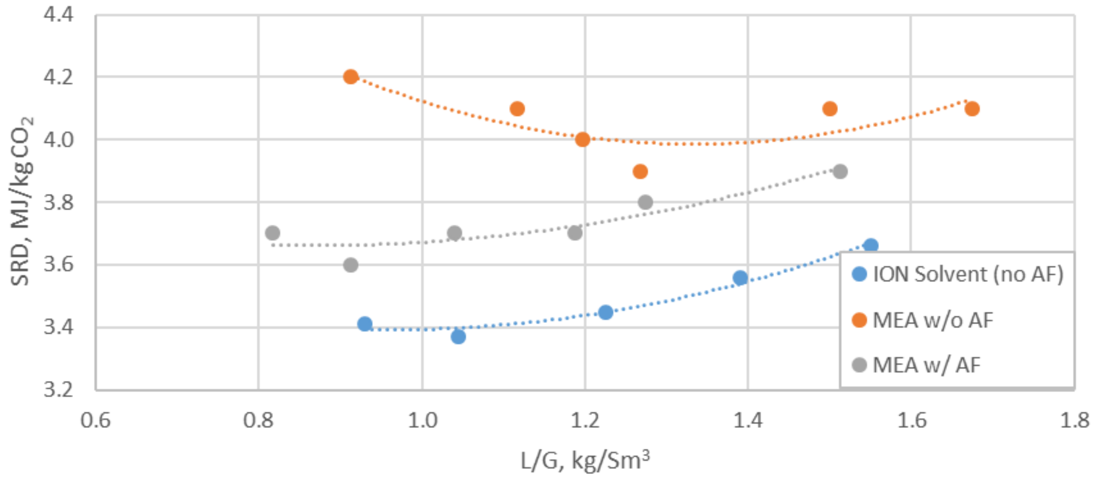

Figure 1 - SRD Comparison on CHP Flue gas at 4.0 vol-% CO_2. ION data taken with solvent operating at ~10% low amine concentration.

The TCM campaign on RFCC flue gas produced a low SRD of 3.25 MJ/kg CO_2 (1398 BTU/lb CO_2) when scrubbing 12.5 vol-% CO_2 flue gas after optimization of operating parameters (Figure 2). A series of testing was performed at 0.5 to 1.0 barg to demonstrate the magnitude of improvement in SRD under higher operating pressures in the stripper. At the time of this reporting, TCM has yet to execute similar MEA baseline testing on RFCC flue gas that can be used for comparison.

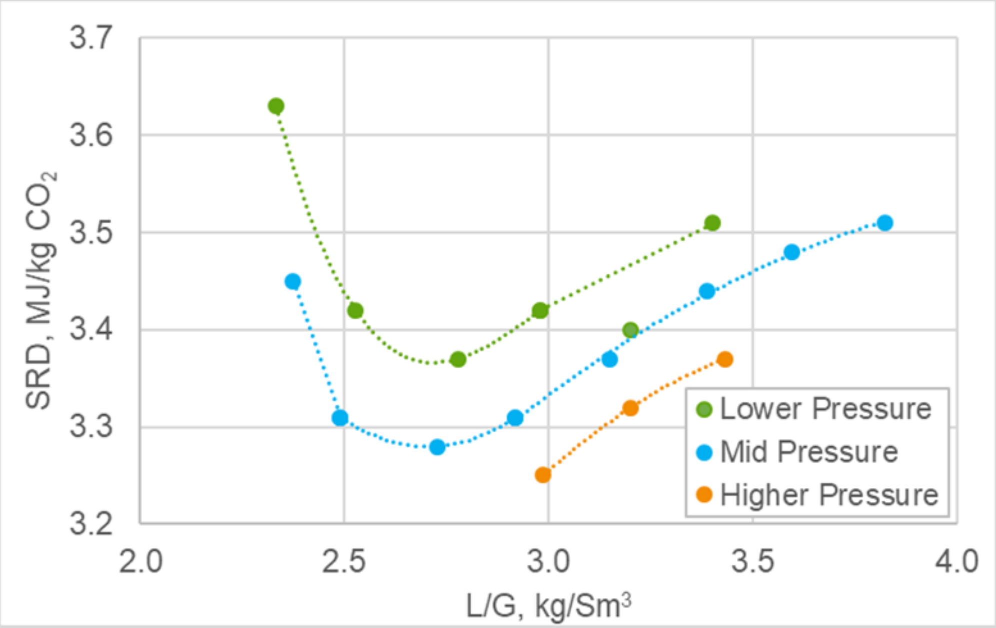

Figure 2 - U-Curve for ION's advanced solvent on RFCC flue gas at 12.5% CO_2. ION data taken while using 18m of packing.

Process Model Validation:

ION has concluded from the results of both the NCCC and TCM campaigns that its module in the ProTreat® process model slightly underestimates the performance of its solvent. The current ProTreat® process model also underestimated the rich and lean loadings of separate plant settings measured at TCM; the resulting working capacity was also undervalued, which implies that the actual plant will perform better than currently predicted. These findings at TCM have led ION to conclude that its commercial scale plant designs provide conservative estimates of actual plant performance. The current ProTreat® model resulted in process designs with energy consumptions of less than 2.5 MJ/kg CO_2 (1075 BTU/lb CO_2) and ION worked with Optimized Gas Treating (OGT), the ProTreat® software developer, to update the ION-specific module based upon the results of the NCCC and TCM test campaigns.

Solvent Make-up Rate:

The solvent make-up rate encountered at NCCC was artificially high due to the lack of process control on the solvent temperatures. The TCM solvent make-up rate, when operating on RFCC flue gas under conditions that best mimic the capture from a coal-fired power plant, matched expectations. The resulting solvent consumption was found to be 50% below the MEA standard. The primary loss of the solvent was found to be from emissions and solvent breakdown. The solvent emissions include losses due to vapor and aerosol formation. The breakdown of the solvent occurs via both thermal and oxidative pathways, where the products leave the plant as volatile emissions or stay in the system as heavy components and/or heat stable salts.

Emissions:

Emissions evaluation were carried out during the NCCC campaign and found to be similar to those of the baseline MEA case, which were acceptable for allowing ION to test at TCM. The emissions during the TCM campaign on 4 vol-% CO_2 CHP flue gas were favorable when compared to those of the MEA baseline campaign, where ION's advanced solvent total emissions were 68% lower than that of MEA. The emissions when testing on flue gas with high CO_2 content, whether CHP with recycle or RFCC, were initially high and required adjustments to the operating conditions and the inclusion of a dry bed to reduce aerosol formation. As of this report, there are no direct comparisons to an MEA baseline that can be used as a metric for ION's emission results on RFCC testing.

Packing height:

ION's advanced solvent is unique in that it has high kinetics combined with low energy consumption. As a result, ION finds a significant improvement in SRD when using 18 m of packing instead of 12 m. Increasing to 24 m does improve the SRD, however, only to some extent and optimization studies conclude that the lower OPEX does not warrant the extra CAPEX. While capturing CO_2 from gas streams above 10 vol-% CO_2, ION typically operated at 18 m packing. Further evaluation of the performance data obtained at TCM indicates that an ION system would require only 50% of the packing height that an MEA system needs.

Material compatibility:

The corrosion coupon analysis during both the NCCC and TCM campaigns showed that carbon steel coupons imbedded in the solvent (both rich and lean locations) had unfavorable results with a high corrosion rate of these materials. However, the 304L and 316L stainless steel, as well as the Duplex and Inconel specialty metals all had very low corrosion rates (<0.01 mils/yr). The only degradation occurring was noticeable on the Inconel coupon in the hot lean solvent (~1 mils/yr). EPDM and Viton gasket material were also tested in the solvent and, as expected, the Viton gaskets were dissolved, whereas the EPDM was perfectly compatible.

Occupational Health, Safety and Environment:

The NCCC and TCM campaigns were executed with a great sense of pro-active awareness of OHS&E. Temporarily high emissions due to aerosol formation were addressed successfully with joint effort. Furthermore, there were only a few minor events, which were swiftly, constructively and transparently addressed.

Conclusions:

ION has conducted a thoughtful, comprehensive, and successful program in close collaboration with all its partners. CO_2 was successfully removed and captured for extended periods of time three gas sources (NCCC coal-fired power plant, TCM CHP flue gas with and without CO_2 recycle, and TCM RFCC flue gas with and without air dilution) at various slipstream flows ranging from 0.5 MWe to 12 MWe. The data gathered on ION's advanced solvent continues to strengthen the development of ION's CO_2 capture technology and positive track record in executing on-site test campaigns in highly industrialized settings. These existing pilot plants do not include the necessary process modifications that ION requires to obtain the lowest possible regeneration energy; processes such as a cold-rich bypass and intercooling, would allow for lowering the demonstrated specific reboiler duty. The resulting data was also used to validate the process model, and, in the absence of testing on a custom test rig specifically designed for ION's advanced solvent, the process model shows SRDs under 2.5 MJ/kg CO_2 (1075 BTU/lb CO_2). When these regeneration energies are factored into the Techno-Economic Analysis (TEA), where ION's technology is compared to the DOE/NETL BBS Case 12, which integrates a highly optimized and commercially available CO_2 capture technology, ION's technology shows:

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Throughout pilot testing, ION has confirmed its understanding of process improvements and analytics that will enable successful operation of its advanced solvent at significantly lower L/G circulation rates, packing heights and regeneration energies than MEA. ION has identified routes to further develop its technology and is looking forward to testing a fully optimized solvent and capture system in the near future. ION anticipates that the recently completed demonstration at TCM, along with future projects, will directly impact the state-of-the-art of CO_2 solvent technologies and facilitate commercial implementation of ION technology at industrial scale.

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 CO_2 levels in the atmosphere are largely attributed to emissions from industrial facilities and the combustion of fossil-fuel for power generation.[1] Solvent-based technologies that interface with flue gas are most common for post-combustion processes and represent the most promising technology for retrofitting existing power plants without carbon capture.

ION's proprietary advanced solvent is among the leading second-generation solvent systems 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,[2,3] small-scale pilot testing with coal,[4-7] and large-scale pilot testing with natural gas-fired and residue fluid catalytic cracker flue gases.[8,9] This reduction is directly correlated to ION's physiochemical solvent characteristics, which include higher carrying capacity, a lower specific heat capacity, and an advanced process design.

ION chose to rapidly develop its technology by leveraging existing facilities with several global and local partners. This strategy was implemented after BP1 was completed on this project. The time and costs associated with system design, construction and commissioning would be avoided when using existing facilities that require only minor modifications. Additionally, the performance metrics of emissions, solvent make-up rates, and material compatibilities can all be evaluated on systems that have been baselined with MEA. The downside is that ION's advanced solvent's empirical performance shown at these facilities will not reflect the lowest values for energy usage. Due to this, a process simulation tool was used to predict the optimal performance, as is standard practice in the industry. The validity of this process simulation tool was confirmed by comparing actual data under non-optimized conditions against the process model results with the same operational set-points. The excellent agreement between real and modeled data strengthen the confidence in the optimized, simulation results.

This project was built off of a successful proof-of-principle campaign at the University of North Dakota Energy & Environmental Research Center (EERC) at the 0.25 MWe scale, testing on both coal and natural gas-fired flue gas.[2,3] ION then obtained this award in 2013, initially to build and test its solvent on a 0.6 MWe coal-fired flue gas slipstream on-site at Nebraska Public Power District (NPPD)'s Gerald Gentleman Station in Sutherland, Nebraska. After initiating the design of the system and realizing the cost and time savings by testing on existing equipment, ION implemented the aforementioned strategy for solvent demonstrations and model validation through pursuit of testing at an existing pilot unit. In 2015, ION performed parametric and steady-state operations at the National Carbon Capture Center's Pilot Solvent Test Unit (NCCC, PSTU), a 0.5 MWe coal-fired post-combustion testing facility located in Wilsonville, Alabama.[4-7] As a result of the successful test campaign at NCCC, ION continued to scale-up with a test campaign at TCM's 12 MWe Amine Plant in 2016 and 2017.[8,9] This report deals with the results and conclusions of ION's test campaigns at both NCCC and TCM.

Project Organization and Structure

ION Engineering was the Prime Contractor for this project through all three budget periods. The relationships of the participating organizations are presented in

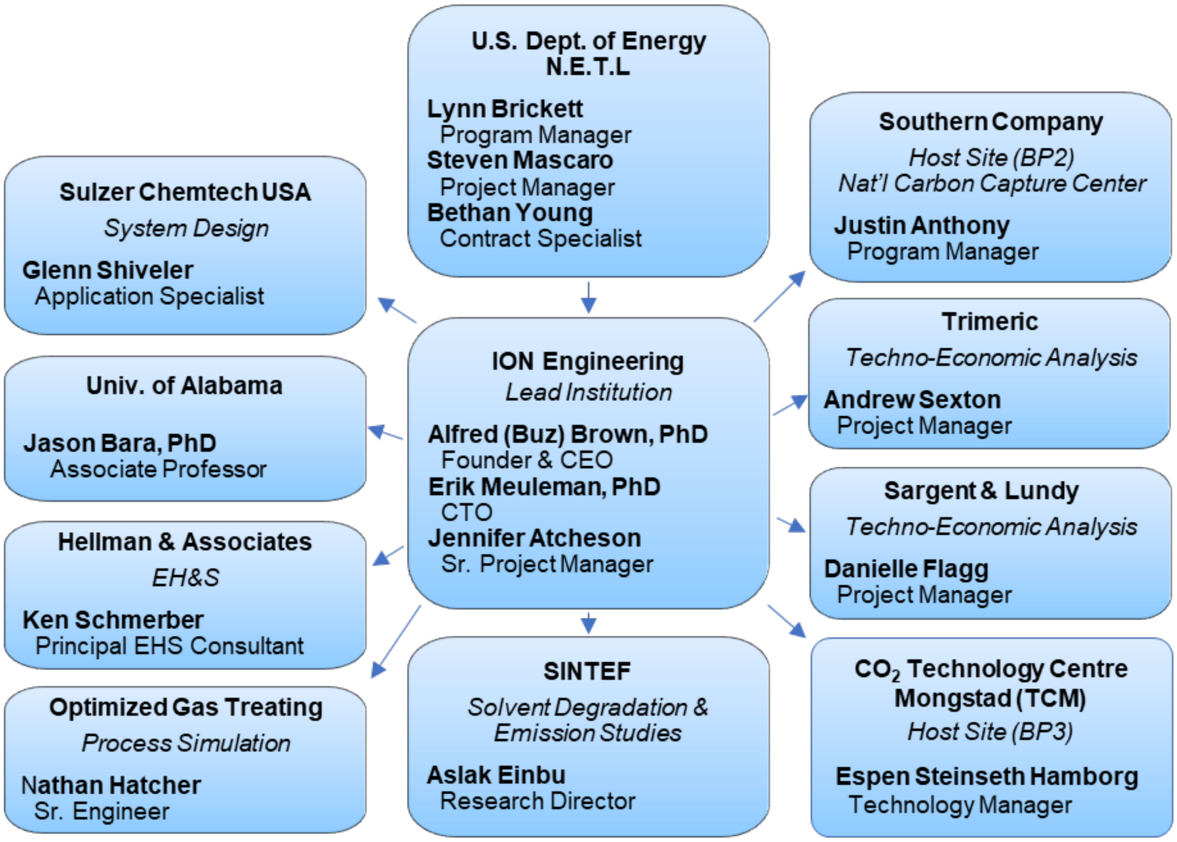


Figure 3. During Budget Period 1, Sulzer Chemtech USA, Inc designed the 0.6 MWe pilot plant system, Optimized Gas Treating developed a proprietary module for their ProTreat® software specific to ION's advanced solvent, Trimeric Corporation developed the initial techno-economic analysis, and Hellman and Associates assisted with the development of the initial EH&S risk assessment. In Budget Period 2, The University of Alabama consulted on the use of the solvent. Southern Company operates the E.C. Gaston Power Plant in Wilsonville, Alabama and manages the National Carbon Capture Center, NCCC. ION performed testing on the Pilot Slipstream Test Unit (PSTU) which is located at NCCC. In Budget Period 3 of this project, ION collaborated with CO_2 Technology Centre Mongstad located on-site at the Statoil Refinery in Mongstad, Norway. ION utilized the existing test unit located on site at TCM. Additionally, the world-renown engineering firm Sargent & Lundy executed the Final TEA for this project and OGT supported their ProTreat® simulation package throughout the evaluation of the TCM campaign data.

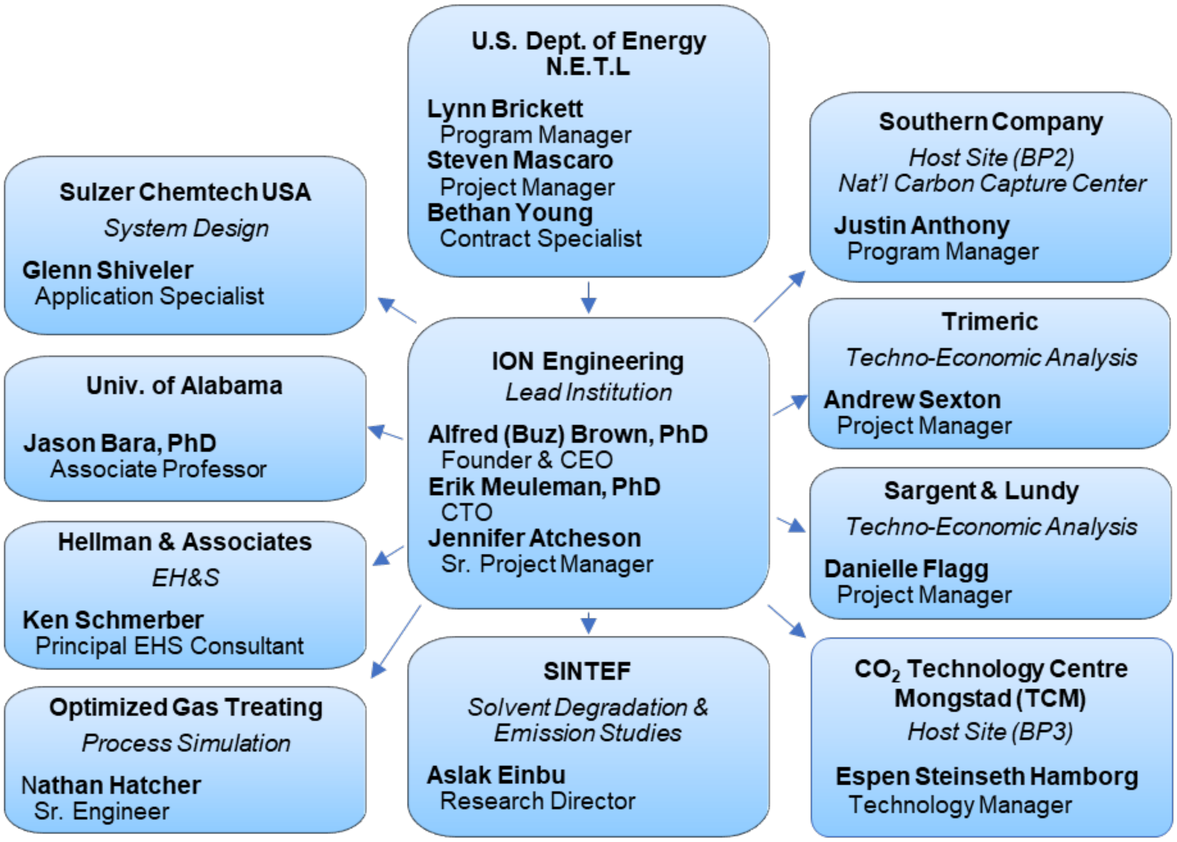


Figure 3 - Participating organizations, responsibility and key personnel.

Project Summary

Statement of Project Objectives

The overall objective of this project is to advance ION's advanced solvent-based carbon dioxide (CO_2) capture process at the equivalent of approximately 0.6 & 12 Megawatts electrical (MWe) scales in order to meet or exceed DOE's goal for second generation solvents of 90% CO_2 capture rate with 95% CO_2 purity at a cost of $40/tonne CO_2 captured by 2025.

Scope of Work

This project was broken down into three budget periods that included a decision point at the end of the first budget period. The project did not proceed to the next budget period until the ION received DOE authorization. The SOPO is comprised of 16 tasks. Task 1 is "Project Management and Planning" and is the only task active for the entire Project Period. Tasks in Budget Period 1 focused on submission of the preliminary TEA, host site selection and permitting, and finalization of the Pilot Design Package. Budget Period 2, originally the build phase for a 0.6 MWe pilot, was changed to be the first testing phase, that took place at NCCC. The tasks focused on the modifications to the PSTU, solvent procurement, installation of the ION mobile laboratory, data systems installation, PSTU shakedown, analysis of the results and completion of an updated TEA and EH&S Risk Assessment associated with testing at the PSTU. Budget Period 3 was the second testing phase, which was conducted at TCM where the primary tasks consisted of data systems installation, solvent procurement, shakedown, analysis of the results and completion of the final TEA associated with testing at TCM. The Project Budget Periods, subtasks, and corresponding dates are organized as presented below:

Budget Period 1: 10/1/2013 - 12/31/2014

The objective of BP1 was to design a 0.5-0.6 MWe carbon capture plant to be operated on a slipstream of flue gas generated by a coal-fired power plant. This small carbon capture pilot was designed to capture at least 90% of the CO_2 from the flue gas, and generate a CO_2 product stream that was > 95% purity. Initially, this pilot was going to be installed and operated at Nebraska Public Power District's (NPPD) Gerald Gentlemen Station. During the design process, the location was changed for installation and operation at the National Carbon Capture Center in Wilsonville, AL.

The tasks executed during this budget period were:

Task 1: Project Management and Planning
Task 2: Initial Slipstream Project Reviews
Task 3: Site Selection and Permitting
Task 4: Final Pilot System Design

Budget Period 2: 1/1/2015 – 12/31/2016

The objective of BP2 was to utilize the existing PTSU at NCCC to test and demonstrate ION's advanced solvent at a 0.5 MWe scale. The existing PTSU underwent minor alterations to accommodate this test campaign, and the focus of the campaign was to obtain performance data during various operating conditions while achieving >90% capture efficiency of CO_2 with >95% product purity. The resulting data, while not representing the best energy performance due to operating on a pilot system not tailored for ION's advanced solvent, was then used to validate the process model that predicted a regeneration energy of 2.5 MJ/kg CO_2 when using ION's advanced solvent.

The tasks executed during this budget period were:

Task 1: Project Management and Planning
Task 5: Host Site Preparation
Task 6: Operational Preparation & Shakedown
Task 7: ION Solvent Testing
Task 8: Data Acquisition, Storage and Analysis
Task 9: Decommissioning and Dismantle
Task 10: Final Systems Analysis

Budget Period 3: 10/1/2015 –12/31/2017

The objective of BP3 was to utilize the 12 MWe carbon capture pilot plant at the Technology Center at Mongstad (TCM) to test ION's advanced solvent. Once again, the focus of the campaign was to obtain performance data during various operating conditions while striving to achieve >90% capture efficiency of CO_2 with >95% product purity. Additionally, the testing provided an evaluation of the solvent on a large, near commercial-scale test unit for the determination of secondary performance metrics such as emissions, solvent breakdown, and materials compatibility. The resulting data was also used to validate the process model that predicted a regeneration energy of less than 2.5 MJ/kg CO_2 when using ION's advanced solvent.

Task 1: Project Management and Planning
Task 11: TCM Host Site Preparation
Task 12: TCM Operational Preparation & Shakedown
Task 13: TCM ION Solvent Testing
Task 14: TCM Data Acquisition, Storage & Analysis
Task 15: TCM Final System Analysis

Project Tasks and Accomplishments

Task 1.0: Project Management

This task addresses coordination, management and planning of project activities that will include, but are not limited to, monitoring and controlling of project scope, technical, budgetary and scheduling activities, project and task planning, asset management, cost tracking, and progress reporting throughout the project period of the award. In Budget Periods 2 and 3, this task will also include providing all documentation and reporting required under the NCCC and TCM Host Site Agreements.

Key accomplishments completed under Task 1.0 include:

- Updated PMP and SOPO throughout the project
- Updated Project Schedule throughout the project
- Generated quarterly reports throughout the project to provide DOE status updates
- Negotiated and signed host site agreements for testing at NCCC and TCM
- Participated in NETL CO_2 Capture Technology Conference in 2014, 2015 and 2016
- Presented results at the following conferences for peer review of results:
    - EUEC, 2015
    - ECI CO_2 Summit, 2015
    - GHGT-13, 2016
- Completed Kickoff Meeting on December 19, 2013
- List other briefings (deep dive, Budget period reviews and decisions, was peer review under this contract?)
- Generated continuation request for BP2 in October 2014
- Generated continuation request for BP3 in February 2015
- ION completed all reporting requirements for NCCC and TCM

BP1 – Design of a 0.6 MWe Carbon Capture System (10/1/2013 - 12/31/2014)

Task 2.0: Initial Slipstream Project Reviews

This task addresses activities necessary to prepare and submit the Techno-Economic Analysis and Technology EH&S Risk Assessment.

Key accomplishments completed under Task 2.0 include:

- During Q1 2014, ION conducted a request for proposals (RFP) for the iTEA work, selected Trimeric Corporation to complete the iTEA
- ION executed the contract with Trimeric for the iTEA, transferred information to Trimeric necessary for the completion of the iTEA and Trimeric initiated work on the iTEA.
- ION and Trimeric completed the Initial Techno Economic Assessment (iTEA) and submitted it to DOE for review.
- Based on feedback from NETL, a revised iTEA was submitted December 5th, 2014. The second revision of the iTEA was developed using a rate-based predictive ProTreat® simulation engine that uses the specific thermodynamic and physical properties of ION's advanced solvent. The data produced from ProTreat® has allowed for process optimization and detailed equipment sizing compared with the initial TEA from June 2014.

- ION also conducted an RFP for the Project EH&S work, selected Hellman and Associates through a competitive bidding process to provide the initial EH&S assessment (iEH&S) along with continued EH&S support throughout the Slipstream Project.
- ION and Hellman & Associates completed the Initial EH&S Risk Assessment (iEH&S) and submitted it to DOE for review.

Task 3.0: Site Selection and Permitting

This task addresses activities for the Recipient to finalize the host site and obtain the necessary permits for Pilot construction and operation.

Key accomplishments completed under Task 3.0 include:

- An additional site was added to the Host Site Evaluation task, NCCC. The two sites evaluated were:
    1. GGS – Nebraska Public Power District's Gerald Gentleman Station in Sutherland Nebraska
    2. NCCC – Southern Company's Wilsonville Power Systems Development Facility in Wilsonville Alabama
- The ION Slipstream core project team thoroughly analyzed each site for technical and project support, existing infrastructure and key qualitative aspects that each unique site had to offer. After much consideration, NCCC was decided upon as the host site for the slipstream project. Site Selection Evaluation and Conclusions memo issued for documentation of NCCC as the preferred host site.
- Completed ION/NCCC legal and technical review of NCCC Technology Collaboration Agreement (TCA).

Task 4.0: Pilot System Design

This task addresses activities necessary for the Recipient to produce the final Pilot System design, including cost to build.

Key accomplishments completed under Task 4.0 include:

- Conducted laboratory experiments to obtain specific solvent property data that were necessary input data to Optimized Gas Treating's (OGT) ProTreat® Process model:
    - Determined equilibrium constant (Kc) values for carbamate formation in different amine, secondary organic and water mixtures in presence of CO_2.
    - Used NMR to confirm above Kc values and the determined temperature dependency, and distinguish between physically dissolved CO_2 and chemically bound (carbamate) CO_2 in Solvent solutions
    - Measured heat capacity values of different unloaded and CO_2 loaded amine mixtures using calorimetry.
    - Wetted wall gas/liquid contactor commissioned and baseline mass transfer kinetic measurements completed for Aq-MEA solution vs. temperature and CO_2 loading.
    - Additional pH measurements made for amine-water and secondary organic-water binaries vs. temperature and CO_2 loading.
    - CO_2 absorption kinetics at different temperatures was monitored using FT-IR.
    - Density, viscosity, and pH measurements of solvent component binaries measured vs. temperature for modeling
- Preliminary Process Hazards Analysis (PHA) was performed with Sulzer

- Sulzer basic design package was reviewed and approved, and detailed design activities were initiated resulting in a detailed design package was completed for ION's Slipstream Test Unit.
- After decisions were made to refocus the project to test on the PSTU at NCCC, Sulzer was contracted to design and estimate costs for the PSTU modifications.
- Two final design packages were transmitted to DOE. The second package for modifications to NCCC's PSTU is what will be implemented.
    - A design package for a 5,250 lb/hr Pilot Unit to be installed in NCCC Bay 2 known as the ION Slipstream Test Unit (ISTU). This design was not utilized, and the system was not built at NCCC.
    - A design package for modifications needed for the NCCC PSTU.

BP2 – Testing at National Carbon Capture Center (1/1/2015 – 12/31/2016)

Task 5: Host Site Preparation

This task addresses activities necessary for the Recipient to perform host site preparation that includes, but is not limited to, identification of modifications needed to suit pilot unit for ION's advanced solvent test campaign, installation of necessary utilities/connections from the power plant necessary for the operation of the slipstream and support trailers, and procurement of testing material for ION's advanced solvent testing.

Key accomplishments completed under Task 5.0 include:

- The HAZOP was completed on the changes to the PSTU that were required by ION.
- The GC, Karl Fischer, TIC and HPLC analyzers were spec'd and procured for installation in ION's mobile laboratory
- The corrosion study plan was developed, and corrosion coupons were procured and installed in the PSTU.
- Completion of the design, fabrication, and delivery of the mobile lab
- Modifications to the PSTU to support ION testing were completed
- ION's advanced solvent was delivered
- The mobile lab was installed and the analytical equipment was setup and calibrated

Task 6: Operational Preparation & Shakedown

This task addresses activities necessary for the Recipient to implement EH&S measures, develop procedures, test plans, and perform Pilot System Commissioning and Shakedown Testing.

Key accomplishments completed under Task 6.0 include:

- Agreements were completed for NCCC including site access requirements for ION, Service Technicians/Contractors and Visitors
- ION PPE (Personal Protection Equipment) for NCCC was procured
- Test plan was developed and transmitted to Southern Company
- Analytical standard operating procedures (SOPs) were developed and approved
- Southern Company Pre-Startup Safety Review (PSSR) was completed
- Pilot system shakedown testing was completed
- Lab Technicians were hired and trained

Task 7: ION Solvent Testing

This task addresses activities necessary for the Recipient to conduct ION's advanced solvent testing on the Pilot System as specified by the Final Test Plans developed in Subtask 6.5.

Key accomplishments completed under Task 7.0 include:

- Completed thermosiphon flow testing
- Completed all parametric testing and steady-state testing as outlined in the ION test plan
- Completed approximately 1,200 hours of continuous testing at the 0.5 MWe PSTU
- Analyzed approximately 1,000 samples onsite in 24 hr/day mobile lab

Task 8: Data Acquisition, Storage and Analysis

This task addresses all activities relating to installation and maintenance of data acquisition equipment and software, data acquisition from pilot unit operations and analysis of the data to further refine the TEA.

Key accomplishments completed under Task 8.0 include:

- Defined the data acquisition plan and completed design for data acquisition, storage and analysis; Required hardware and software identified, procured, and installed
- Compared ION's model output with actual data acquired from the PSTU campaign
- Completed SEM/EDS corrosion analysis for coupons installed at the PSTU
- Completed NCCC data analysis of CO_2 capture performance, specific heat performance, solvent lifetime performance and corrosion coupon results.
- ION collaborated with SINTEF to complete solvent degradation analysis utilizing their in-house Solvent Degradation Rig (SDR)
    - Completed sample and internal control analysis for calibration model to be used for online analysis prototype
    - Submitted update to Solvent Stability Study to include information from SINTEF SDR campaign
- Completed SINTEF analysis of NCCC samples for identification of degradation products
- Utilizing data from the SDR campaign and NCCC sample analysis, ION received positive feedback from TCM on evaluation of ION suitability for testing in the TCM facility

Task 9: Decommissioning and Dismantle

This task addresses activities necessary for the Recipient to decommission, dismantle and remove ION's equipment.

Key accomplishments completed under Task 9.0 include:

- Completed decommissioning with all ION equipment removed from NCCC

Task 10: Final Systems Analysis

This task addresses activities for the Recipient to prepare the NCCC Techno-Economic Analysis (TEA) in accordance with Attachment 1 – "Basis for Techno-Economic Analysis" and the final Technology EH&S Risk Assessment in accordance with Attachment 2 – "Basis for Technology EH&S Risk Assessment".

Key accomplishments completed under Task 10.0 include:

- Completion and transmittal of all NCCC required reporting
- Presentation at TCM, ION Response to Technology Risks addressed by Gassnova
- Completion and transmittal of Solvent Stability Assessment, Updated EH&S Risk Assessment, BP2 Campaign Report and 2016 TEA

BP3 – Testing at CO_2 Technology Centre Mongstad (10/1/2015 – 12/31/2017)

Task 11: TCM Host Site Preparation

This task addresses activities necessary for the Recipient to perform host site preparation that includes, but is not limited to, verification of engineering drawings and procedures, identification/recommendation of potential modifications needed to suit pilot unit for ION's advanced solvent testing, and procurement of testing material for ION's advanced solvent testing.

Key accomplishments completed under Task 11.0 include:

- Concluded HSE assessment of ION's advanced solvent in TCM Amine Plant
- Procurement, delivery, and completion of regulation requirements for ION's advanced solvent
- Completion of Multicomponent Liquid Analyzer (MLA) design for TCM and communication of work scope to TCM for installation and data acquisition
- ION team assembled at TCM and completed TCM on-boarding and safety training
- Installation of MLAs, thereafter providing near real-time data of the composition of ION's advanced solvent during its campaign at TCM

Task 12: TCM Operational Preparation & Shakedown

This task addresses activities necessary for the Recipient to implement TCM environmental health and safety measures, develop analytical procedures, test plans, and perform Pilot System Commissioning and Shakedown Testing.

Key accomplishments completed under Task 12.0 include:

- Composed the TCM Test Plan, Data Plan and Sample & Analysis Plan
- Reviewed the TCM amine plant P&IDs and identified any necessary modifications required for testing with ION's advanced solvent
- Completed travel plan and communication plan
- ION's TCM compliance engineer as well as ION's operations manager for TCM-site were hired and trained in Boulder.
- TCM plant start-up for ION test campaign completed on Oct 10, 2016
- Milestone of Amine Capture Plant Shakedown completed on Oct 21, 2016
- Continued updates of ION Test Plan as campaign progressed

Task 13: TCM ION Solvent Testing

This task addresses activities necessary for the Recipient to conduct testing of ION's advanced solvent on the Pilot System as specified by the Final Test Plans developed in Subtask 12.5.

Key accomplishments completed under Task 13.0 include:

- ION tested continuously up until Nov 11, 2016 when the TCM plant was shut down for scheduled upgrades to intercooling on the absorber and installation of a demister for the RFCC gas. During the outage, ION's advanced solvent was stored in one of the large storage tanks, blanketed with nitrogen and continuously circulated within the tank.

- After TCM completed all their scheduled upgrades, ION started back up on Dec 27, 2016
- CHP testing from 6% up to 13% CO_2 in preparation of the RFCC flue gas campaign was successfully completed on February 16th. During the CHP testing, CO_2 was captured from the flue gas at capture rates of 60-99% and typically was held at 85-90% capture. During this time, strategies for preventing or lowering emissions were identified and implemented.
- RFCC flue gas was introduced on February 21st and was the flue gas source utilized through the end of the testing campaign. CO_2 was captured from the flue gas by 60-95% and was typically at 85-90%. During testing, strategies for preventing or lowering emissions were successfully executed when required. ION was the first to operate on RFCC flue gas at TCM amine plant at this scale, and for this duration (2.5 months).
- At the conclusion of the TCM Campaign on April 28, 2017, ION had captured just short of **15,000** tCO_2 within approximately **2,750** hours of operation.

Task 14: TCM Data Acquisition, Storage & Analysis

This task addresses all activities relating to installation and maintenance of data acquisition equipment and software, data acquisition from pilot unit operations and analysis of the data to further refine the TEA.

Key accomplishments completed under Task 14.0 include:

- Throughout testing, ION continuously analyzed data for reporting and continued test plan development
- Completed model validation with ProTreat® software with comparison to TCM experimental data
- EPRI was on-site for one week completing their verification protocol with two primary focuses:
  - Verification of data output from TCM during ION steady state conditions utilizing RFCC gas
  - Verification of the ION Multi-component Liquid Analyzer during steady-state and dynamic operation

Task 15: TCM Final System Analysis

This task addresses activities for the Recipient to prepare the final Techno-Economic Analysis (TEA) in accordance with Attachment 1 – "Basis for Techno-Economic Analysis". This task also includes the preparation and reporting of the final TCM Report to TCM stakeholders.

Key accomplishments completed under Task 15.0 include:

- ION updated the design case process model after receiving an updated version of the ProTreat® Software. The results of this model were then delivered to Sargent & Lundy to assist in completing the final TEA.
- Sargent & Lundy completed the 2017-TEA in December, with great results showing a range of cost of capture of $35-44/tonne. ION transmitted this TEA report to DOE at the end of December 2017.
- The ION team participated in a "Lessons Learned" workshop with the TCM team and its owners, Gassnova, Statoil, Shell and Total on-site at Mongstad, Norway.
- ION completed a deep dive of TCM test campaign results through a briefing with DOE/NETL in September 2017.

Results and Discussion

BP1 – Design of a 0.6 MWe Carbon Capture System

Introduction to the Small-Pilot Design

In laboratory, bench-scale, and small-scale pilot testing with coal-fired flue gas, ION's advanced solvent has demonstrated significant benefits, has outperformed competing technologies and is among the leading second generation solvent systems for post-combustion CO_2 capture. The laboratory and pilot scale testing for ION's advanced solvent has consistently demonstrated regeneration energy requirements less than 60% in comparison to traditional aqueous mono-ethanolamine (MEA) coupled with CO_2 solvent carrying capacities 35% higher than MEA, with less solvent degradation due to impacts of flue gas impurities such as sulfur oxides (SOx). The data gathered from this test program is anticipated to facilitate advancement of CO_2 capture towards commercialization and implementation.

Sulzer Chemtech USA, Inc (Sulzer) was commissioned to design and fabricate a carbon capture pilot for use with ION's proprietary, low-aqueous advanced solvent. The process takes a flue gas slipstream up to a maximum 6,000 lb/hr from the NCCC's coal burning power plant exhaust in order to demonstrate the performance of ION's proprietary CO_2 capture technology. Process steps included caustic scrubbing to remove SO_2, a cooling unit to control the gas temperature, removal of CO_2 by regenerated solvent, and water wash to recover solvent droplets in the exhaust gas. A system design was provided with equipment to regenerate the solvent for recirculation through the CO_2 absorption unit. Sulzer designed a system able to absorb CO_2 and established the benchmark using a well-known solvent mono-ethanolamine (MEA) in order to establish the benchmark for solvent and energy consumption. Once the unit had been commissioned and benchmarked, ION would supply its advanced solvent to compare its performance to the outcome to the benchmark. In addition to designing the pilot plant for ION, Sulzer also developed a control strategy that would have been used for the future development of the control system.

The Sulzer design for the CO_2 Capture Demonstration Unit featured these characteristics:

- Application of Sulzer structured packing and internals featuring low pressure drop even at high capacities
- Minimum product hold-up due to structured packings
- High safety of operation by having:
    - Small holdup
    - Simple but effective closed loop control and interlocking system
    - Automatic operation
    - Process alarms, trips and interlocks
    - Redundant high and low-level trips and high-pressure trips (hard-wired)
    - Limit switches on actuated valves so that unit will shut down if any valve is in an unknown position
    - Pump running relays/interlocks so that plant will shut down if any pump is running when it should not be
    - Local hard-wired emergency stop buttons
    - Local hand/auto/off stations for all motors
    - Control room hard wired emergency stop button

    - Leak tight equipment design to minimize process leakage out from pressurized system
- Small space requirement in order to reduce investment costs and space required for installation
- Economic design regarding investment and operating costs
- Heat Integration system implemented to reduce the operating cost of the plant.

Conclusion for the Small-Pilot Design

Budget Period 1 concluded with the delivery of a complete design package to DOE/NETL for evaluation. This package included the PFD, detailed design drawings, general layout drawings, stream tables, and a control strategy for installation of this unit in Pilot Bay 2 at NCCC. However, at the decision point of the project ION chose to rapidly develop its technology by leveraging existing facilities. The time and costs associated with system design, construction and commissioning would be avoided when using existing facilities. Additionally, the performance metrics of emissions, solvent make-up rates, and material compatibilities can all be evaluated on systems that have been baselined with MEA. The downside is that ION's advanced solvent cannot be operated with established processes that are required for the best performance, or lowest energy usage. The data obtained on existing facilities would be used to validate the process simulation tool, and the expected low energy usage of ION's advanced solvent.

BP2 – Testing at NCCC

Introduction to NCCC Campaign

The overall objectives of this project were to scale-up ION's advanced solvent-based CO_2 capture process at the equivalent of approximately 0.5 Megawatts electrical (MWe) scale PSTU located at the National Carbon Capture Center in order to meet the Department of Energy (DOE) goal for second generation solvents of $\geq 90\%$ CO_2 capture rate, with 95% CO_2 purity at a cost of <$40 per tonne CO_2 captured by 2025. Additional objectives included: validation of ION's advanced solvent specific simulation module, completion of 1,000 hours of continuous testing, and an assessment of solvent lifetime, where these last two objectives were required for future consideration of a TCM testing campaign.

ION applied an operational philosophy that concentrated on two key priorities throughout the spectrum of parametric and steady state test conditions to ensure the generation of high quality data that allow for successful execution of the project:

- 1st Priority – Maintain process & water balances
- 2nd Priority – Flue Gas treating to meet DOE goal of 90%+ removal of CO_2

To meet the project objectives, the project entailed of a full process simulation, evaluation of existing equipment of the PSTU and ultimately fitting of the capture process.

Equipment and Process Evaluation

Using baseline MEA process data provided by NCCC, ION modeled MEA performance conditions in the PSTU using the ProTreat® simulation software. Completing this evaluation prior to the test campaign enabled ION to perform detailed analysis of the PSTU process and equipment. Given the characteristics of ION's advanced solvent, optimal test conditions were identified and results from the actual testing campaign were subsequently verified against the predicted model results.

Some minor changes to the PSTU equipment were requested after completing a thorough review of boundary conditions and existing equipment design, assisted by results from the ProTreat® simulations.

The NCCC, located in Wilsonville, Alabama, is a pre- and post-combustion carbon capture technology research, development, and testing facility. The Post-Combustion Carbon Capture Center (PC4) area at NCCC was completed in 2011 and was the focus of ION's test campaign. Flue gas is supplied via slipstream to the PC4 facilities by Plant E.C. Gaston Unit 5, an 880 MW coal-fired boiler operated by Alabama Power, a subsidiary of Southern Company. The NCCC PC4 facilities includes multiple testing configurations, including the 0.5 MW PSTU that ION occupied during the 2015 test campaign. Upstream of PC4, flue gas pre-treatment includes particulate removal (hot ESP - electrostatic precipitation), NO_x removal (SCR - selective catalytic reduction), and flue gas desulphurization (wet-FGD).

PSTU Process Configuration

The PSTU was designed specifically for testing amine-based solvents for CO_2 removal from coal-fired flue gas. The general PSTU process configuration is illustrated in Figure 4. The PSTU contains a caustic scrubber (shared unit operation with other PC4 facilities), direct contact cooler, absorption column, followed by a conventional amine regenerator with thermosiphon reboiler for solvent regeneration and a single bed wash tower downstream of the absorber. The PSTU was designed and built as a robust MEA CO_2 scrubbing process. The flue gas entry point into the actual PSTU (since the pre-scrubber unit is shared with additional PC4 operations) is the Direct Contact Cooler (DCC). The PSTU column information is detailed in Table 2.

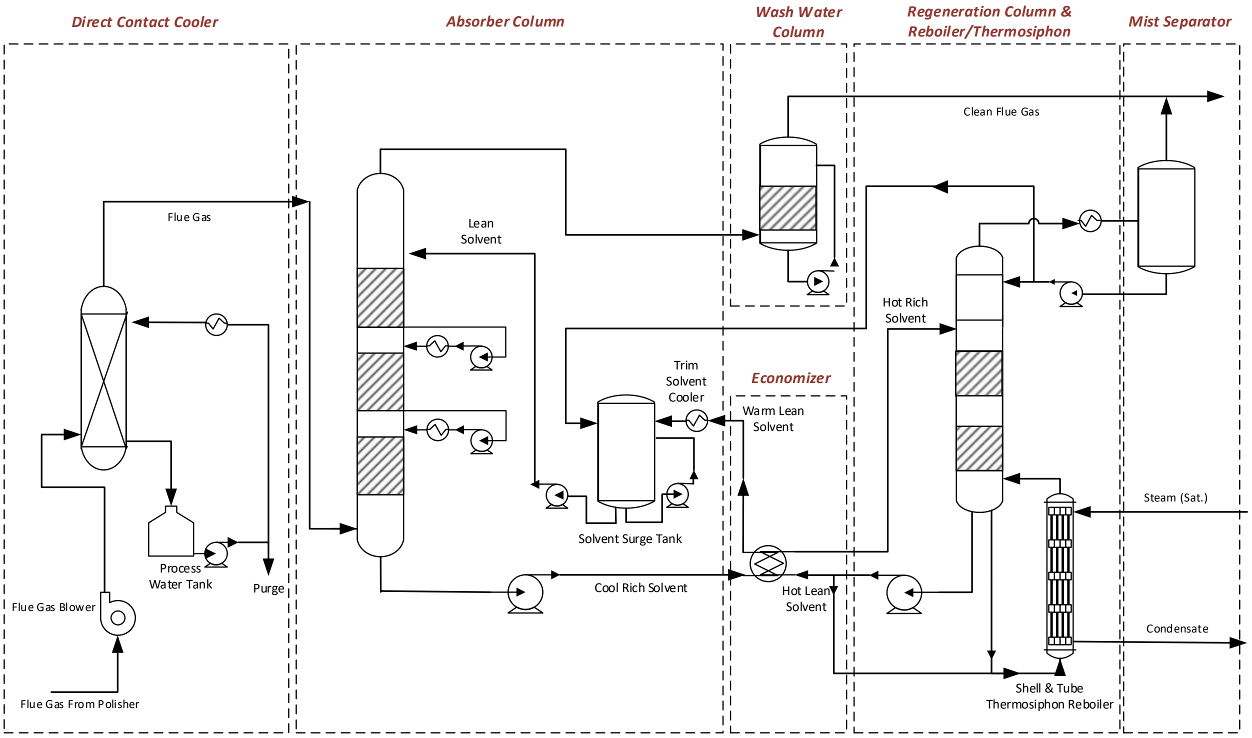


Figure 4 - Generalized process flow diagram of the PSTU at NCCC

Table 2 - Column Properties

Property	Units	Pre-Treatment	DCC	Absorber	Regeneration
Column diameter	mm	743	597	641	591
Packing height (total)	mm		3,024	6,048	6,048
Number of sections		1	1	3	2
Packing type			Mellapak 252.Y	Mellapak 252.Y	Mellapak 252.Y
Material of construction		316 SS	316 SS	316 SS	316 SS

PSTU Detailed Process Configuration

The flue gas entering the PSTU is depicted on the lower left side of Figure 4, which occurs after passing through a polisher equipped with MellapakPlus™ M252Y structured packing and a Sulzer VMister™ that introduces aqueous caustic (recirculated) to further remove SO_x (not shown here). For the PSTU, the flue gas meters in at a flow rate of approximately 2,268 kg/hr (0.6 MWe), and contains approximately 10-13 mol% CO_2 and SO_2 below 2 ppm at approximately 160 °F. The aqueous caustic will be used in a semi-batch mode. The caustic is expected to pick-up additional SO_2 along with NO_2 and a small amount of CO_2 during normal operation.

The second process step occurs in the PSTU using a dedicated DCC or cooler/condenser. This is the flue gas entry point into the actual PSTU (since the pre-scrubber unit is shared with additional PC4 operations). The DCC is equipped with MellapakPlus™ M252Y structured packing and a mist eliminator. This unit operation cools the inlet flue gas from approximately 160 ºF down to a normal operating temperature of approximately 110 ºF. ION required an additional amount of flue gas cooling for optimal technology operation and solvent efficiency, and specified a standalone chiller skid that would take the existing Cooling Tower Water (CTW) utility supplied at 90 ºF, and drop the temperature down to approximately 55 ºF. This 55 ºF chiller water will circulate to an existing heat exchanger that interfaces with the Process Water (PW). PW, now chilled to approximately 65 ºF, is sprayed into the DCC counter-currently to the flue gas stream, effectively cooling the flue gas down to the 85 ºF design temperature. The PW is mostly recycled, with a small volume PW make up stream available. This unit operation also mitigates entrainment of aqueous caustic carryover from the pre-scrubber, in order to protect solvent quality downstream in the absorber column.

The third unit operation occurs in the absorber. The absorber column is equipped with three packed-bed absorber sections comprised of MellapakPlus™ M252Y structured packing. Each section is equipped with a VKR2 liquid solvent distributor plate and a mist eliminator installed at the top of the column. The absorber unit also includes solvent intercooler loops between the beds to optimize the solvent performance at lower operating temperatures. The bottoms of the top and middle beds are each equipped with a SKP draw chimney tray and 4” down pipe. The reaction between CO_2 and ION’s advanced solvent is exothermic and there will be an increase in temperature for both the exiting solvent stream and the exiting flue gas stream.

From the absorber, CO_2 rich solvent leaves the bottoms and passes through a cross exchanger / economizer heat exchanger. ION requested, and had installed, insulation for this cross exchanger in order to minimize ambient heat loss and improve efficiency. The insulation minimizes ambient energy losses at the cross exchanger, to maximize heat recovery and further optimize the overall process gains.

The rich solvent travels from the cross exchanger to the next critical unit operation – the Regenerator Unit. The regenerator column is equipped with two packed beds, 28 layers each, comprised of MellapakPlus™ M252Y structured packing with a VKR2 distributor and a mist eliminator installed. Upon entering the Regenerator Unit, the rich amine stream could possibly be phase-mixed and/or flashed depending on process conditions. The bottoms of the equipment utilizes either a forced or natural thermosiphon reboiler. Enthalpy from the reboiler will drive ION's advanced solvent to release CO_2 and thus regenerate lean solvent to be recycled back into the absorber. Hot lean solvent cools through the cross-exchanger and passes back to the absorber through particulate in-line filters.

The final process step takes the flue gas stream from the absorber column and contacts it with wash water to remove and recover solvent vapor. This water wash column includes a single section of MellapakPlus™ M252Y structured packing with a single VKR2 distributor and mist eliminator.

Special Equipment Required for ION Test Campaign

ION Chiller

ION installed a portable chiller directly into the water pump-around loop on the direct contact cooler (DCC). Preliminary design indicated the need to increase the cooling capacity of this operation. ION took note of significant plant transients which increased the minimum achievable lean solvent delivery temperature to the absorber column by more than 13 °F (>7 °C).

Insulated LRXC

ION insulated the solvent cross exchanger (economizer) to attempt to approach an adiabatic heat transfer operation. Prior to testing with ION, the existing solvent cross exchanger E-404 was uninsulated and a significant amount of ambient heat loss occurs at this unit operation. The advantage of insulating the cross exchanger was to mimic an ideal environment which would facilitate evaluation of optimal pressure drop across either side of the heat exchanger.

Flash Separation Bypass

ION installed a bypass solvent transfer line around the Inlet Separator flash tank which was unnecessary for operation of ION's advanced solvent in the PSTU.

Mobile Laboratory

The ION Mobile Laboratory is a portable, self-contained analytical chemistry lab. A need to provide 24-hour support for near-real-time sampling and analysis of solvent and water conditions during the pilot solvent test campaign led to the fabrication of the lab. The following metrics were measured and tracked throughout testing: Solvent Water Content, Solvent Carrying Capacity, and Solvent Composition. Process control related directly to results obtained from the lab throughout the pilot test campaign. The lab was staffed 24 hours a day and results from the three main analytical techniques were uploaded into a master database for tracking, trending and process control decisions. A retrofitted intermodal container (also known as a shipping container, small size 20' x 8' x 8') was converted to include the following analysis: Karl Fischer titration (KF), Total Inorganic Carbon (TIC), and Gas Chromatography (GC).

Test Methodology

Table 3 shows the top-level test plan that was executed at NCCC, where the first portion of the testing campaign was to perform parametric testing to optimize run conditions while using ION's advanced solvent. The steady-state demonstration was then executed in order to evaluate the secondary solvent metrics of emissions, breakdown products (including heat stable salts), and material compatibility.

Table 3 - Test Plan executed at NCCC

NCCC TEST PLAN				
Steps	**Actions**			
1	**Coal Conditions Parametric Testing**			
	Flue Gas Flow Rate	**L/G**	**Reboiler Duty**	**CO2 Captured**
1.1	Fixed Condition # 1	High	Range: Low to High	>90%
		Medium	Range: Low to High	>90%
		Low	Range: Low to High	>90%
1.2	Fixed Condition # 2	High	Range: Low to High	>90%
		Medium	Range: Low to High	>90%
		Low	Range: Low to High	>90%
2	**Coal Conditions Steady State Testing**			
2.1	Steady state operation at optimum conditions obtained during parametric testing: up to 1,000 hrs			

After completing modifications to the PSTU and identifying the optimal test conditions for parametric testing, two control strategies were prioritized to further define a successful test campaign.

1st Priority – Maintain process & water balances

ION Engineering maintained a water balance by operating at or around a prescribed temperature difference between the flue gas containing CO_2 entering the absorber, and the treated flue gas exiting the absorber. Make-up water was added to the solvent as necessary to maintain a consistent solvent composition. The water concentration in the solvent was confirmed with Karl Fischer titrations conducted over the entire testing campaign at NCCC.

2nd Priority – Flue Gas treating to meet DOE goal of 90%+ removal of CO_2

Limited control of lean solvent temperature and significant transients due to process constraints required ION to moderate upper absorber temperatures by variation of lean solvent loading and/or lean solvent flow rate if necessary. Both mechanisms where highly effective; however, higher steam flow rates and capture rates above 95% resulted from this method of operation.

Results of the Test Including Data Analysis

Test Hours Accumulated

The official run time on the PSTU was 1,116 hours. The testing started on June 24, 2015 at 8:42PM CST (when flue gas was first supplied to the absorber with the solvent flowing). Testing stopped August 10, 2015 at 9:03AM CST.

CO_2 Capture Performance

ION was able to capture ≥ 95% CO_2 at a range of L/G testing conditions, satisfying the project objective of ≥ 90% CO_2 capture.

Specific Heat Performance

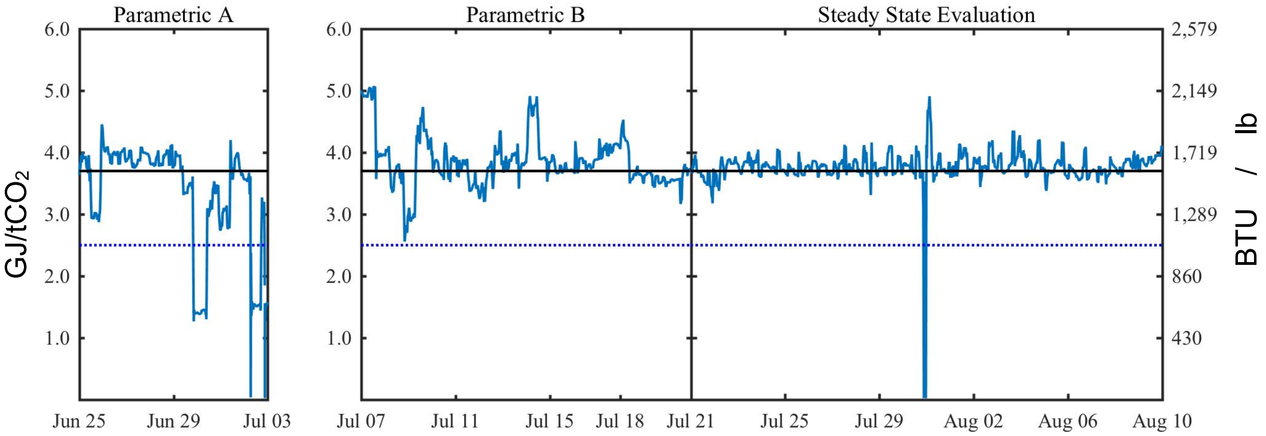


Figure 5 - ION's process performance at NCCC (blue line) and ION's design case performance predicted by ProTreat(R) (dotted line)

Figure 5 shows ION's process performance for the duration of the campaign. ION's specific energy result obtained while at NCCC was 1,600 BTU/lbCO_2 during steady state, where the design case using ION's advanced solvent is 1,090 BTU/lbCO_2. ION captured almost 100% of the available CO_2 throughout this time frame, as is indicated in Figure 6. There were several factors that contributed to the higher regeneration energies obtained during testing, compared to what was predicted by the ProTreat® Model. Utilizing a single bed of packing was likely the biggest energy penalty compounded by over-stripping and obtaining capture rates exceeding 97%. There was an unforeseen outage from plant E.C. Gaston from July 3th to July 6th interrupting the parametric testing for a short duration.

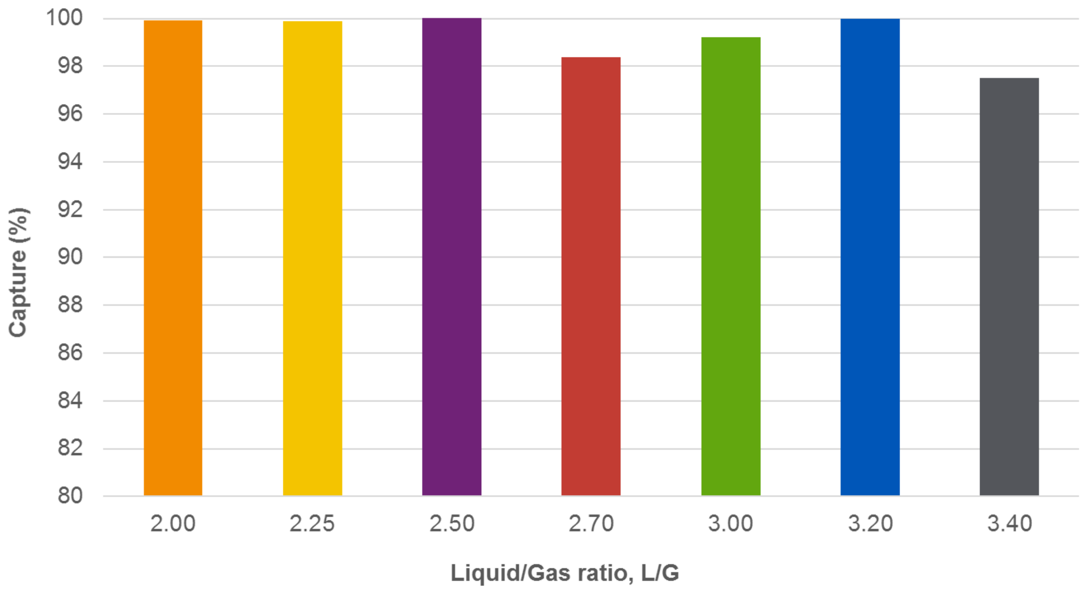


Figure 6 – ION's CO2 capture rates at NCCC for varying L/G conditions

Solvent Lifetime

Amine-based solvents are known to undergo molecular degradation due to the standard process conditions of a carbon capture plant; this process transforms active solvent into less effective byproducts and is normally mitigated by implementing solvent replacement methodologies (and their associated costs). For coal-fired carbon capture, solvent degradation also includes irreversible reactions with flue gas contaminants.

Studies of heat stable salts (HSS) showed that the highest detected compound was sulfate at about 0.2 wt.% of the entire system after the 1,116-hour exposure (Figure 7). Sulfate is not thought to be a degradation byproduct of ION's advanced solvent; rather, it is hypothesized to originate in carried-over sulfur from E.C. Gaston, or the polisher unit supplying flue gas to the PSTU and reacting with excess oxygen in the flue gas. It is important to note that ION's advanced solvent was never purged. Nonetheless, ION never drained or reclaimed solvent during the test campaign. No impact on solvent performance was observed with respect to specific heat requirement (i.e. steam flow) or capture efficiency, even as degradation products and heat stable salts increased.

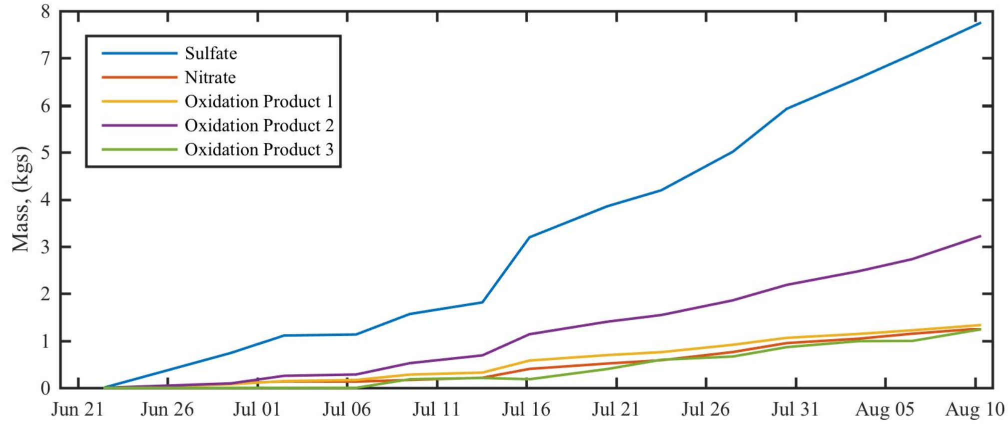


Figure 7 - Accumulation of heat stable salts

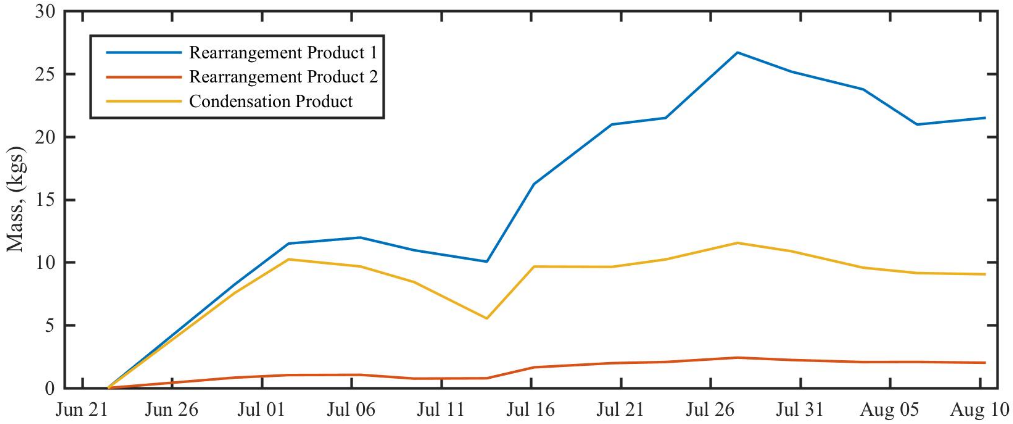


Figure 8 - Solvent degradation

ION's advanced solvent tested in the PSTU was sampled and analyzed for degradation products using GC/MS. Of the degradation products identified, the largest suspected degradation product accumulated to 0.4 wt.% at the completion of the test campaign (Figure 8).

Operational considerations were rectified to best suit the stable operation during the testing campaign. ION did not observe large accumulations of HSS or solvent degradation over the 1,116-hour period, suggesting solvent longevity, although longer testing periods would be needed to confirm solvent durability sufficient for commercial operation.

Metal and Corrosion

Transformational technologies for carbon capture using amines can, and have in the past, presented process conditions that call for expensive, corrosion-resistant materials for the construction of gas treating facilities. ION demonstrated the morphological and chemical tenacity of a carbon steel and three stainless steels at the surface level. The steel samples, in the form of disk coupons, were exposed throughout the testing campaign using ION's advanced solvent.

Scanning electron microscopy (SEM), energy-dispersive spectroscopy (EDS), and weight-loss analysis as per ASTM G1-G4 standard methodologies were used to determine acceptable and non-acceptable steel materials for ION's advanced solvent.

Based on the results, ION's advanced solvent indicates a less corrosive potential than MEA. Published pilot scale corrosion studies of MEA in carbon and mild steels showed unacceptably high corrosion rates (> 7 mils per year).[10] However, carbon steel coupons in the absorber column at NCCC using ION's advanced solvent showed much lower corrosion rates (< 0.05 mils per year). When taking into consideration the substantial process equipment costs associated with constructing a CO_2 capture facility, low corrosion rates is a very important factor to define materials of construction. Carbon steel was less resolute in the regeneration column; lower grade stainless steels were found to be adequate there. Of the metals tested under flue gas conditions, the 304 stainless steel was the most compatible material for ION's advanced solvent system, including the harsh operating conditions associated with regeneration. For future projects with ION's advanced solvent, a lesser grade steel, such as 304 grade stainless steel, will reduce the capital investment required for commercial-sized gas treating facilities.

General Observations or Process Deviations

Lean Solvent Absorber Inlet Temperature

Temperature control of the lean solvent entering the absorber was greatly hindered by two factors; (1) location of the trim cooler before the solvent surge tank, (2) insufficient heat removal capacity of the heat exchanger. The location of the trim cooler heat exchanger led to sluggish control of the lean solvent temperature, due to both the large thermal mass of the solvent in the surge tank and the solvent heating from the lean solvent pump. Temperature control was ultimately affected by the lack of heat exchanger capacity. In operation, this exchanger was typically running at 100% duty with a stable temperature differential which never achieved the process temperature set point.

One of the most challenging and limiting aspects of the test campaign was controlling the lean solvent temperature entering the absorber. CO_2 capture rate, water balance and solvent inventory are all directly impacted by any fluctuation of the inlet lean solvent temperatures.

DCC/Contact Cooler

The direct contact cooler (DCC) was equipped with a commercial chiller unit to cool the gas contact water loop rather than using the existing cooling tower water. The addition of the chiller unit was chosen to mitigate the risk of excess water intake to the absorber in the inlet flue gas leaving the DCC by enabling lower flue gas temperatures than possible with existing cooling tower water. In operation, there were several issues with the chiller and control of inlet flue gas temperature (Figure 9).

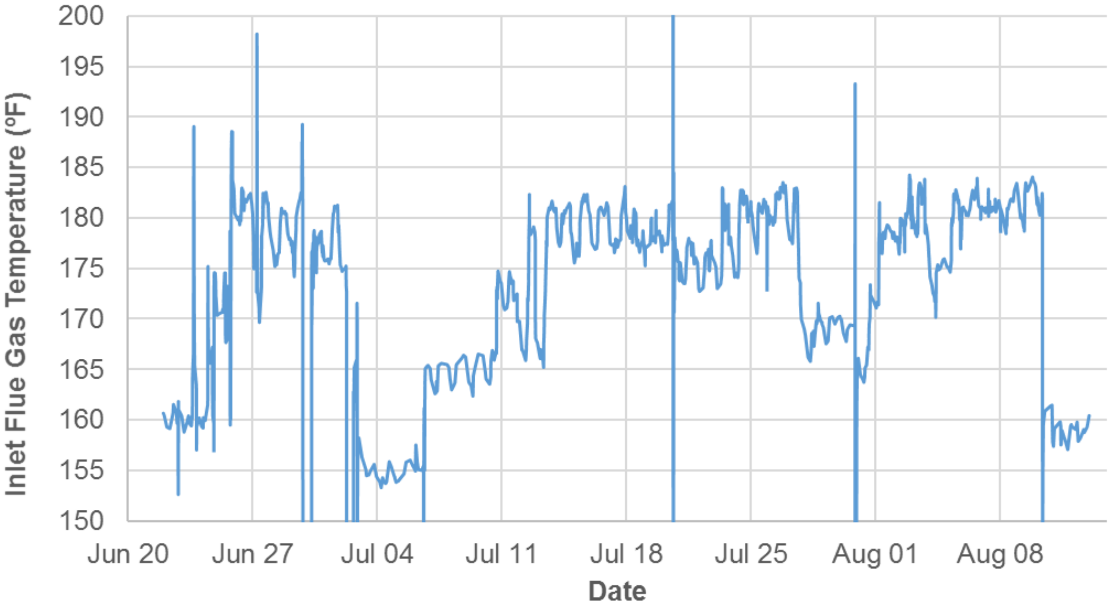


Figure 9 - Plot of direct contact cooler (DCC) inlet flue gas temperature vs time

The first unexpected issue was that the chiller unit was equipped with a flow switch that would shut down the chiller when the process control valve would close below 25% open. This would lead to large flue gas temperature swings until the chiller could be restarted. From that point the chill loop process control valve had to be left to manual control to avoid chiller shutdown. The chiller would have been better designed with a full flow idle loop with branching to the DCC heat exchanger such that the low flow would never be activated.

The second issue with the chiller unit was that the maximum temperature set point was too low (20 °C), preventing higher flue gas temperatures to be specified for water balance control.

The largest issue with the chiller unit was that it was undersized for the process conditions experienced at the NCCC. Flue gas temperatures observed typically were 79-82 °C and frequently exceeded 82 °C. The DCC was designed for a maximum inlet flue gas temperature of 71 °C, but during the test period unique operating conditions resulted in elevated temperatures. These conditions were a result of the following:

- Flue gas demand: The PSTU pre-scrubber simultaneously provides flue gas to several developer projects which may at times require different pressure profiles. During the ION test, the flue gas blower was required to be operated at its maximum capacity. The compression energy added by the blower to the flue gas providing the inlet pressure requirements to fulfill all developer needs on this common system was higher than anticipated.
- Ambient conditions: The test occurred during the months of June – August, which are typically the hottest months of the year in an area where 38 °C is not uncommon for an afternoon high. This, compounded with the blower demand, contributed to the high inlet flue gas temperature.

- Cooling capacity: The cooling water systems at the NCCC were also close to their upper limit, due to the simultaneous operation of other developer equipment and the ambient conditions experienced. However, the cooling water temperatures were still below the stated maximum design temperature for the duration of the test.

Regardless of the above stated contributing factors to the elevated flue gas temperatures experienced during the test, a sufficiently-sized heat exchanger would be adequate for a commercial platform to meet the requirement for temperature-controlled inlet flue gas.

NCCC Campaign Discussion and Conclusion

Throughout the majority of the ION testing campaign at NCCC, ION's advanced solvent was considerably and purposefully over-stripped and also operated at a higher L/G than would be designed for a commercial operation. Successfully managing the temperature profile in the absorber column, as well as preventing excess solvent loss to the wash water tower, were the two main reasons for over-stripping and operating at higher liquid flow rate. This operating philosophy deviated from ION's design case. There was considerable difficulty managing the real-time process limitations of more than 13 °F (> 7 °C) observed on the inlet lean solvent feed into the absorber column. Upstream plant transients, combined with the position and limited capacity of the trim cooler compounded this process constraint. The insufficient control of the lean solvent temperature entering the absorber column prevented ION from operating the solvent at preferred conditions.

An additional complication to the management of the absorber temperature profile was found to be characteristics of the solvent itself. The beneficial characteristics of ION's advanced solvent are identified as a high working capacity (and thus, low L/G), and fast kinetics which are preserved to near completion of the CO_2 absorption reaction. Detailed process design is a path to dealing with the claimed benefits of low L/G solvents. Fitting a process to existing equipment is a challenge; designing equipment to fit a technology is a much better approach for commercialization. With less solvent needed to capture a set target amount of CO_2, there is inherently less overall system mass to absorb the thermal energy produced when the CO_2 capture reaction occurs. This higher absorber temperature condition required mitigation steps for this campaign and now becomes a consideration during future process design activities.

The discrepancy in specific heat of CO_2 processing between ION's design case (2.5 GJ/tonne or 1,090 BTU/lbCO_2) and what was observed during NCCC operation (3.6 GJ/tonne or 1,600 BTU/lbCO_2) can be attributed to the operational strategy used at NCCC. In order to control the temperature profile in the absorber, ION's advanced solvent was operated at a 50% higher L/G than the design case. This operational strategy shifts the temperature bulge lower in the absorber column and mitigates the risk of additional aerosol formation and reduces vapor-liquid equilibrium (VLE) losses. The energy penalty associated with the high L/G was further compounded because, even though the system was operating at 150% of the design case L/G, the lean solvent was still being stripped down to the design case lean CO_2 loading. The ultimate result was capture efficiencies that were well above the 90% target, which are achieved at a much higher specific reboiler duty.

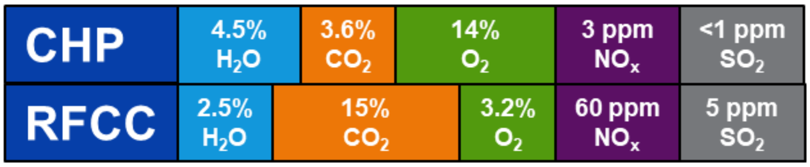
ION's testing at NCCC is supportive of the fundamental ION process model. The testing at NCCC was not able to reproduce the design case specific reboiler duty due to process limitations (operation on a pilot-plant that was not specifically designed for the use of an advanced solvent). However, when the operational conditions of the steady state testing performed at NCCC were incorporated into a ProTreat® process model, the resulting parity plot showed excellent agreement (see ProTreat® Validation Section, below). The validation of the ProTreat® process model indicates that a pilot-plant specifically designed for use with ION's advanced solvent is capable of achieving the design case specific reboiler duty of 2.5 GJ/tCO_2.

Despite some limitations encountered during the operation of the PTSU, important information about ION's advanced solvent was gained during this test campaign. Some key takeaways include: stable operational performance at multiple conditions, low corrosion rates, no observed foaming, and a quickly responding system lending to an ease of operation. The performance of ION's advanced solvent was analyzed for consideration to test at the TCM carbon capture facility. The parameters of concern for all new solvents are regarding emissions, both types and quantity, material compatibility, and solvent breakdown (where potentially toxic components can accumulate over prolonged use). ION successfully demonstrated throughout the test campaign at NCCC that its advanced solvent performs similar or better to MEA for all these performance metrics. Additionally, the validation of the process model indicate that this advanced solvent is still one of the best options available to achieve the DOE goals of 90% capture at a cost of <$40 per tonne of CO_2.

BP3 – Testing at TCM

Introduction to TCM Campaign

The test campaign at TCM was divided into two separate campaigns, where the first campaign was testing on flue gas from the adjacent natural-gas fired Combined Heat and Power (CHP) plant. The second campaign was testing with Residue Fluid Catalytic Cracker (RFCC) flue gas, which more closely approximates the composition of coal-fired flue gas. Figure 10 shows the primary constituents of each of the flue gases available at TCM.[11]



CHP	4.5% H_2O	3.6% CO_2	14% O_2	3 ppm NO_x	<1 ppm SO_2
RFCC	2.5% H_2O	15% CO_2	3.2% O_2	60 ppm NO_x	5 ppm SO_2

Figure 10 – Comparison of flue gas composition between CHP and RFCC sources

The Amine Plant at TCM has the capability to recycle captured CO_2 back into the flue gas to increase the CO_2 concentration in CHP flue gas from 3.6 vol-% up to 14 vol-%. Likewise, the RFCC flue gas can be diluted with air to drop the CO_2 concentration from 15% down to 4%.[12] With this flexibility, the CO_2 concentration of either flue gas can be adjusted to a value that closely approximates flue gas from a coal-fired power plant (typically 12-13 vol-%). However, the large oxygen concentration in the CHP flue gas can also lead to high make-up rate due to the solvent uptake of oxygen, and subsequent oxidative degradation of the solvent. The RFCC flue gas closely approximates coal-fired flue gas, not only in CO_2, but also in O_2, NOx and SO_2. These molecules are typically captured by the solvent and bind the solvent to create heat-stable salts (HSS). The larger the concentration entering the absorber, the higher the solvent make-up rate due to these losses. The only major differences are the presence of mist-aerosols of sulfuric acid and absence of fly-ash.

At the start of the test campaign in October 2016, only the CHP flue gas was available for testing, and only up to 6 vol-% CO_2. The RFCC was not yet available due to planned plant upgrades. TCM installed a Brownian Diffusor to address aerosol concerns related to the incoming RFCC gas. Additionally, the cooling duty for the absorber wash sections was increased so that higher levels of CO_2 can be captured without emissions issues.

The CHP campaign began in October with testing at 4 vol-% CO_2 and gradually worked up to 12.5 vol-% in preparation for testing with the RFCC flue gas. The operational conditions and several performance metrics obtained with CHP flue gas at 12.5 vol-% CO_2 did not change when the flue gas is switched to RFCC. The primary metrics of capture efficiency, specific reboiler duty and optimal L/G ratios only change with CO_2 concentration, regardless of the source. Secondary metrics, such as emissions, breakdown rates and solvent makeup rates, were dependent on the flue gas source where the solvent stability is altered because of the change in uptake of O_2, SO_2 and NOx. ION concluded its CHP test campaign in mid-February 2017, and immediately proceeded to the RFCC campaign which lasted through the end of April 2017. The solvent was changed out at the start of the RFCC campaign to evaluate the above-mentioned secondary metrics based on the same starting conditions of the solvent.

Process Description

Figure 11 shows the process flow diagram for the TCM Amine Plant.[13] For the portion of the testing using the CHP plant as the feed source for the flue gas used at the Amine Plant at TCM, the flue gas has a specified capacity and minimum turndown of 67,200 Sm^3/hr, and 25,000 Sm^3/hr, respectively. The CHP testing utilized a gas flow rate of 50,000 Sm^3/hr. The flue gas feed used for the RFCC campaign was supplied by the refinery has a specific capacity and minimum turndown of 60,000 Sm^3/hr and 20,000 Sm^3/hr, respectively. After the installation of the BD filter, the maximum gas flow rate from the refinery was about 37,000 Sm^3/hr, and typically ION used a flow of 35,000 Sm^3/hr.[12]

The DCCs for each flue gas source are used to cool the incoming flue gas down to the target of 20 °C, and saturate the flue gas with water vapor. This is a typical conditioning of the flue gas prior to introduction into the amine absorber column. The amine absorber is a rectangular polypropylene-lined concrete column with a cross-section of 3.55 m x 2.00 m and a height of 62 m. The amine-flue gas contact area in the absorber consists of three beds of stainless-steel structured packing with a total height of 24 m across three beds, where the lower bed has a height of 12 m, and the middle and upper are both 6 m tall. ION utilized various amounts of packing height throughout the test campaign, as called for in the test plan.

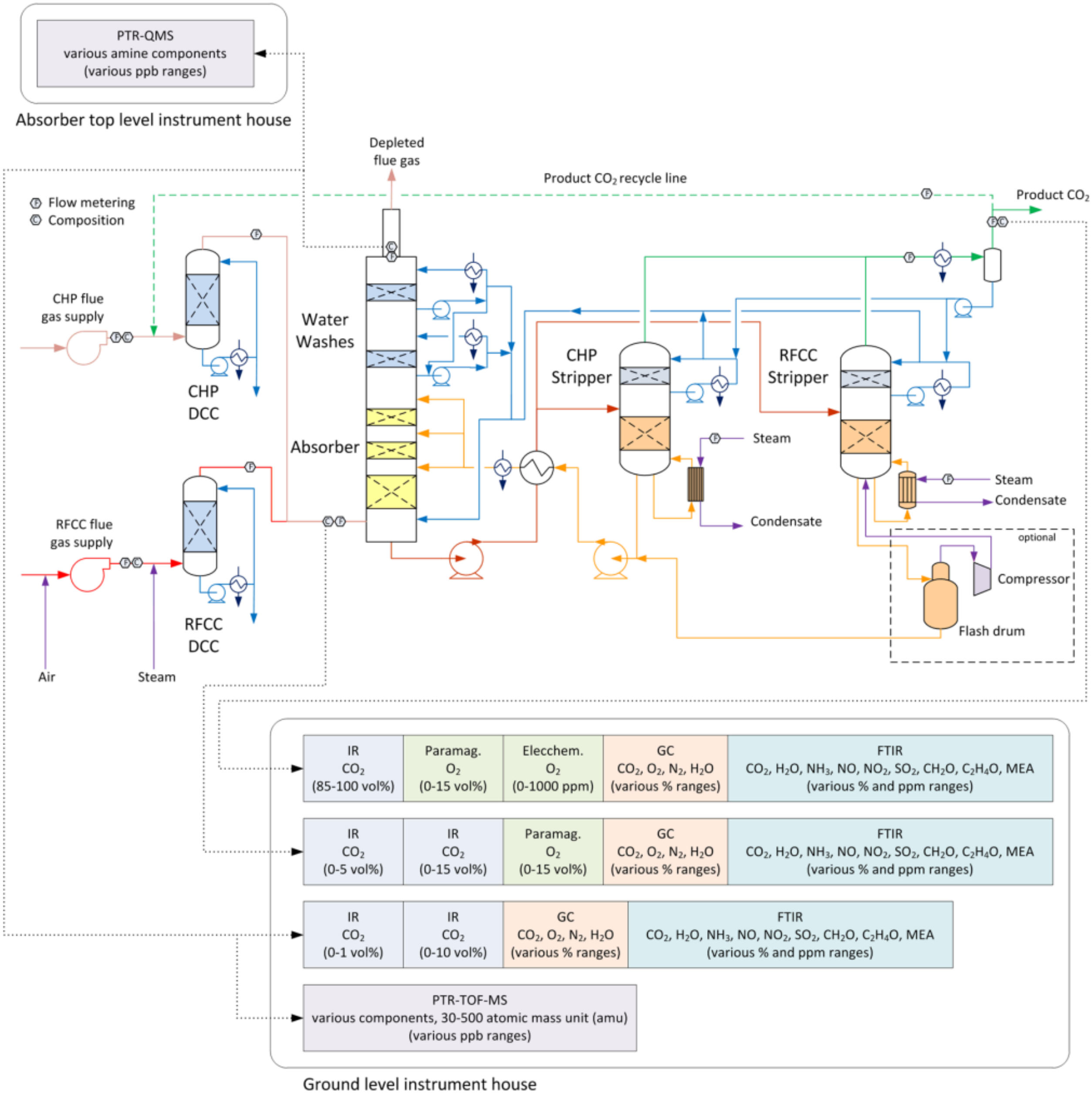


Figure 11 - The TCM amine plant with two flue gas sources, CHP and RFCC, and the corresponding two strippers. Flue gas analyzers and flow meters are located at absorber inlet (I), outlet/depleted flue gas (II) and CO_2 product (III). The dotted green line shows that CO_2 can be recycled back to the absorber inlet for tests at elevated CO_2 concentration in the flue gas flow. (Figure from Gjernes et al., Procedia GHGT-13, 2017)

At the upper part of the absorber, two water wash sections are installed with the purpose to scrub and clean the flue gas of carryover solvent vapors and associated breakdown products. Both of the water washes consist of a 3 m high stainless steel structured packing and were also used to maintain the water balance in the system by adjusting the circulating water temperature of the upper water-wash section. While the lower water-wash has been operated as a typical water wash, the upper water wash has been used as both a water and acid wash for the tests presented in this report. By adding acid to the upper water wash to enhance solvent capture, this ensured that the emissions were within the accepted limits. The consequence of this action is that any amine emissions captured in the upper wash are lost to the system and becomes waste. It is therefore desirable to test the need for an acid wash during the campaign, and endeavor to revert to a dual water wash system.

In order to maintain a desirable water balance the flue gas temperature leaving the lower water wash should be within a few degree of the 20 °C flue gas temperature entering the amine absorber.

The solvent then passes through a liquid-liquid heat exchanger to the regeneration side of the process. This heat exchanger transfers heat from the hot, lean solvent into the cold CO_2-rich solvent. The approach observed on this exchanger was approximately 13 °C. TCM has two stripper/reboiler systems (CHP and RFCC) available to recover the captured CO_2 and return CO_2-lean solvent back to the absorber. The CHP stripper, with a diameter of 1.25 m and height of around 28.2 m, was designed to process the amount of CO_2 that is generally captured from a flue gas containing 3.5-6% CO_2. An 8 m high stainless-steel structured packing bed is located in the lower region of the stripper column, which is where the solvent is stripped. In the upper part of the stripper there is a rectifying water-wash section which consists of a 1.6 m structured SS packing however, ION did not require the use of this wash section during testing.

The RFCC stripper/reboiler was used to recover the captured CO_2 and return CO_2-lean solvent back to the absorber when testing was performed on flue gas with CO_2 content above 6 vol-% (CHP + recycled CO_2, or RFCC with and without air dilution). This stripper column has a diameter of 2.17 m and height of around 30 m and is designed to process the amount of CO_2 that is generally captured from a flue gas with a CO_2 content up to 15 vol-%. An 8 m high stainless-steel structured packing bed is located in the lower region of the stripper column. In the upper part of the stripper there is a rectifying water-wash section which consists of a 1.6 m structured packing (this wash section not used by ION).

To provide the required heat for the stripping process, a steam-heated thermo-siphon reboiler system is connected to each of the stripper columns. Medium Pressure (MP) steam is used for both the CHP and RFCC strippers.

Aside from the water washes on the absorber column, and the DCCs, there were two other processes that used cooling water. The overhead condenser, located on a common line that was shared by the CHP and RFCC strippers, was used to knock down the water content of the CO_2 product gas. This was typically operated to cool the product gas to around 20 °C. Additionally, a trim cooler was present after the lean-rich cross exchanger which allowed for control of the solvent temperature entering the absorber. All cooling processes were fed by ocean water that typically ranged from 6-12 °C, were the cooling duty was only limited by the maximum flow rate achievable by the hardware.

CHP Test Results

ION is very encouraged by the results of this campaign and has drawn several very positive conclusions from the data obtained. ION's advanced solvent has consistently outperformed TCM's MEA base cases,[13] which is summarized in Table 4.

During the parametric study, the best-case SRD achieved by ION at 3.5 vol-% CO_2 was 3.37 MJ/kg CO_2 with 50,000 Sm^3/hr flue gas flow rate. This represents a reduction of approximately 10% in steam energy compared to the base MEA case at TCM (3.62 MJ/kg CO_2),[13] and was achieved without the need for additives to control foaming.

Table 4 – Comparison of ION CHP results at 3.5% CO_2 to MEA base cases at TCM

	MEA (2014)	**MEA + Antifoam (2015)**	**ION (2016)**
CO_2 Concentration, %	3.6	3.6	3.5
Capture, %	90.0	87.4	91.8
SRD, MJ/kg CO_2	4.1	3.62	3.37

During the testing, the CO_2 concentration in the flue gas was adjusted by combining the CHP flue gas with recycled product CO_2. Intermediate CO_2 concentrations in the flue gas were tested while working the CO_2 concentration up to mimic what would be expected at a coal-fired power plant (11-15%). With 6.1% CO_2 in a 50,000 Sm^3/hr flue gas flow, the operating conditions were adjusted and the lowest SRD demonstrated was 3.24 MJ/kg CO_2. Increasing the concentration up to 9.2% CO_2 in the flue gas resulted in an SRD of 3.23 MJ/kg CO_2. The final step up to 13.1% CO_2 in the flue gas resulted in a SRD of 3.33 MJ/kg CO_2. There are currently no MEA baseline cases at elevated CO_2 concentrations against which to compare these results. Also, these results do not represent the optimal run conditions for each CO_2 concentration tested, as no optimization experiments were conducted.

Table 5 shows the key performance indicators (KPI) for a select group of tests that were executed during the CHP campaign. Each of the work packages (WP) listed in the table, apart from WPÅ.1, show the best operating conditions at each of the CO_2 concentrations utilized during the CHP campaign. These best operating conditions were not the results of an optimization study, but were the results obtained while executing the parametric test plan. Tests WPÅ.1 was conducted after the RFCC campaign was concluded, and thus were performed with aged solvent that had an appreciable amount of breakdown products. This test was performed as a repeat of WP2.6 but using the aged solvent (where WP2.6 was taken on near virgin solvent). The water and lean CO_2 content of the solvent was constant in the two experiments, meaning the active components were reduced in content by the amount of breakdown products in the solvent. The results of this last test, compared to those of WP2.6, show the breakdown products present in the solvent result in a 5% decrease in performance.

Table 5 – Table of operating conditions and resulting KPI of key tests performed during the CHP campaign (ION amine concentration at 5-10% lower than the target value).

List of KPIs for inclusion in the CHP campaign						
KPI	**Units**	**WP2.6**	**WP2.24**	**WP28.a4**	**WP28.a8**	**WPÅ.1**
Sample Date		22-Oct-16	3-Nov-16	29-Dec-16	4-Jan-17	28-Apr-17
Sample Time		18:05	9:00	21:30	4:00	4:00
CO2 in Flue Gas	%vol	4.2	6.1	9.2	13.1	4.2
L/G	kg/Sm3	1.42	1.6	2.19	3.69	1.45
Specific Reboiler Duty	MJ/kg CO_2	3.43	3.24	3.23	3.35	3.59
Specific Cooling Duty	MJ/kg CO_2	2.53	2.87	2.99	3.15	2.56
Specific Electrical Duty	MJ/kg CO_2	N/A	N/A	N/A	N/A	N/A
CO2 Capture Efficiency	%	85.4%	91.6%	89.0%	89.9%	82.6%
CO2 Product Purity	%vol	99.4%	98.8%	98.9%	98.1%	98.4%
Amine Consumption	Ratio to MEA	80% to 100%				
Emissions to atm	Ratio to MEA	11.3%	19.2%	41.9%	30.5%	19.4%

Metals analysis of the solvent showed that ION's advanced solvent had very low corrosive properties for the materials used to construct the TCM Amine Plant (a separate section of this report will detail the results of the corrosion coupons).

Emissions were relatively low during the CHP campaign when testing on flue gas with low CO_2 concentrations (3.5-6.0 vol-%). When the CO_2 concentration increased towards 13 vol-%, the maximum absorber temperature increased to 78 °C. This higher temperature in the absorber resulted in greater Vapor-Liquid Equilibrium (VLE) losses (evaporation of solvent components), which contributed to slightly higher emissions. Additionally, when aerosols are generated, which occurs with large flue gas temperature swings, then the vaporized solvent can attach to the aerosols and pass through the water washes. The risk of aerosol formation and/or growth can be mitigated by appropriately adjusting the process controls to deal with the higher absorber temperature. A significant portion of the testing completed during the CHP campaign was focused on the necessary process changes to control absorber temperature swings and reduce emissions. The resulting operations reduced the risk of aerosol formation and kept the emissions levels to similar conditions experienced during the 3.5-6.0 vol-% CO_2 testing, when the absorber column was below 63°C.

RFCC Test Results

The ION campaign using RFCC flue gas, which typically mixed air with the flue gas to achieve a CO_2 concentration of 12.5 vol-% and an oxygen concentration of 7 vol-%, was started with virgin solvent in the system. The decision to change-out the solvent was made in order to distinguish solvent breakdown products, makeup rates, and emission effects between the two flue gas sources. The RFCC campaign began on February 20, 2017, immediately following the successful demonstration of 90% capture of CO_2 from CHP (+ recycle) flue gas at 13.1 vol% CO_2 concentration.

Table 6 shows the KPIs for select testing performed in the RFCC campaign. The WP4.6-U test was part of a U-curve series of tests and represented the minimum SRD. This condition was repeated March 4-6, 2017, and again March 14-16, 2017, to build up run times under these conditions and evaluate the reproducibility of the results. The WP8.3(a-c) tests are the second series of tests that were conducted for several days under constant operating conditions. The WP8.3 testing was conducted when EPRI was on site to provide 3rd party verification of testing procedures, telemetry, and lab analysis.

The remaining tests included in Table 6are WP4.17, which is the test that achieved the lowest SRD of all the tests conditions performed in the RFCC campaign. The operating conditions that were established in WP4.17 that were repeated in WP8.3a-c. A comparison of the results shows that the later tests slightly underperformed with respect to SRD, which is to be expected based on solvent degradation which can be mitigated through solvent make-up and/or reclamation in an ION designed facility. Finally, test WPK.3 was included in the list of important experiments as it was the non-optimized, best-case removal for flue gas with 14.5 vol-% CO_2 concentration.

Table 6 – Table of operating conditions and resulting KPI of key tests performed during the RFCC campaign (ION amine concentration at 5-10% lower than the target value).

List of KPIs for inclusion in the RFCC campaign									
KPI	**Units**	**WP4.6-U**	**WP4.6B**	**WP4.6C**	**WP4.17**	**WPK.3**	**WP8.3a**	**WP8.3b**	**WP8.3c**
Sample Date		Mar 1, 2017	Mar 4-6, 2017	Mar 14-16, 2018	Mar 11, 2017	Mar 28, 2017	Apr 18, 2017	Apr 19, 2017	Apr 20, 2017
Sample Time		14:45	Mar 4: 3:45 Mar 5: 5:00 Mar 6: 12:20	Mar 14: 5:00 Mar 15: 5:00 Mar 16: 4:00	5:45	3:45	11:30	3:40	3:30
CO2 in Flue Gas	%vol	12.4	12.6	12.5	12.6	14.5	12.4	12.5	12.6
L/G	kg/Sm3	2.73	2.75	2.78	2.99	4.07	2.23	2.23	2.21
Specific Reboiler Duty	MJ/kg CO_2	3.28	3.36	3.31	3.25	3.39	3.36	3.37	3.38
Specific Cooling Duty	MJ/kg CO_2	3.11	3.15	3.07	3.04	3.12	2.84	2.83	2.82
Specific Electrical Duty	MJ/kg CO_2	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
CO2 Capture Efficiency	%	89.2%	88.1%	85.8%	91.1%	85.4%	89.5%	89.0%	88.8%
CO2 Product Purity	%vol	97.1%	98.1%	98.7%	99.2%	99.2%	99.5%	99.5%	99.0%
Amine Consumption	Ratio to MEA	50%			N/A	N/A	85%		
Emissions to atm	Ratio to MEA	No data for MEA operation under similar conditions are available for comparison at time of publication							

All the testing during ION's RFCC campaign was carried out with 18 m of packing used for CO_2 capture. The consequence of using 18 m instead of 24 m of packing is that the residence time of the solvent in the absorber is lower, leading to higher lean flow rates for similar capture efficiencies. With the utilization of more packing, the flow rate would have been reduced to achieve the same residence time, and the energy lost to heating solvent in the stripper would be reduced per tCO_2 captured. In an ION-designed process, optimized for ION's advanced solvent, packing heights would be adjusted to achieve the highest level of performance while staying within emissions permit limits.

ION completed an extensive set of parametric tests during the RFCC campaign. The results of these tests have demonstrated the optimum L/G for obtaining low SRDs. The best SRD was achieved at the highest tested operating pressure in the stripper, where the value was 3.25 $MJ/kgCO_2$. Operating at this higher pressure required more steam to the stripper sump, where the stripper sump temperature also increased. Reducing the pressure of the stripper led to higher water vapor losses and, as expected, an increase in SRD.

Similar to the CHP campaign analysis of the solvent, the metals analysis showed that the solvent had very low corrosive properties for the materials used to construct the TCM Amine Plant. No additives were utilized or are expected for future use with ION's advanced solvent to control corrosivity.

Similar to the CHP campaign, when the CO_2 concentration was increased to 12.5 vol%, the absorber maximum temperature increased up towards the maximum achieved in testing of 78 °C. This higher temperature in the absorber resulted in greater VLE losses, which contributed to higher emissions passing the water washes and leaving the absorber stack. The acid wash was utilized more frequently in the RFCC campaign to assist in reducing emissions. The acid wash showed to be most effective in removing light gaseous molecules (>90% removal). Despite emissions losses and solvent breakdown through multiple pathways, the observed solvent loss rate was still 50% lower than that of MEA.

Comparison of CHP and RFCC Performance

U-Curves/SRD

Optimization experiments were conducted in both the CHP and RFCC campaigns to determine the run conditions at which the best energetics could be achieved for a given flue gas. Figure 12 shows the results of two of these optimization curves where the CHP flue gas at 4.0 vol-% CO_2 and RFCC flue gas at 12.5 vol-% CO_2. The CHP data was acquired using the CHP stripper, which is designed for the operating conditions required for lower CO_2 concentrations. The final difference between the two sets is that the RFCC testing was performed at 35,000 Sm^3/hr gas flow rate, which is lower than the 50,000 Sm^3/hr flow rate used for CHP testing. The slower flow rate leads to more residence time in the absorber, and improves the capture of CO_2 by the solvent.

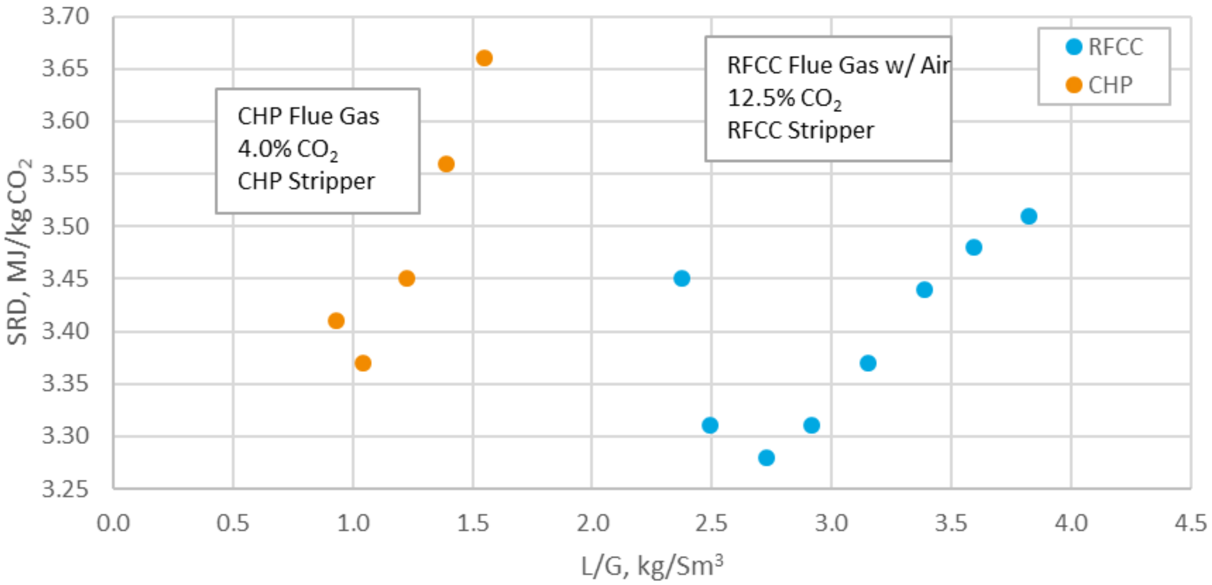


Figure 12 - U-Curves generated for CHP flue gas and RFCC flue gas.

These results show that the optimal capture of CHP flue gas at 4 vol-% CO_2 is only slightly higher than what was obtained on the RFCC gas stream at 12.5 vol-% CO_2. The results in Figure 12 indicate that there is a slight decrease in SRD, but one that is not as pronounced as what TCM demonstrated with MEA in the baseline campaign.[iv] The mechanism of ION's advanced solvent that would reduce the benefit of SRD on flue gas with higher CO_2 concentration is unknown at this point.

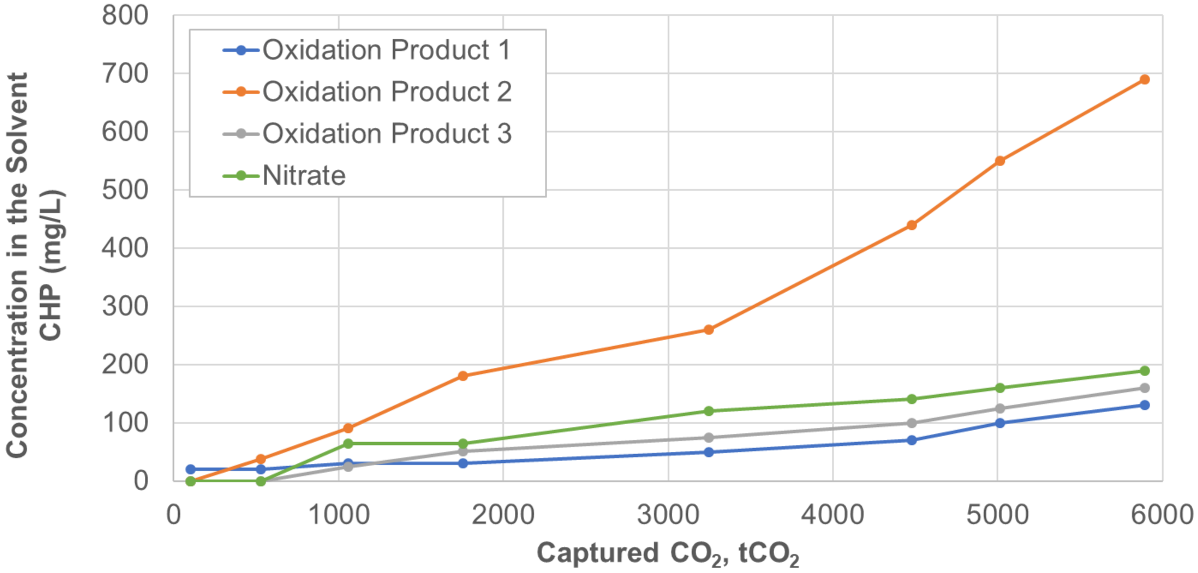
Solvent Composition

The evaluation of the heat stable salts (HSS) formation rates in the solvent can provide information on the dominant degradation pathways for both the CHP and RFCC campaigns. The concentrations are plotted against the total CO_2 captured by the solvent in each of the campaigns. Figure 13 shows the results of the solvent analysis on four individual HSS throughout both campaigns: Oxidation Products 1, 2, 3, and nitrate. Other HSS that were monitored were generally found at or below the detection limits for the analysis during the test campaigns, leaving only a few points for evaluation. The data was evaluated with the expectation that the CHP campaign would have more oxidative degradation and the RFCC campaign would have more thermal degradation due to running the stripper reboiler temperature at the very top end of the solvent limit.

Starting with oxidation product 1 in Figure 13, the formation rate as a function of tonnes of CO_2 captured is very similar for both the CHP and RFCC flue gas sources, where the accumulation of oxidation product 1 is slightly higher with the RFCC flue gas.

Oxidation product 2 show a significantly higher accumulation rate (relative to the amount of CO_2 captured) during the CHP campaign where the oxygen content in the flue gas is two to three times higher than that of the RFCC flue gas. Oxidation product 2 is an oxidative decomposition product of the solvent and can thermally decompose to oxidation product 3 and CO_2. Therefore, it makes sense that the accumulation of oxidation product 3 increases at a faster rate in the CHP campaign where there is more oxidation product 2.

Finally, the nitrate comparison is shown at the bottom of the charts in Figure 13. The NOx concentration in the CHP flue gas is significantly lower (<5ppm)[11,12] than what is present in the RFCC flue gas (60ppm)[11] and the two charts show the effect of the higher concentration. A percentage of NOx is captured by the solvent and the end products are nitrate HSS; thus, as was expected, the nitrate HSS values are elevated in the RFCC results.



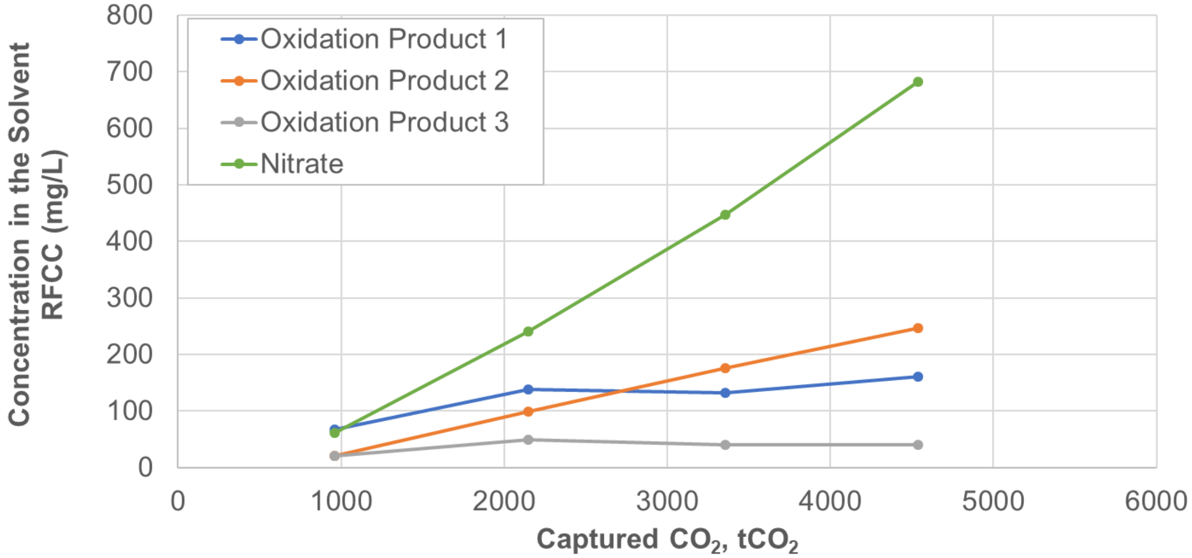


Figure 13 – HSS formation for the CHP (top) and RFCC (bottom) campaigns as a function of total CO_2 captured

Emissions

Table 7 shows how the emissions from ION's CHP campaign compare with the TCM MEA campaign.[11] The table shows the results based on the incoming flue gas concentration of CO_2, where ION was testing on approximately 4 vol-% CO_2 CHP flue gas for the two weeks of testing in Oct 2016. The concentration was increased to 6 vol-% in November testing and for completion the higher concentrations of 8.1 vol-% and 12.5 vol-% CO_2 are shown.

The results show that ION's advanced solvent losses are slightly lower than what was demonstrated with MEA. Combining the various breakdown products into a single, comparable value shows that ION's advanced solvent has significantly lower breakdown emissions. This compares very favorably with MEA total emissions (solvent and breakdown) of 20.8 ppm, when utilized under similar operating conditions.

Table 7 – Comparison to the TCM MEA campaign emissions.

		MEA campaign	IONs Campaign			
Emission Component	Unit	3.7% CO_2	4% CO_2	6% CO_2	8.1% CO_2	12.5% CO_2
Solvent	ppm	0.5	0.4	0.1	0.1	0.1
Breakdown Products	ppm	20.3	6.3	6.9	13.3	12.3
Total Emissions	**ppm**	**20.8**	**6.7**	**7.0**	**13.3**	**12.3**

Corrosion Coupon Analysis

TCM installed several corrosion coupons into the system to evaluate solvent impact on typical industrial materials. The coupons were installed at two locations, one in the rich stream, just after the heat exchanger on the stripper side (hot rich solvent) and the second one was in the lean stream, just prior to the heat exchanger (hot lean solvent). Table 8 shows the results from this corrosion study.

The corrosion coupons were installed prior to the start of testing and left in place throughout the entire ION test campaign (including down times and periods were TCM was upgrading the system). They were removed after the campaign and evaluated to determine weight loss of the materials. As can be seen in Table 8, the carbon steels tested, S235 carbon steel (similar to US naming of C1010 carbon steel) and (A106 Gr B – pipe grade carbon steel) had no remaining coupons at the conclusion of the testing in either installed location. Even though the coupons could have broken free and not fully dissolved by the end of the campaign, the assumption in the calculation is that these coupons were completely lost. The corrosion rates for the carbon steel coupons all represent a worst-case scenario at an average value of 65.3 mils/yr, given that the coupons may have simply broken free prior to complete dissolution. By way of comparison, ION also utilized a carbon steel coupon of a very similar variety to S235 (C1010) and has included those results for comparison in Table 8. The NCCC test was conducted over a shorter period of time, and the carbon steel coupon was still present at the end of the campaign, leading to a more accurate mass loss due to the solvent. The resulting corrosion rates obtained during the NCCC campaign from hot lean solvent was 40.9 mil/yr for C1010 carbon steel.

Table 8 – Corrosion coupon results table.

		Before exposure			After exposure			
materials	**Location**	**water washed and dried**	**installation date**	**withdrawal date**	**Thorougly water washed and dried with absolute alcohol**	**weight Loss**	**TCM Results**	**NCCC Results**
		g			*g*	*g*	*CR (mpy)*	*CR (mpy)*
S235 Carbon steel	Hot Lean	53.0233	10/11/2016	4/30/2017	nd	53.02	65.317	40.883
304 L		55.7469	10/11/2016	4/30/2017	55.7448	0.00	0.003	0.011
316 L		55.7957	10/11/2016	4/30/2017	55.7946	0.00	0.001	0.002
A106 Gr.B		53.0386	10/11/2016	4/30/2017	nd	53.04	65.252	N/A
Inconel 625		60.395	10/11/2016	4/30/2017	59.5038	0.89	1.020	N/A
Duplex		55.008	10/11/2016	4/30/2017	55.0080	0.00	0.000	N/A
Duplex w/Stellite 12		58.494	10/11/2016	4/30/2017	58.4898	0.00	0.005	N/A
S235 Carbon steel	Hot Rich	40.5621	10/11/2016	4/30/2017	nd	40.56	65.495	N/A
316 L		42.5932	10/11/2016	4/30/2017	42.5912	0.00	0.003	N/A
304 L		42.4908	10/11/2016	4/30/2017	42.4888	0.00	0.003	N/A
A106 Gr.B		39.9247	10/11/2016	4/30/2017	nd	39.92	64.384	N/A
Inconel 625		45.8333	10/11/2016	4/30/2017	45.8316	0.00	0.003	N/A
Duplex		41.1124	10/11/2016	4/30/2017	45.1118	-4.00	N/A	N/A
Duplex w/Stellite 12		44.204	10/11/2016	4/30/2017	44.2005	0.00	0.006	N/A

Two other samples were evaluated at TCM that can directly be compared to the results obtained during the NCCC test campaign. The 304L and 316L samples in the hot lean solvent showed similar low corrosion rates as were obtained at NCCC. The other alloys tested with coupons include Inconel 625, and two Duplex coupons. The Inconel alloy had a CR of 1.0 mils/yr in the hot lean solvent and an insignificantly small CR in the hot rich solvent. The duplex coupon, which is the material used in constructing the Amine Plant, also showed little to no corrosion.

ION Multi-component liquid analyzer (MLA)

ION designed and developed a portable prototype for continuous extractive liquid sampling and analysis by attenuated total reflectance (ATR) Fourier transform infrared (FTIR) spectrometry. Additionally, stand-alone software for component analysis was also developed. The analyzer determines the concentration of the solvent main components at near real-time. Two analyzers were installed for use at TCM and are referred to as MLA-1 and MLA-2.

Due to the portability and robustness of the MLA, it can be installed in the field, thus eliminating the requirement to be installed close to a lab for a sample loop. A weatherproof and environmentally controlled enclosure was designed and fabricated to house each of the MLAs (Figure 14). Two prototype MLA units were installed in January at TCM with one unit monitoring the cold lean side and the other unit monitoring the cold rich side.

When the MLA system is started, the FTIR collects spectral data at regular intervals. The spectra data is stored both locally on the laptop and in a cloud data warehouse. The MLA software reads the spectra data and calculates the solvent composition. The analysis takes less than a minute.

Figure 14 – MLA units installed in weatherproof enclosures at TCM.

Results

This campaign was the first real-world implementation of the MLA.

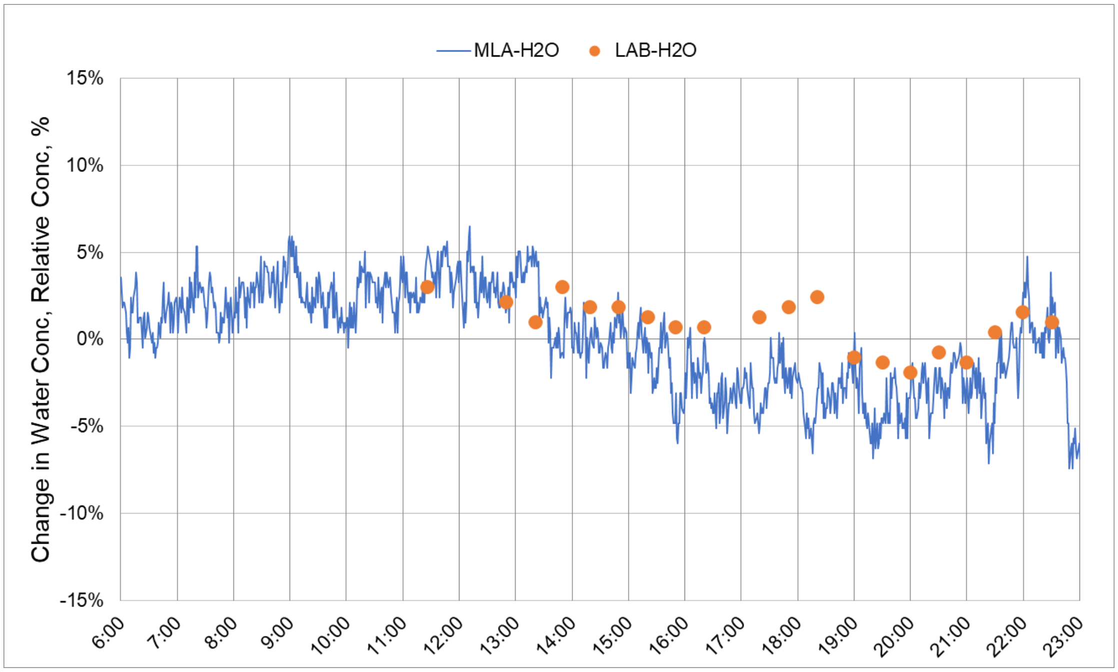


Figure 15 shows the comparison of MLA and lab data for the relative changes from the target H_2O composition. The average relative error of the MLA water determination was -5.0%, which is an acceptable determination for near real-time analysis.

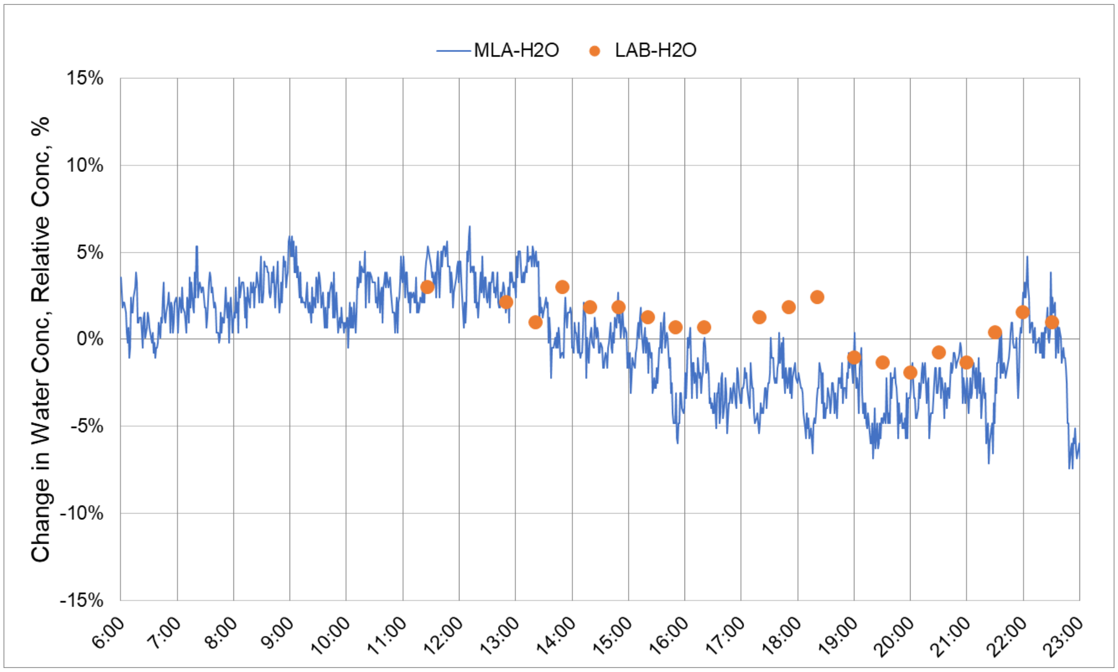
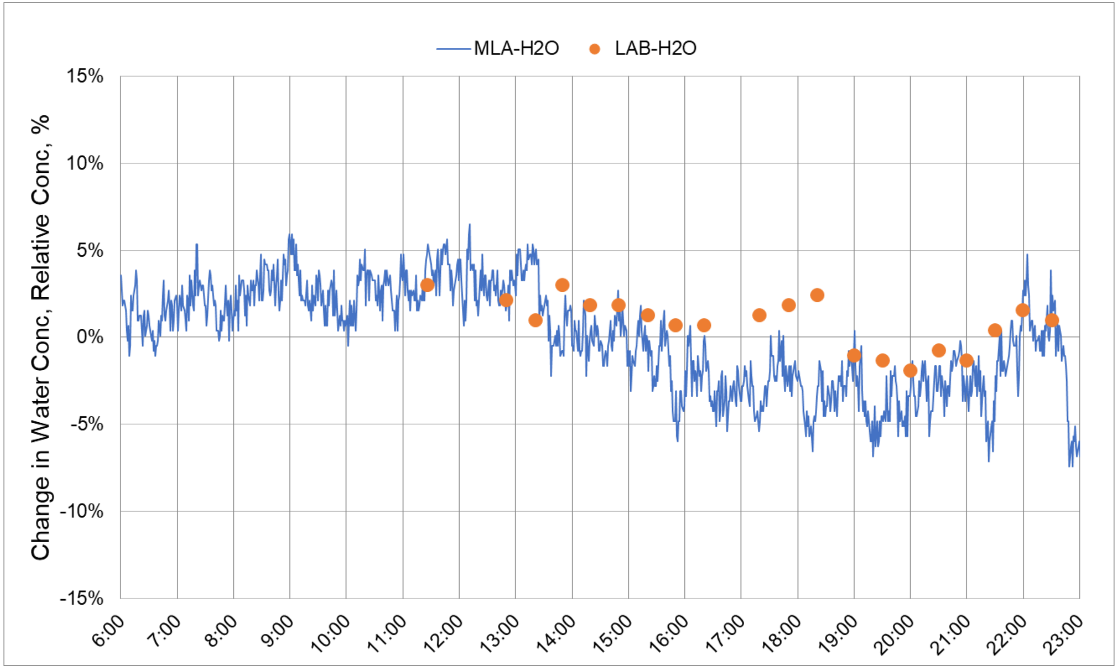


Figure 15 – Relative values of lab versus MLA-H2O concentrations. The change in H2O concentrations are relative to the average H2O concentration over the entire test. The lab data presented in this chart was obtained and provided by TCM using the Karl-Fischer determination of water concentration. The average relative error in the MLA water determination after retraining the software is 1.7%.

Figure 16 shows the comparison of MLA and lab data for absolute CO_2 values. The MLA tracked the initial steady state of the CO_2 loading and then the subsequent increase and decrease of the loading. The average relative error of the MLA CO_2 determination is -7.5%. As the CO_2 is loaded, there is a slight decrease of the weight percentage of the solvent and H_2O, which is necessary in maintaining the mass balance. This effect can be seen in Figure *15*. The MLA was sensitive enough to track these slight differences. At about 22:30 the trial was terminated where the SST dropped dramatically and consequently the CO2 concentration increased. Overall, the fast-tracked development from lab to installation of the MLAs at the industrialized TCM-site has been remarkably successful.



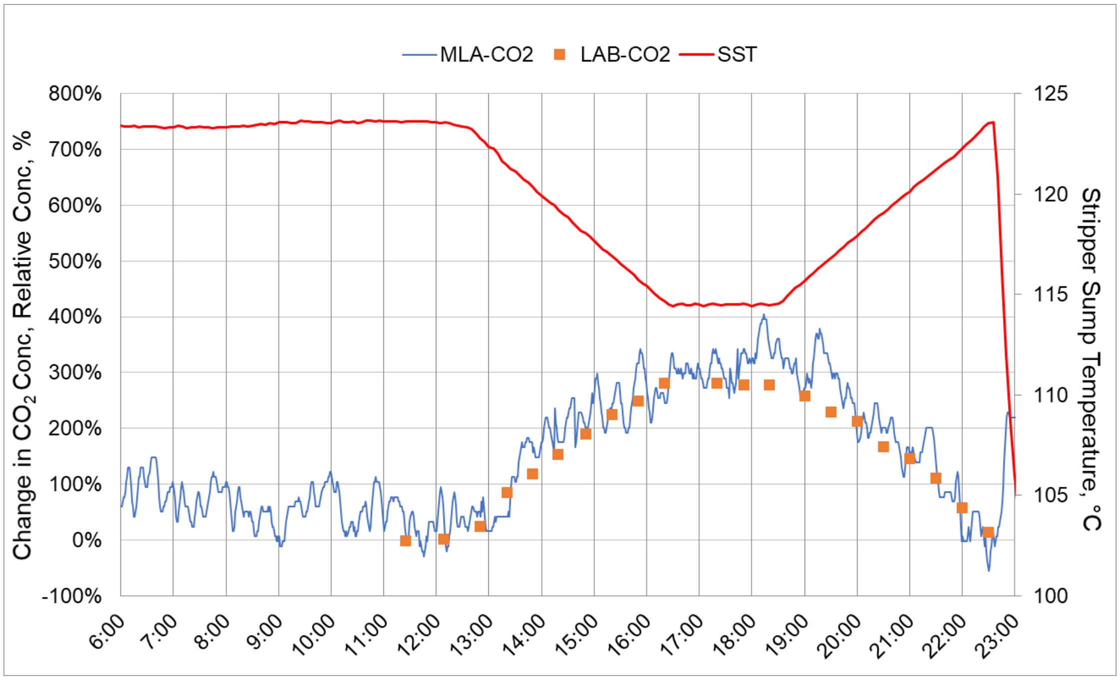


Figure 16 – Relative values of TCM lab versus MLA CO2 concentrations shown against the changes in stripper sump temperature (SST). The change in CO2 concentrations are relative to the initial CO2 concentration (lab

data) before SST changes. Large SST drop on the right is result from a planned complete stop of steam flow to the stripper.

Campaign Totals

ION's run time on solvent testing using both CHP and RFCC flue gases totaled 2,775 hours. From mid-October until the end of the total test campaign (end of April), ION captured 14,819 tCO_2. The test hours and amount of CO_2 captured in each month during the campaign are listed in Table 9. Figure 17 shows the total tonnes of CO_2 captured and total number of test hours accumulated over the course of the ION test campaign.

Table 9 – Test Hours Accumulated and CO_2 captured during the ION testing campaign.

Month	Campaign	Start (Date)	End (Date)	Total Testing (hr)	Total CO_2 Captured (tonne)
October	CHP	10.10.2016	31.10.2016	398.5	1,058
November	CHP	01.11.2016	11.11.2016	235.5	1,099
December	CHP	27.12.2016	31.12.2016	103.0	684
January	CHP	01.01.2017	20.01.2017	401.9	2,408
February	CHP	07.02.2017	16.02.2017	238.2	1,083
February	RFCC	21.02.2017	28.02.2017	179.5	1,128
March	RFCC	01.03.2017	31.03.2017	665.7	4,687
April	RFCC	01.04.2017	24.04.2017	370.0	2,184
April	CHP	03.04.2017	28.04.2017	182.2	488
Total				**2,774.5**	**14,819**

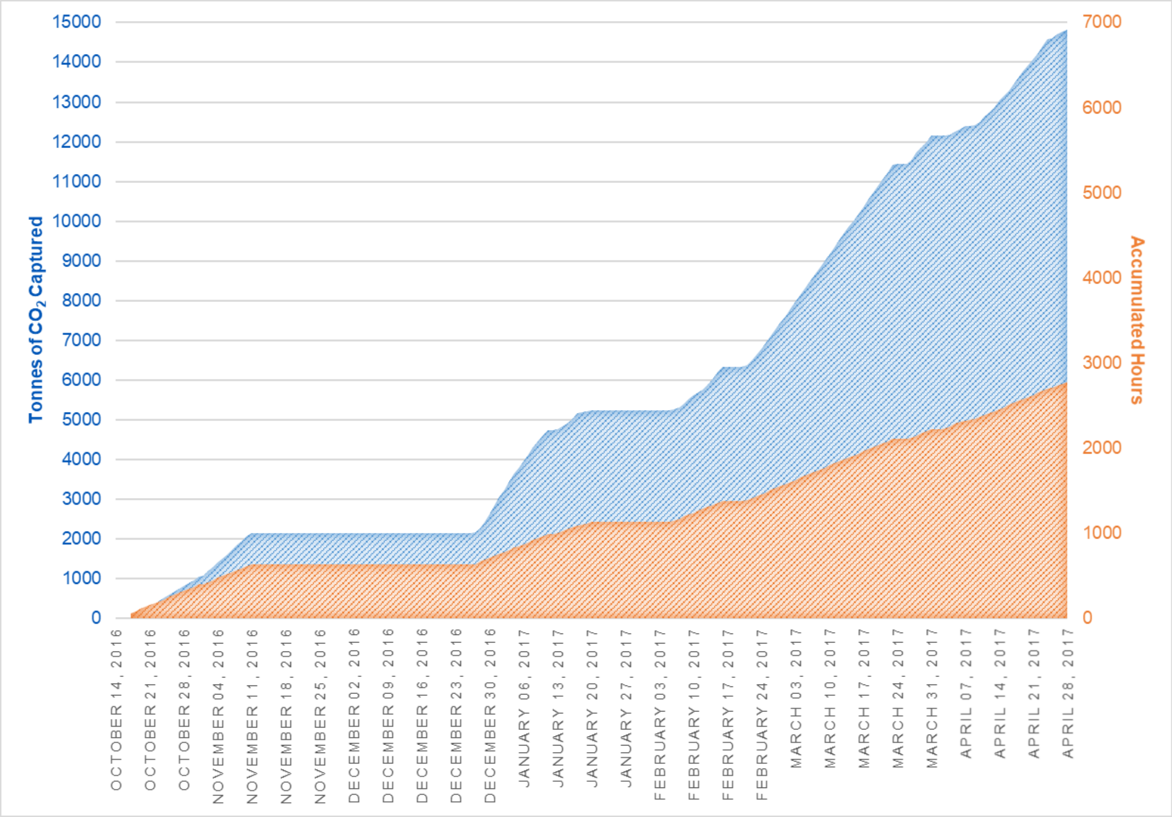


Figure 17 – Total CO_2 captured and total hours of test hours accumulated through the ION testing campaign.

The RFCC campaign started up on Feb 21, 2017 and ran through April 28, 2017, and the Amine Plant was available for testing to ION for 56.1 days of this 59.4 days. The downtimes are attributed to an instance where the RFCC blower was shut down for cleaning (3.2 days) and an acid leak on the acid wash (0.1 days). ION was successfully testing on 50.9 days, there were stoppages of 0.3 days due to emissions, and stoppages for 4.8 days for process changes. These durations lead to on-stream times of 99.3% when taking into account only issues related to the use of ION's advanced solvent, and 90.8% when also including process change stoppages.

TCM Campaign Conclusions

The comparison of ION's advanced solvent performance at various concentrations of CO_2 in the flue gas scrubbed by the TCM absorber showed some surprising results. The expectation heading into the test campaign was that the higher the CO_2 concentration in the flue gas, the lower the SRD achieved when operating under optimized conditions. Several U-curve experiments were performed through both the CHP and RFCC campaigns and the minimum on the U-curve suggests that there is only a minor, and possibly insignificant improvement in energetics while scrubbing flue gas with higher CO_2 concentration. TCM showed data obtained in a baseline MEA campaign that demonstrated a significant reduction in SRD when increasing from 4 vol-% CO_2 up to 9 vol-% CO_2. More research is necessary to determine the mechanism that prevented ION's advanced solvent from achieving similar gains during the TCM campaign.

The solvent composition study has shown that operations with CHP flue gas result in a slightly faster decomposition rate of the solvent when compared to the RFCC campaign. This decrease is seen when the data is normalized to the amount of CO_2 captured. The higher oxygen concentration is the suspected cause of the higher degradation rate. The HSS tracked in the solvents used in each of the campaigns suggest that oxidation of the solvent and higher oxygen concentration in the CHP flue gas leads to higher rates of formation for this HSS.

Comparing the emission rate normalized to the amount of CO_2 captured during each campaign also showed interesting results. The end of the CHP campaign has a significantly reduced rate, even though the CO_2 concentration in the flue gas is high (up to 12.5 vol-% CO_2). Comparing this emission rate at the end of the CHP testing to the first 6,000 tonnes of CO_2 captured from RFCC, where both sets of data were obtained while scrubbing flue gas with 12.5 vol-% CO_2, shows that under similar conditions the RFCC flue gas has a higher emission rate. This is most likely due to the presence of aerosols that make it through the Brownian Diffuser and act as seeds for accumulating solvent as they pass through the absorber. More information and a detailed study would be required to fully evaluate the cause of the apparent increase in emissions from RFCC flue gas.

Corrosion coupons were used throughout the entire campaign and were evaluated after the completion of all testing. The results are similar to what was seen on previous testing at NCCC, where the carbon steel coupons showed high corrosion rates. The 304L, 316L, and Duplex steels all showed negligible corrosion (<0.01 mils/yr), while only the Inconel 625 steel showed some noticeable corrosion in the hot lean solvent stream (~1 mils/yr).

ION implemented an online liquid monitoring system for real-time analysis of solvent, water and CO_2. Overall, the MLA performed better than expected with clear detection of near-real-time trends. With these promising results in the initial pilot release, ION believes the MLA to be a useful and important tool for both monitoring liquid compositions as well as providing a mechanism to automate and optimize the control of the process.

Process Model Validation

While the results of the test campaigns at NCCC and TCM provide some excellent results for demonstrating the energy saving performance of ION's advanced solvent, the primary benefit of these campaigns is to provide data (emissions, solvent breakdown rates, and corrosion rates) on coal, and coal-like flue gases. Additionally, the telemetry and key performance indicators from steady state operations can be used to validate ION's process model. The validation of this process model is more important in advancing the case for a commercial system based on ION's advanced solvent than the demonstrated test results on a 0.5 MWe (NCCC) and 12 MWe (TCM) pilot plant. This is because the pilot plants utilized in this program are designed for MEA use, and do not incorporate the necessary process enhancements to fully realize the benefits of ION's advanced solvent. This section describes the work done to build and validate the ProTreat® Process model that utilizes ION's advanced solvent to achieve an optimized facility that can achieve a specific reboiler duty of 2.5 MJ/kg CO_2.

The Design Case (2.5 MJ/kg CO_2)

ION has utilized a proprietary module of ProTreat®, developed by Optimized Gas Treating, to design a carbon capture plant optimized to take advantage of the properties of ION's advanced solvent which can achieve specific reboiler duties of 2.5 MJ/kg CO_2. OGT's ProTreat® is the best fit for modeling amine solvents because it is a true rate-based simulation, which sets it apart from other commercially available packages. The process flow diagram from the ProTreat® process model is shown below in Figure 18. There are no exotic process additions necessary to achieve the low SRD; only intercooling of the solvent in the absorber and the use of a cold-rich bypass stream into the stripper. The flue gas (stream 100) enters through the DCC, where it is cooled to 30 °C before entering (102) the absorber that utilizes 24 m (2x 12 m) of packing (252.Y Mellapak Plus) to scrub the CO_2 using ION's advanced solvent. The top of the absorber has another set of packing for the water wash, in order to scrub the gas of the amine vapors prior to its release to atmosphere (103). The water wash is used to maintain water balance in the amine plant by controlling the exit flue gas temperature to approximately 30-31 °C.

ION's advanced solvent enters the absorber (79) at 45 °C after the trim cooler and passes through the first 12 m of packing for carbon capture. The L/G in this model is 1.92 kg/kg. After 12 m of packing has been utilized, 100% of the solvent is pulled out and passed through an inter-stage cooler to reduce solvent temperature from 58 °C to 50 °C. The solvent is returned to the absorber to utilize the last 12 m of packing for capturing carbon from the flue gas. It leaves the absorber (40), combines with the excess water knocked out in the water wash (35) and then is moved to the regeneration system.

The first step in the regeneration process is to heat the solvent in the Lean Rich Cross Exchanger (LRXC) to pick up heat from the already stripped solvent (stream 44) before introducing it into the stripper column. At the base of the stripper is a kettle-type reboiler that heats the solvent to the target regeneration temperature, and in the process, liberates CO_2 and water vapor from the solvent. As the water vapor travels up through the stripper column it condenses out as it contacts cooler solvent, thus enhancing CO_2 vaporization by transferring the heat of vaporization into the solvent. This remaining water vapor and CO_2 gas stream exits through the top of the stripper and on to the overhead condenser before leaving the system as the CO_2 product stream (82). A portion of the rich stream bypasses the LRXC and is added directly to the top of the stripper (50), which is termed the cold rich bypass (CRB). The benefit of this stream is two-fold, where first the CRB stream contacts the hot gases leaving the stripper with cooler liquid and condense out as much water as possible. This action prevents the escape of energy (water vapor heat of vaporization energy) from the regeneration column by transferring it into the cooler solvent, which reduces the required reboiler duty for leaning out the solvent. The second benefit is that a flow imbalance exists at the LRXC that results in a higher driving force (ΔT), which achieves a higher temperature of hot-rich solvent entering the stripper.

The challenge with a low L/G system, such as the one that utilizes ION's advanced solvent, is that the flow of warm rich solvent into the stripper column cannot knock out sufficient water vapor, and thus energy is lost. The CRB stream is a well-known process for assisting in the knockout of water vapor with a direct contact cooler in the stripper. The flow rate of the CRB is measured in a fraction of the total rich flow and when the L/G is high such as for MEA, the fraction needed for the CRB is relatively low (~10%).[14] However, as the L/G is lowered, more CRB flow is needed to capture the water vapor. ION's advanced solvent can achieve low L/G because it can be leaned to very low levels without any additional energy penalties, thus achieving a high CO_2 carrying capacity. ION has worked out the optimal CRB split ratio to balance the knockout of water vapor while also maintaining a useful transfer of heat energy in the LRXC. Utilizing enough packing to saturate the rich solvent with CO_2 results in a) a very large working capacity, thus b) reducing the L/G needed for 90% capture, and c) reducing the SRD for carbon capture.

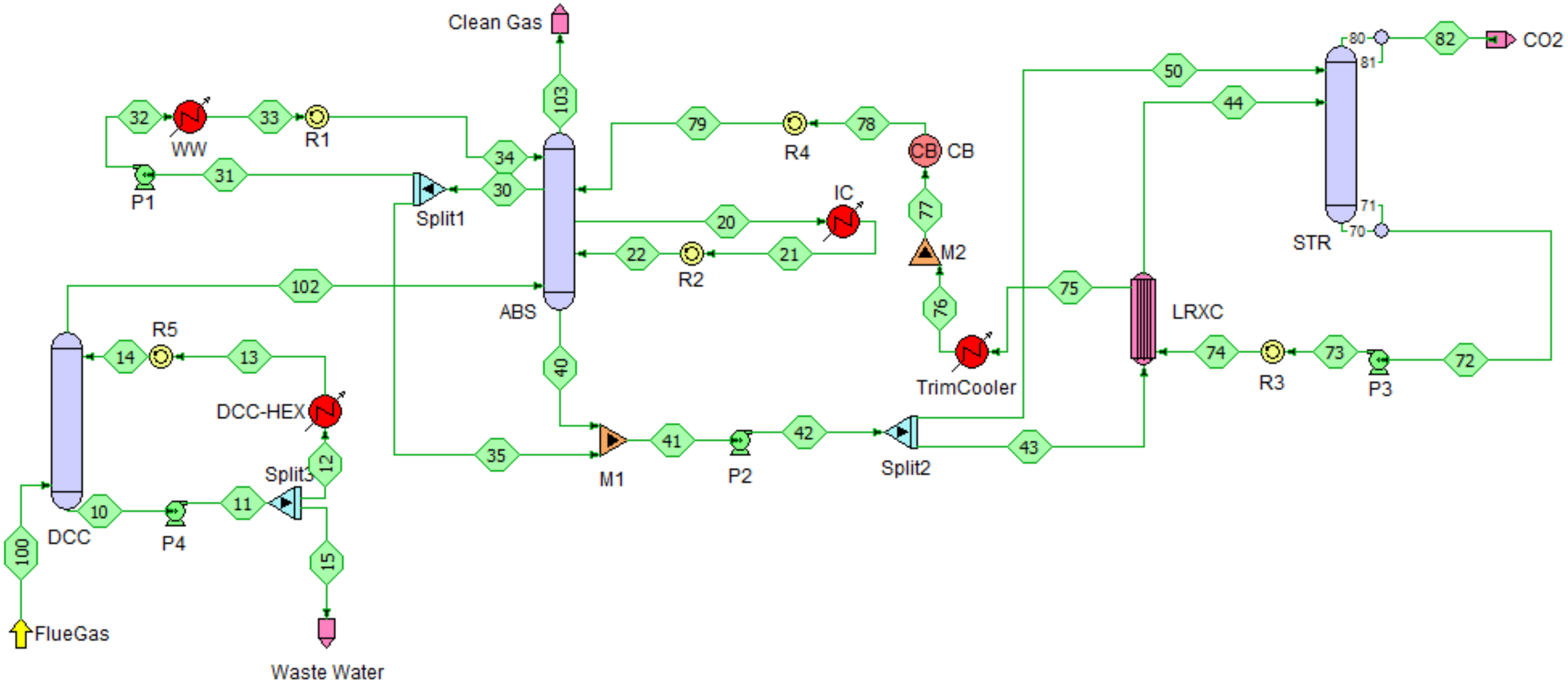


Figure 18 – ProTreat® model of the design case using ION's advanced solvent for 90% carbon capture at a specific reboiler duty of 2.5 MJ/kgCO$_2$.

Validation Comparisons

Testing on existing plants, where only minor modifications were used when incorporating ION's advanced solvent, the empirical results will not yield the energy savings that have been shown above in the design process model. The primary obstacle in achieving the low SRDs is that there is not enough knockout capability in the stripper to prevent excess energy (via steam) from leaving the stripper to the condenser. A CRB strategy is needed to keep the energy in the system. Additionally, TCM does not currently have the capability for solvent cooling in the absorber via an inter-stage cooling system. This cooling increases the uptake of the CO_2 in the absorber, and further increases the carrying capacity of the solvent.

ION was able to build models of both NCCC and TCM in ProTreat® and model the capture processes using the same parameters that were tested in the field.[15] The following sections demonstrate how the test results at both NCCC and TCM were compared against the results from the process model, in order to verify the accuracy of the model and build confidence that a custom-built plant would achieve the designed performance of 2.5 MJ/kg CO_2.

NCCC ProTreat® Model Results

Using data provided by NCCC obtained during benchmarking with a traditional MEA solvent, ION simulated the PSTU process prior to start-up in order to develop the test plan and to narrow down the number of parametric test conditions to be tested prior to the steady state performance period. This enabled ION to run a highly effective and efficient parametric test campaign given the short timeslot available for testing at the PSTU.

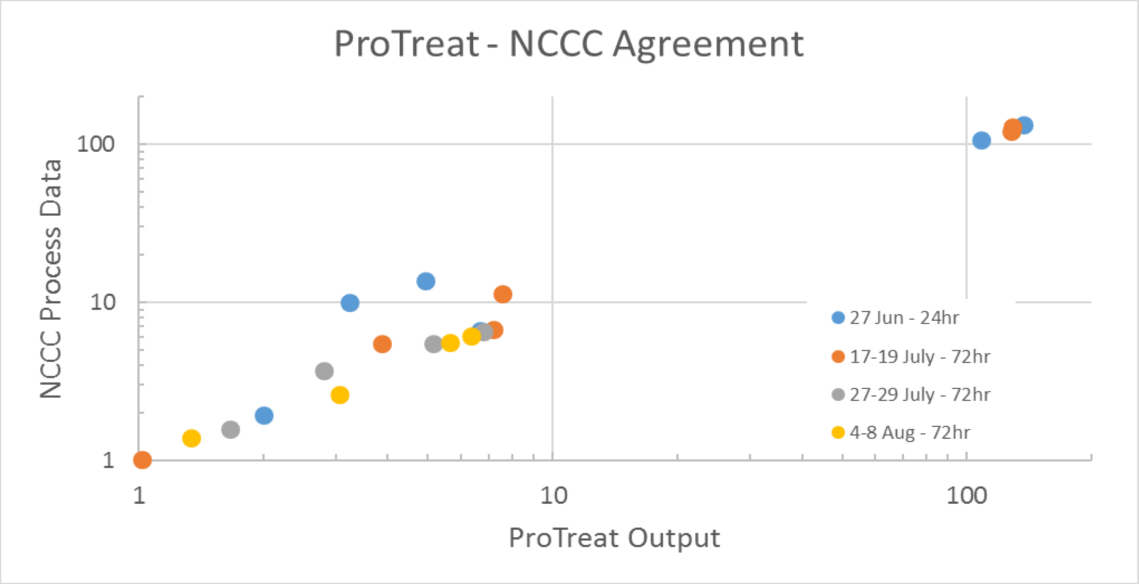


Figure 19 – ProTreat® parity plot showing the comparison of NCCC data against the ProTreat® results. The only two blue dot outliers were from initial parametric testing, when the system likely had not yet achieved steady state operations.

The modeled design case was successfully validated at a variety of process conditions during operation at the PSTU – both parametric and steady state operating conditions. Convergence between the model and actual NCCC data is excellent and shown in Figure 19, where the only two blue dot outliers were from initial parametric testing, when the system likely had not yet achieved steady state operations.

TCM ProTreat® Model Results

During the TCM campaign, ION tested over 150 operating configurations with 76 of those configurations being on RFCC flue gas. Figure 20 shows scatter plots that indicate the diversity of operating conditions that were covered in the RFCC test campaign. These data provided a wide range of operations for use validating the process model. Of these operating conditions, 51 were loaded into ProTreat® to generate model results for comparison. In Figure 20 are highlighted markers (orange) indicating the operating conditions of the 11 experiments that were used to generate a parity plot. These 11 experiments cover a wide range of testing conditions and Figure 21 shows the resulting parity plot, where the results of the model are compared to the empirical data. The ProTreat® process model successfully predicts the key parameters such as densities, capture rate, SRD, working capacity and stripper sump temperature.

From these results, the data has demonstrated how well the actual and modeled results converge over this wide range of operating conditions. ION is very comfortable with the process model and intends to further refine the model in the next phase of the technology development.

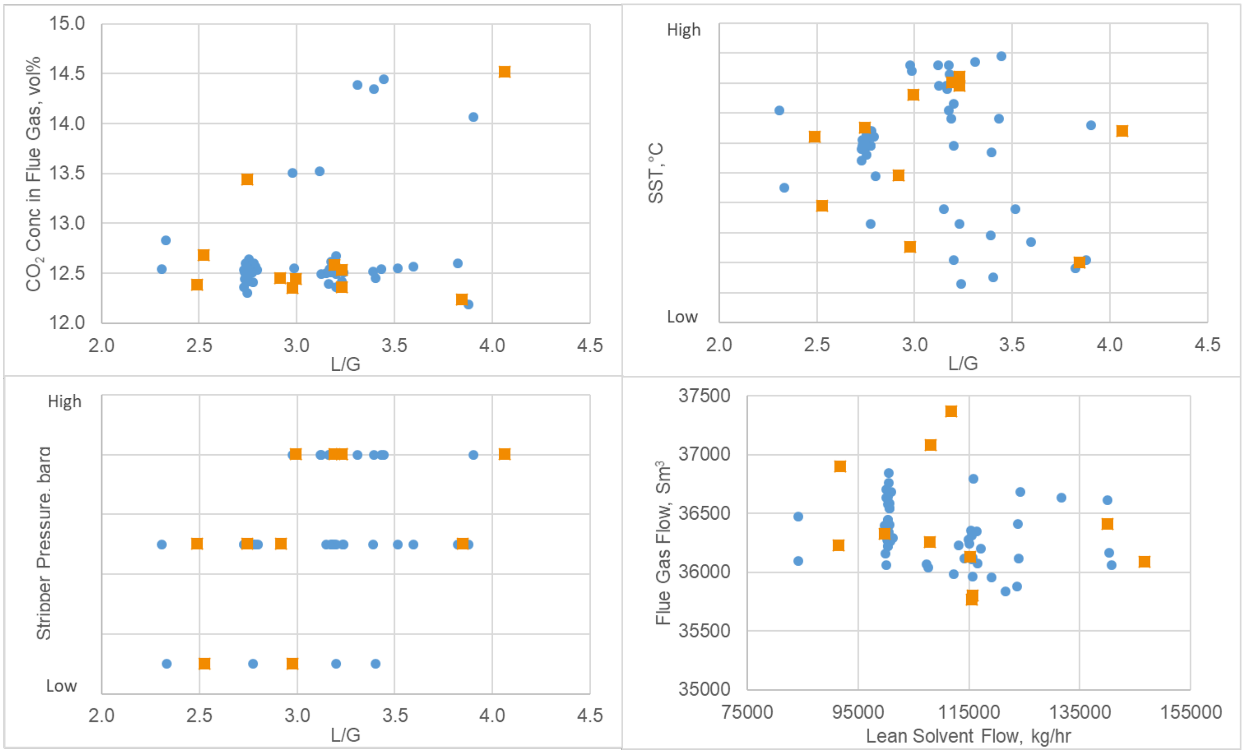


Figure 20 - Scatter plots showing the range of variables tested on RFCC flue gas. The orange markers represent the 11 experiments that are used to generate the parity plot. These 11 experiments were chosen to cover a wide range of operating conditions and demonstrate how well the model predicts experimental behavior over a full suite of testing.

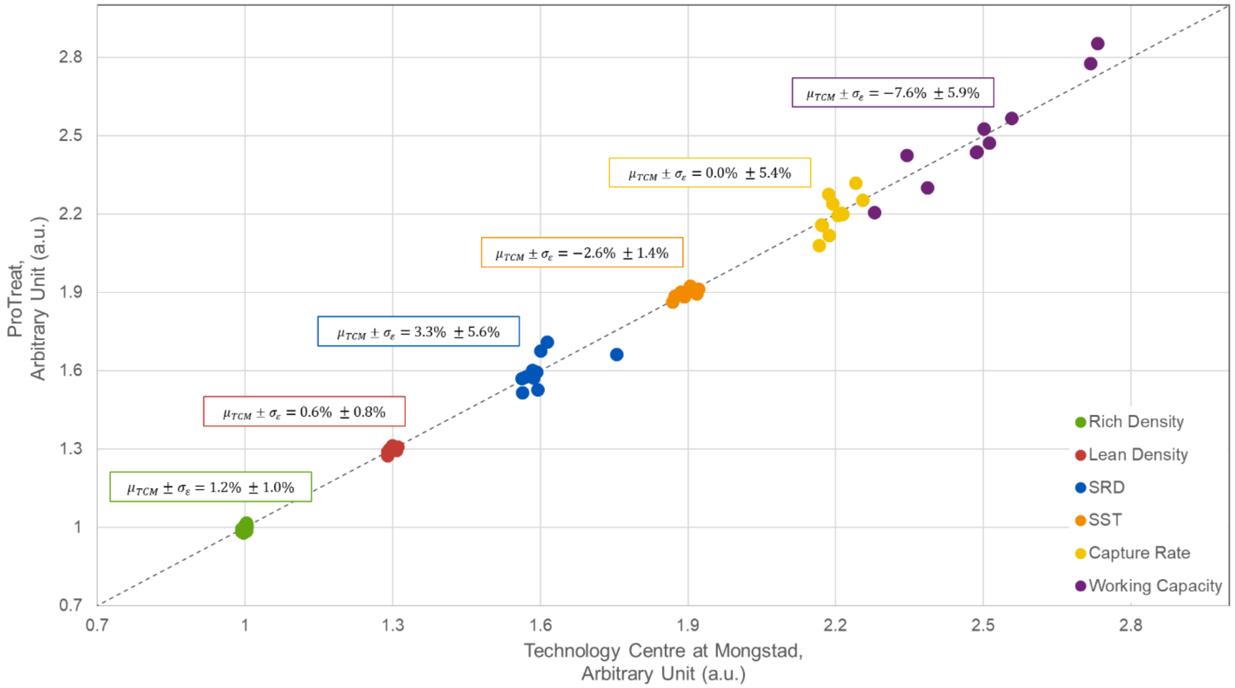


Figure 21 – Parity plot showing the agreement between the TCM process data and the results from the ProTreat® Model. The values listed are the average relative error and standard deviation between the modeled data and the experimental data.

Techno-Economic Analysis

ION contracted Trimeric Corporation to conduct the preliminary TEA as part of the requirements for the awarded slipstream project. At the conclusion of the NCCC testing, ION contracted Sargent & Lundy (S&L) to conduct the final TEA (2016-TEA). In 2017, after the completion of the TCM testing campaign, S&L revisited the final TEA and confirmed the 2016-TEA results while also including several sensitivity studies to show the magnitude of cost changes when certain system parameters are changed (2017-TEA).

Preliminary TEA Summary

The Preliminary TEA is an economic analysis of the anticipated performance of ION's advanced solvent at a 550MWe scale in accordance with DOE guidelines. The economic analysis was based on a ProTreat® simulation of ION's advanced solvent; costing and subsequent economic performance are based on vendor quotes, previous experience and structured to match QGESS economic guidelines. ION worked extensively with OGT to develop a fundamental rate-based model that can be used to predict solvent performance at varying scales and operating conditions.

The estimated coal rate required to produce 550 MWe-net with ION's advanced solvent process is 11% lower than reported for the Econamine™ process (Case 12 from the 2012 Bituminous Baseline Study, or BBS). [DOE 2012]

The final process simulation for this project illustrated significant benefits to ION's advanced solvent technology in comparison to aqueous MEA. For ION's advanced solvent, L/G ratio was 2.1 kg/kg for a reboiler duty of 2.6 MJ/kg CO_2. Total plant costs for the capture and compression system were estimated by applying a Lang factor to the purchased equipment costs. The total plant costs for ION's capture system were estimated at $325MM ($229MM for capture and $95MM for compression). This value includes compression and dehydration. These total estimated plant costs are approximately 45% lower than the reported Econamine™ total plant costs, which were documented at $593MM ($506MM for capture and $87MM for compression). However, it is important to note that the DOE 2012 cost estimates were developed with some differences in methodology and as a result may not be directly comparable in every regard.

An overall economic analysis suggests that application of ION's advanced solvent may result in a 28% decrease in the total increase in COE with TS&M relative to Case 12 with Econamine™; in terms of $ per metric ton (MT) of CO_2 captured, application of ION's advanced solvent may decrease costs by 27% relative to Case 12 ($48/tonne of CO_2 captured for the ION capture process versus $66/tonne of CO_2 captured for Case 12; these values include TS&M).

Technical Approach for the 2017-TEA

Key Project Goals

The DOE/NETL BBS Case 12 performance and costs will be used as the basis for comparison to ION's proprietary solvent technology for CO_2 capture. Similar to the BBS case study, the CO_2 capture system is designed to achieve 90% capture with a product purity of ≥ 95% and suitable for transportation via pipeline for storage. The compression system is designed for a delivery pressure of 2,215 psia (15.3 MPa) for the CO_2 product stream.

In addition, the facility is designed to achieve a net power generation of 550 MW. The overall facility will be designed to provide auxiliary power to the base plant as well as additional process steam and auxiliary power required for the CO_2 capture system. The base plant will be designed with air quality control systems (AQCS) to achieve pollutant emissions identified in either the BBS case or current applicable environmental regulations; whichever is more stringent.

The overall COE associated with a new supercritical coal-fired boiler equipped and the CO_2 capture cost will be evaluated. The goal is to demonstrate that ION's proprietary solvent technology can achieve an incremental COE associated with CO_2 capture equal to or less than the cost estimated in the DOE/NETL reference cases; reported in a 2011 dollar basis as $56/MWh and $56/tonne (excluding TS&M costs), respectively.

Scope and Approach for 2017-TEA

The scope of the 2017-TEA is to incorporate the results of the TCM testing into the previously completed TEA. As noted by ION, minimal changes are expected to the base design of ION's CO_2 capture island based on the results from the TCM testing.

Several potential cost savings alternatives were identified as part of the testing. The results of this economic analysis will help ION to identify potential alternatives to optimizing the CO_2 capture island for future applications and demonstrations.

Process Description

Base Plant

The base plant consists of a supercritical pulverized coal-fired boiler. Supercritical boilers are more efficient and allow for lower fuel consumption and therefore result in lower emissions when compared to subcritical boilers.

The design is based on burning a typical Illinois # 6 bituminous fuel, as defined in the DOE/NETL Report BBS Case 12. The steam generated in the boiler is passed through high, intermediate, and low pressure turbine sections to produce sufficient power to operate the plant and maintain a net generation of 550 MW. The flue gas produced during the combustion process will be directed through a series of equipment, according to the following simplified flow diagram (Figure 22), to control emissions upstream of the CO_2 capture island. As discussed previously, some additional AQCS control systems would be required in order to meet the current regulatory requirements for a new coal-fired boiler installed in the United States today (e.g. dry sorbent injection, activated carbon injection, and waste fixation) as compared to the requirements in 2011 at the time of the DOE/NETL Report. However, these systems are not included to maintain consistency with the DOE/NETL Report methodology.

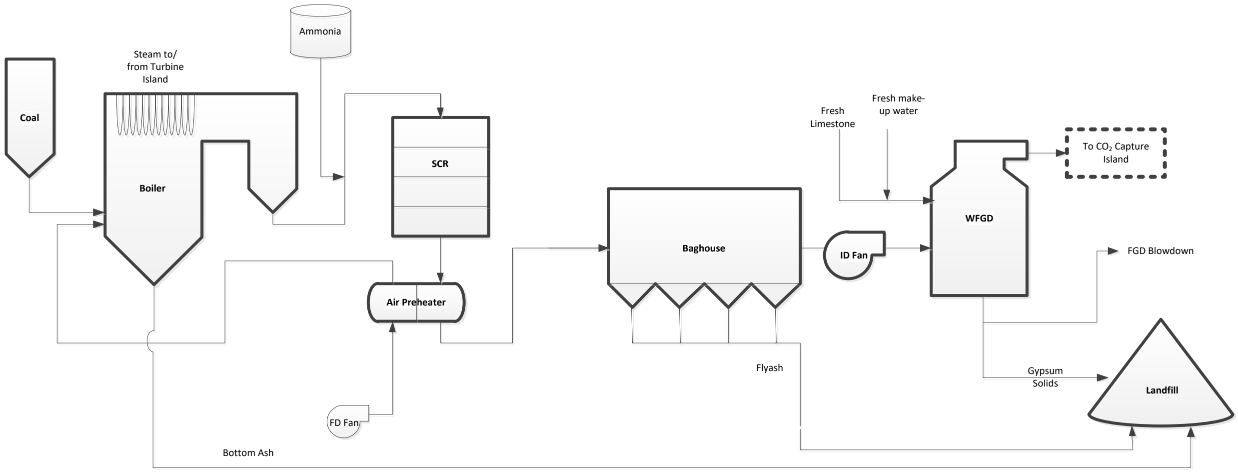


Figure 22: Base Plant Configuration

A selective catalytic reduction (SCR) system reduces NO_X, including NO and NO_2, by the addition of 19% aqueous ammonia in the presence of catalyst. NO_X emissions are regulated on a regional basis, and for new units are typically controlled using SCR technology which is considered to be Best Available Control Technology (BACT) for NO_X emissions.

Due to the generation of SO_3 in the boiler and in the SCR, dry sorbent injection (DSI) in the form of hydrated lime would be required in a 2016 regulatory environment in order to comply with the MATS Rule. With a DSI system, lime is injected into the flue gas upstream of the air preheater where it reacts primarily with SO_3. Due to firing a high sulfur fuel, it would be beneficial to add DSI to help reduce SO_3 emissions upstream of the FGD and CO_2 capture island; this would improve the operation of the CO_2 capture island. Installation of DSI can also help to maximize the overall efficiency of the boiler by reducing the cold end temperatures in the air preheater. However, DSI was not included in the DOE/NETL reference cases; therefore, in order to represent a direct comparison to the DOE/NETL reference cases a DSI system was not included.

The flue gas then passes through a Ljungstrom® style regenerative air preheater where the hot flue gas is used to preheat ambient air used in the boiler for combustion, improving the overall efficiency of the boiler. The regenerative air preheater was selected as it minimizes air infiltration into the flue gas path, reducing the pressure drop and size for the equipment downstream. To improve the efficiency of the boiler, the combustion air temperature can be increased by targeting a lower temperature of the flue gas at the outlet of the air preheater.

In a 2016 regulatory environment, the Mercury and Air Toxics Standards (MATS) Rule specifies ultra-low levels of mercury emissions for new coal-fired EGUs. In order to comply with the MATS Rule, powdered activated carbon (PAC) would be injected into the flue gas downstream of the air preheater to adsorb mercury using an activated carbon injection (ACI) system. A line item for an ACI system for mercury control was included in both the capital and O&M costs for the DOE/NETL reference cases but no costs were included for this system. For a direct comparison to the DOE/NETL reference cases the capital and O&M costs associated with an ACI system were not included.

Downstream of the air preheater, flue gas is directed to a pulse jet fabric filter (PJFF) type baghouse, which collects the particulate matter present in the flue gas. High efficiency particulate collection would be required as part of the MATS Rule in a 2016 regulatory environment but was also not included in the TEA capital cost in order to be consistent with the DOE/NETL reference cases.

Flue gas then passes through an induced draft (ID) fan, where the pressure is increased from the negative pressure at the outlet of the baghouse to a positive pressure required to pass the flue gas through the downstream wet flue gas desulfurization (WFGD) system.

In the WFGD, limestone and water, and are introduced to the flue gas to remove SO_2. WFGD technology is often determined to be BACT for SO_2 emissions, especially with a high-sulfur fuel similar to the Illinois # 6 used as the basis of this design. Calcium sulfite, or gypsum, is generated in the WFGD process and removed from the system with water. A small portion of the water must be removed from the process to control the chloride concentration in the WFGD.

Process water streams are highly regulated by the ELGs and must be treated to very stringent standards if discharged or alternatively these streams could be evaporated. More stringent ELG requirements were published in 2015; in order to satisfy these more stringent requirements the FGD blowdown (wastewater) and the FGD byproduct (gypsum solids) would be combined with the particulate collected in the baghouse to fixate the FGD wastewater and produce a suitable by-product for disposal. Addition of pebble lime would also be added for proper fixation. Waste fixation was not included in the previous DOE/NETL costs, rather FGD byproduct was assumed to be sold for beneficial reuse at zero profit and the blowdown stream was assumed to be treated with standard physical and chemical wastewater treatment. For a direct comparison to the DOE/NETL reference cases the cost of the plant was estimated using these assumptions and did not include a waste fixation system.

CO_2 Capture Island

The CO_2 capture system is designed to achieve 90% capture with a product purity of ≥ 95%. Figure 23 below shows the overall configuration of the CO_2 capture island equipment.

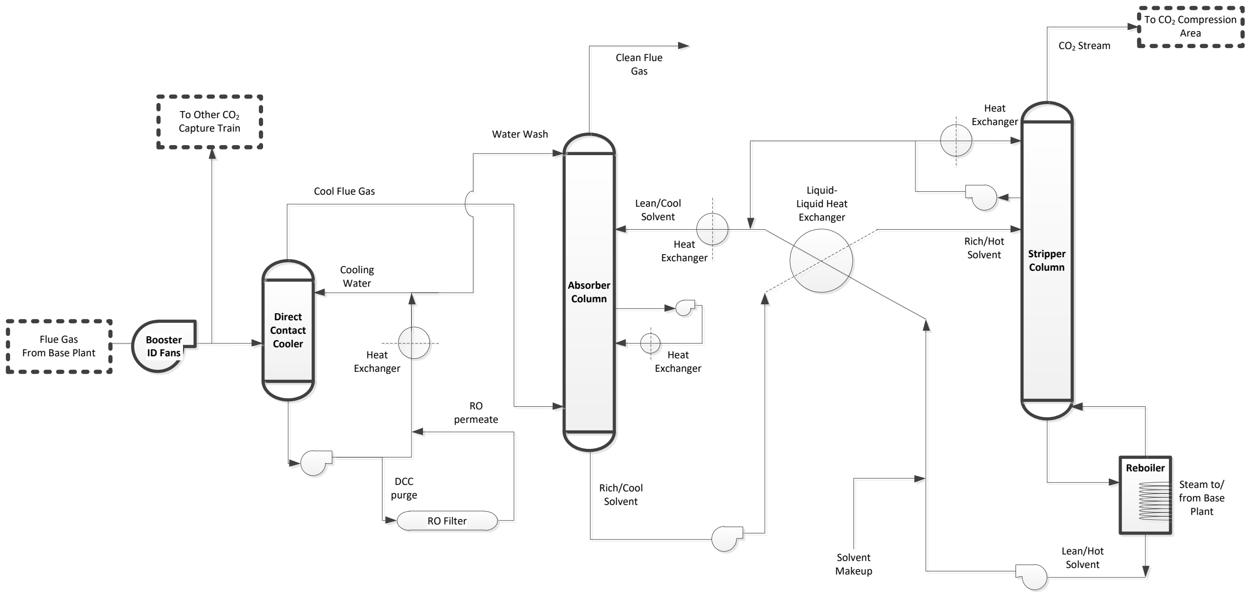


Figure 23: CO_2 Island Configuration

In the Direct Contact Cooler (DCC), the flue gas passes through a counter-current packed tower, where contact cooling water is recirculated to cool the flue gas from approximately 57°C (135°F) to 35°C (95°F). The contact cooling water is recirculated through a plate and frame heat exchanger using plant cooling water as a cooling source. Residual particulates, sulfates, and other soluble components will build-up in the cooling water over-time; to minimize the contaminants in the contact cooling water and avoid plugging concerns in the DCC, a side stream is removed and treated in a reverse osmosis (RO) filter and then returned to the process. The overall purpose of this unit operation is to cool the flue gas and reduce any residual SO_2 present to trace amounts.

The cool flue gas then passes through a counter-current packed Absorber Column, where the ION proprietary solvent absorbs CO_2 present in the flue gas. Several levels of packing, spray towers, and trays facilitate the appropriate liquid-to-gas contact to ensure a high level of CO_2 absorption; approximately 90% of the CO_2 in the flue gas is absorbed into the lean solvent. The temperature of the solvent in the absorber is controlled through an intercooler. The intercooler is a plate and frame heat exchanger which cools the semi-rich solvent using plant cooling water. A water wash, supplied by the DCC cooling system, is staged at the top of the absorber vessel to moderate slip of solvent vapor due to entrainment in the flue gas. Finally, the flue gas exits through a mist eliminator located in the top of the Absorber and is exhausted through a lined chimney.

Prior to regeneration, rich-cool solvent leaving the base of the Absorber Column passes through a series of plate and frame heat exchangers which transfer heat from the hot-lean (regenerated) solvent to the rich-cool solvent.

Rich-solvent preheated by the lean/rich exchanger enters the top of a counter-current packed Stripping Column, where CO_2 is removed from the reagent through the addition of heat energy to break the weak intermediate bond between the solvent and the dissolved CO_2. The reboiler at the base of the Stripping Column generates steam by boiling a fraction of the water present in the solvent; the steam provides energy that heats the counter-flowing solvent liquid and dilutes the vapor phase CO_2 concentration. The reboiler continues to add heat at the bottom of the Stripping Column to drive the stripping process to completion.

Lean solvent from the bottom of the Stripping Column is pumped back to the solvent circuit. The hot lean solvent is directed to the lean/rich exchanger to use the recovery of sensible heat to preheat the rich solvent as described above. This preheating method helps to recover some of the energy used to strip the CO_2, reducing the overall energy requirements of the stripping process. A mixture of CO_2 and steam, generated in the reboiler from boiling a fraction of the water present in the solvent, exits the top of the Stripping Column and is sent to the CO_2 compression system.

The compression system is designed to for a delivery pressure of 2,215 psia (15.3 MPa) for the CO_2 product stream and involves eight stages of compression including an intercooler after each stage. Moisture removed from the dehydration system and during the compression process is discharged back to the plant using local drains.

Integration with Base Plant

As part of the integration of the CO_2 capture island into the base coal-fired plant, the flue gas from the outlet of the FGD is sent to a booster ID fan, which increases the pressure of the flue gas in order to overcome the pressure loss through the direct contact cooler, absorber, and chimney. In addition, steam for regeneration of the solvent is extracted from the crossover between the IP and LP sections of the turbine and sent to the reboiler at the base of the Stripper Column; the associated condensate is returned to the main condenser. Finally, cooling water is circulated to/from the plant cooling tower to the various users within the CO_2 capture island.

Design Basis

Table 10 summarizes the major inputs and assumptions used as the basis for the design of the new green-field supercritical coal-fired power plant and CO_2 capture system. These inputs were based on information provided in DOE/NETL Report BBS Case 12 and assumptions based on typical industry standards and engineering judgment.

Table 10: Summary of Design Inputs and Assumptions

Variable	Units	BBS Case 12	ION 2017-TEA	Source[1]
Steam Cycle	--	Super Critical	Super Critical	BBS Case 12
Fuel	--	Illinois No. 6 Bituminous	Illinois No. 6 Bituminous	BBS Case 12
Boiler Size	MW_{net}	550	550	BBS Case 12
	MW_{gross}	802	730	S&L Design
Heat Input	MMBtu/hr	6,601	5,917	S&L Design
Excess Air	%	Not Identified	7.7[2]	Calculated
Fly/Bottom Ash Ratio	%	80/20	80/20	BBS Case 12
Economizer Outlet Temperature	°F	Not Identified	750	Engineering Judgment
SCR Inlet NO_X	lb/MMBtu	0.5	0.5	BBS Case 12
SCR Efficiency	%	85	90	S&L Design
Ammonia Slip	ppmv	2	2	BBS Case 12
APH In-Leakage	wt%	Not Identified	5.8[3]	Calculated
APH Outlet Temperature	°F	337	308	Calculated
Baghouse PM Collection	%	99.8	99.9	S&L Design
WFGD SO_2 Removal	%	98	99.5	Calculated
WFGD Outlet Temperature	°F	135	128	Calculated
Inherent Mercury Capture	%	90	95	Engineering Judgment
CO_2 Capture Efficiency	%	90	90	BBS Case 12
CO_2 Stream Purity	%	99.6	≥ 99	ION Design
CO_2 Product Stream Pressure	psia	2,215	2,215	BBS Case 12

Note 1: Indicates the source of the value used as the basis for the 2017-TEA.

Note 2: While excess air and in-leakage were not expressly identified in BBS Case 12, each was calculated by matching the O_2 percentage at the air preheater inlet.

In addition to the design inputs and assumptions identified above, S&L also evaluated the anticipated permit limits to which a new supercritical coal-fired boiler would be subjected. For each of the major AQCS components these anticipated permit limits were used to identify the performance requirements for the design of the equipment to allow operating margin below the permit values. Table 11 summarizes the design values and anticipated emission limits for each regulated pollutant based on the DOE/NETL Report.

Table 11: Summary of Air Emissions Design Basis

Pollutant	Units	Design Guarantee	Design Emission Limit	Basis for Emission Limit
Filterable PM	lb/MMBtu	0.0075	0.013	BBS Case 11/12
SO_2	lb/MMBtu	0.026	0.086	BBS Case 11/12
NO_X	lb/MMBtu	0.05	0.07	BBS Case 11/12
Mercury	lb/GWh lb/TBtu	N/A	0.0114 1.14	BBS Case 11/12

For many of the pollutants, the anticipated emission limits and design values based on 2016 regulations would vary from those identified in the DOE/NETL Report BBS Case 12. However, to maintain consistency with the DOE/NETL Report, the design values above were used in this evaluation.

Deviation from BBS Case 12

Boiler Island

A steam-cycle heat balance was developed to evaluate the size of the boiler required to produce a net power output of 550 MW while generating sufficient power and process steam for the plant auxiliaries and CO_2 capture island.

Plants require power to run the auxiliary and balance of plant equipment; based on S&L's experience this corresponds to approximately 11% of the gross generation. The DOE/NETL report assumed an auxiliary consumption for the base plant of approximately 5% which is not consistent with S&L experience, especially considering this plant will have motor driven feedwater pumps rather than turbine driven, a mechanical draft cooling tower, and substantial AQCS auxiliary power requirements. However, to maintain consistency with the base plant sizing outline in the DOE/NETL Report, S&L utilized the same base plant auxiliary power consumption percentage as the basis of the DOE/NETL report.

In addition, the process requires a large quantity of process steam. Based on the process requirements defined by ION and based on S&L's expertise, the steam was removed from the crossover between the IP and LP sections of the turbine. This reduces the steam flow to the LP turbine section, reducing the overall size of the turbine and providing a small cost savings in comparison to a full-size 730 MW steam turbine. Finally, the CO_2 capture and compression island uses approximately 50MW of additional auxiliary power, based on the information provided by ION in the preliminary TEA.

Pollution Control Equipment

In a 2016 regulatory environment, additional flue gas treatment would be required beyond that previously included for the DOE/NETL Report BBS Case 12. For units burning high sulfur coal and equipped with SCR, SO_3 emissions are anticipated to be very high. WFGD systems are not as efficient at removing SO_3 and are typically limited to ≤ 50% reduction; SO_3 would need to be removed upstream of the WFGD using a DSI system. This system was not accounted for in the costs for BBS Case 12; however, a DSI system would be necessary for any amine-based CO_2 capture system, especially for plants burning Illinois #6 bituminous coal. If large concentrations of SO_3 were to slip past the WFGD and enter the CO_2 capture island it would impact the chemistry of the recirculating DCC water, including the design of the associated RO filter, as well as potentially reacting with the solvent in the Absorber Column to form aerosols as is common in any amine-based technology. A DSI system could mitigate this issue for any amine-based CO_2 capture system. However, to maintain consistency with the DOE/NETL Report, a DSI system is not included in the TEA.

The MATS Rule also provided very strict limits on mercury for new EGUs. The DOE/NETL Report BBS Case 12 relies on the high inherent capture typical of a unit burning high chloride bituminous fuels with high unburned carbon and equipped with a baghouse and WFGD. However, the ultra-low mercury limits established for new EGUs in the MATS Rule would strongly favor an ACI system to help provide the necessary capture, which would be greater than 97% for the design coal. To maintain consistency with DOE/NETL Report, additional mercury control is not included as part of the TEA.

The basis of this report is a NO_X permit limit of 0.07 lb/MMBtu with an inlet concentration of 0.5 lb/MMBtu, which is typical of an average permit limit, and consistent with the DOE/NETL Report BBS Case 12; however, SCR technology has historically been designed to achieve 90% reductions in NO_X emissions. Thus, for the purposes of providing additional operating margin, the basis of the equipment design is 90% reduction with an outlet emission rate of 0.05 lb/MMBtu.

The baghouse will be designed to consistently achieve an outlet filterable particulate matter emission rate of 0.01 lb/MMBtu, which is typical for a state-of-the art design; lower particulate emissions will ensure less particulate buildup in the DCC recycle stream and reduce the overall size of the RO filter. The WFGD and direct contact cooler will reduce particulate emissions further.

The amine-based CO_2 capture process requires low SO_2 concentrations in the flue gas entering the CO_2 absorber of approximately 10 ppm. State-of-the-art WFGD systems have recently been guaranteed as low as 0.04 lb/MMBtu, and improved contact with additional spray levels have been assumed to provide better SO_2 reduction, achieving an outlet SO_2 concentration of 10 ppm. This minimizes the solvent makeup rate in the CO_2 capture island.

As previously discussed, EPA's ELG Rule establishes limits on pollutants in waste water streams discharged from a plant. For new plants, the rule mandates zero pollutant discharge from waters used to transport ash and flue gas mercury control (FGMC) wastewater. One way to avoid additional water treatment at the facility would be to use dry bottom ash and fly ash handling. Dry systems as such also are more efficient due to less auxiliary power consumption; therefore, dry ash handling was used in this evaluation. In a 2016 regulatory environment, the liquid blowdown from the WFGD would need to be fixated and disposed of in a landfill to avoid additional wastewater treatment. However, to maintain consistency with the DOE/NETL Report, it is assumed the blowdown is treated with standard physical-chemical wastewater treatment on-site.

All other wastewater streams except cooling tower blowdown are treated by a wastewater treatment facility on-site (physical-chemical treatment). The only source of water effluent from the plant will be cooling tower blowdown; which should satisfy any water emission requirements.

CO_2 Island

The basis of the DOE/NETL Report BBS Case 12 is Fluor's Econamine FG+™ process, which uses a standard absorber/stripper combination, and MEA as the solvent. The ION proprietary solvent technology has been used as the basis of the CO_2 Capture Island, and the equipment sizing and design are based on the results of a computer simulation model and data from the NCCC's PSTU and TCM's Amine Plant testing campaigns. The main differences in designs in comparison with the Econamine FG+™ using MEA design are:

- Milder materials of construction
- Lower regeneration energy requirements
- Process Improvements to further lower energy requirements

The major design improvements in the CO_2 Capture Island that ION has claimed are less expensive materials of construction. Based on the pilot scale testing, ION determined that milder grades of stainless steel can be used for the main process equipment without the need of a corrosion inhibitor, as in the Econamine FG+™ process. For the purposes of this report, it was assumed that any equipment that contacts the solvent can be constructed of 304 stainless steel materials of construction; including the Absorber Columns, Stripper Columns, heat exchangers, reboilers, pumps, and piping. This results in a lower capital investment for these components.

ION indicated that a lower regeneration energy is required to strip the CO_2 from ION's proprietary solvent as compared to the DOE/NETL BBS Case 12. The steam conditions (temperature and pressure) are the same as the BBS Case 12, however, the rate of steam required for the proprietary ION solvent is less per pound of CO_2 regenerated. This limits the lost generation due to process steam from the base plant steam cycle.

Economic Evaluation

Economic Parameters

Capital and O&M costs were developed by S&L in 2016 dollars, the detailed capital and O&M costs. The basis for this evaluation is a new green-field coal-fired power plant located generically in the United States; assumptions were made to establish the basis for some costs, such as foundation design.

All costs comparisons and evaluations will be in a June 2011 dollar basis, which corresponds to the revised cost evaluation developed by DOE/NETL in August 2012. The capital and O&M costs were adjusted from a 2016 dollar basis to a June 2011 dollar basis using a compilation of the CERA IHS North American Power Capital Costs Index ("CERA PCCI Index") values. Data is available for the CERA PCCI Index from 2000 through the first quarter (Q1) of 2015. An average semi-annual escalation rate of 0.55% was calculated between Q1 of 2011 and Q1 of 2015. For the purposes of this report, this average semi-annual escalation rate will be used to adjust costs for comparison in this report.

Capital Costs

Base plant and CO_2 capture island equipment costs were estimated based on S&L proprietary costs, budgetary pricing, allowances, or information provided by ION. Installation costs were estimated in house. Labor costs were estimated for each individual subcontracted process or component rather than a blanket percentage over the whole project, and include the associated labor indirect costs which apply to this type of work such as overtime, per diem, contractor's G&A and profit.

Indirect project costs, such as engineering, construction management, startup and commissioning support, construction materials and initial fills for testing were also included in the estimate.

In accordance with the estimates developed for the DOE/NETL Report, BBS Case 11 and 12 additional costs were added to the total direct and indirect cost of the project in order to generate the Total Overnight Cost. These items include the following and were applied at similar percentages to those costs estimated by DOE/NETL:

- Project Contingency – 15% of Total Direct Installed Cost (including Engineering)
- Owner's Costs including Land and Financing – 17% of Total Direct and Indirect Cost
- Inventory Capital (Fuel and Consumables) – 2% of Total Direct and Indirect Cost
- Inventory Capital – Operating Spare Parts – 0.5% of Total Direct and Indirect Cost

The overall cost for the 550 MW_{net} power plant for the base plant and auxiliaries, equipped with CO_2 capture and compression, is estimated in 2016 dollars to be $2,502,671,000 or $4,550/kWnet based on installing a plant consistent with the DOE/NETL Report basis.

Comparison to DOE/NETL Capital Costs

The DOE/NETL Report costs which will be used to evaluate the cost-effectiveness of the ION's CO_2 Capture Island were developed on a June 2011 dollar basis. In order to compare the cost effectiveness of this technology, the capital cost developed for the TEA (estimated in 2016 dollars) must be converted to a common dollar basis with the DOE/NETL Report.

The capital cost developed for the TEA was adjusted from 2016 to June 2011 using the CERA PCCI Index.

A comparison of the TEA to the DOE/NETL BBS Case 12 on a total capital cost basis does not adequately reflect the lower cost of CO_2 capture associated with ION's proprietary solvent technology. A comparison of the capital cost of only the CO_2 capture island (including process contingency), estimated in the TEA to be approximately $322 million dollars (presented in June

2011 dollars), to the estimated capital cost of the CO_2 capture system in the DOE/NETL BBS Case 12, estimated to be approximately $458 million dollars, shows the ION proprietary solvent technology to be much lower in capital cost.

The TEA does not include a separate capital cost estimate for a 550 MW_{net} base plant without CO_2 capture as defined by the DOE/NETL in BBS Case 11 and used to evaluate the incremental cost of electricity associated with CO_2 capture. However, comparison of the TEA capital cost to the DOE/NETL BBS Case 11 would artificially inflate the differential cost of the CO_2 capture system with respect to COE for the ION system due to the discrepancy in estimating methodologies as compared to the DOE/NETL BBS Cases. The incremental cost of the CO_2 capture system based on the proprietary ION solvent should be evaluated with respect to the overall capital cost of a smaller plant, similar to the comparison between the DOE/NETL BBS Cases 11 and 12, but based on the same cost estimating basis as the TEA.

Therefore, in order to provide a representative incremental cost of CO_2 capture, the TEA costs were compared to a capital cost for a smaller plant, estimated by scaling the base plant costs using a ratio of 580 MWg for the base plant without CO_2 capture to the 730 MWg base plant with CO_2 capture, and assuming a 0.6 scaling factor in most cases which is typical for power plant scaling. The results is a reduction of approximately 10% [$(580\text{ MWg} / 730\text{ MWg})^{0.6}$] to the base plant costs in order to estimate an equivalent DOE/NETL BBS Case 11 capital cost for comparison.

Incremental Capital Cost of CO_2 Capture

To determine the incremental capital cost of applying CO_2 capture, using ION's proprietary solvent technology, to a 550 MW_{net} plant site the capital cost developed for the TEA was compared to the base plant cost without CO_2 capture. The incremental cost accounts not only for the cost of the CO_2 Capture Island and associated balance of plant equipment but also for the increased size of the base operating plant to accommodate the additional auxiliaries (steam and power) required to operate the CO_2 capture island. All of the costs compared below are on a June 2011 dollar basis.

Based on this comparison, the incremental capital cost to install a plant equipped with a CO_2 Capture Island using ION's proprietary solvent technology while maintaining a net power production of 550 MW is approximately $660 million.

The incremental cost of the ION proprietary solvent technology is lower than the incremental capital cost of CO_2 capture as defined in the DOE/NETL Report by a comparison between BBS Cases 11 and 12.

Operating Costs

Operating costs were estimated based on a capacity factor of 85%. Unit costs for consumables were estimated by S&L and ION. Fixed O&M costs for operators, maintenance material and labor, and administrative labor costs were also included based on typical assumptions. S&L included property taxes and insurance as part of the fixed O&M costs in the TEA applied at the same percentage (1.6% of Total Overnight Cost) as applied in the DOE/NETL Report.

The total annual operating cost, including fixed and variable O&M, for a 550 MW_{net} power plant for the base plant and auxiliaries and equipped with CO_2 capture and compression, is estimated in 2016 dollars to be $243,088,000 or $440/kWnet in the 2011 regulatory climate, excluding the CO_2 transportation, storage, and monitoring costs (approximately $40M).

Comparison to DOE/NETL Annual Operating and Maintenance Costs

The DOE/NETL Report costs which will be used to evaluate the cost-effectiveness of the ION's CO_2 Capture Island were developed on a June 2011 dollar basis. In order to compare the cost effectiveness of this technology, the annual O&M cost developed for the TEA (estimated in 2016 dollars) must be converted to a common dollar basis with the DOE/NETL Report.

Similarly to the capital cost of the TEA, the annual O&M costs were adjusted from 2016 to 2011 using the CERA PCCI Index. Table 12 shows the O&M cost developed based on the 2016 regulatory environment, adjusted O&M costs for the 2011 regulatory environment consistent with the DOE/NETL BBS Case 12; all costs are reported in June 2011 dollars.

Table 12: TEA O&M Cost Comparison Converted to June 2011 Dollar Basis

Description	**ION 2017-TEA (June 2011 dollars)**
Total Fixed Operating Cost	**$80,365,000**
Annual Operating Labor	$11,937,000
Maintenance Labor	$24,407,000
Maintenance Material	*Included above*
Administrative Labor	$5,707,000
Property Taxes and Insurance	$38,314,000
Total Variable Operating Costs	**$20,398,000**
Water Cost	$110,000
Water Treatment Chemicals	$2,241,000
Limestone	$4,661,000
Powdered Activated Carbon (PAC)	Not Included for Consistency
CO_2 Island Costs (solvent and water treatment)	$1,171,000

Description	**ION 2017-TEA (June 2011 dollars)**
19% Aqueous Ammonia	$7,012,000
Hydrated Lime	Not Included for Consistency
Pebble Lime	Not Included for Consistency
SCR Catalyst	$924,000
Fly Ash Disposal	$2,747,000
Bottom Ash Disposal	$682,000
Gypsum Disposal	Not Included for Consistency
Additional Waste Disposal (DSI Byproducts/PAC/Waste Fixation)	Not Included for Consistency
Bag and Cage Replacement	Not Included for Consistency
Total Fuel Cost	**$129,531,000**
TOTAL ANNUAL O&M COST[1]	**$229,444,000**

The TEA does not include the development of a separate estimate of annual O&M cost for a 550 MW_{net} base plant without CO_2 capture as defined by the DOE/NETL in BBS Case 11 and used to evaluate the incremental cost of electricity associated with CO_2 capture. However, to be consistent with the capital cost comparison, in order to evaluate the incremental cost of electricity associated with CO_2 capture the line items of the O&M costs associated with the base plant were scaled to estimate the O&M cost of a smaller plant.

Incremental O&M Cost of CO_2 Capture

In order to determine the incremental cost of applying ION's proprietary solvent technology to a 550 MW_{net} plant site the annual O&M cost developed for the TEA was compared to the base plant annual O&M cost without CO_2 capture (based on a 2011 regulatory environment consistent with the DOE/NETL). The incremental O&M cost accounts not only for the CO_2 Capture Island reagents and auxiliaries but also the increased operating costs associated with an increased base plant as previously discussed. All of the costs compared below are on a June 2011 dollar basis.

Based on this comparison, the additional cost for O&M for a 550 MW_{net} plant equipped with a CO_2 Capture Island using ION's proprietary solvent technology is approximately $63 million; not including the cost for transportation, storage, and monitoring (TS&M) of the CO_2 which results in an additional $37 million.

The incremental O&M cost of the ION proprietary solvent technology is lower than the incremental O&M cost of CO_2 capture as defined in the DOE/NETL Report by a comparison between BBS Cases 11 and 12, summarized in Table 13

Table 13: Incremental O&M Cost of CO_2 Capture Island (Comparison of BBS Case 11 and BBS Case 12)

Description	**BBS Case 11 (June 2011 dollars)**	**BBS Case 12 (June 2011 dollars)**
TOTAL ANNUAL O&M COST	$175,107,995	$262,730,838
	$318/kWnet	$478/kWnet
Incremental O&M Cost of CO_2 Capture per DOE/NETL	BASE	$87,622,843
		$159/kWnet

Lifecycle Costs

The lifecycle costs of a power plant take into consideration the capital cost expenditures as well as the annual O&M costs for the facility. The lifecycle costs of the plant is an input to calculating the cost of electricity (COE), reported on a $/MWh-net basis. For the purposes of this report it was assumed the plant generates 550MW_{net} at an 85% capacity factor. The total overnight cost is annualized using a capital charge factor (CCF). Based on the DOE/NETL Report, for the BBS Case 12, assuming high risk and a 5 year capital expenditure period, the appropriate CCF is 0.1243. For the base plant, with limited risk, the CCF is 0.1165 as identified in the DOE/NETL Report. These same values were used to evaluate the TEA COE.

Table 14 summarizes the total overnight capital cost, annual O&M costs, and COE for a new green-field coal-fired supercritical boiler designed to produce a net power generation of 550 MW with ION's proprietary solvent technology (TEA) and without (Equivalent BBS Case 11).

Table 14: 2017-TEA Lifecycle Costs and Cost of Electricity Analysis

Description	**Equivalent BBS Case 11* (June 2011 dollars)**	**ION Case w/ CO_2 Capture (June 2011 dollars)**
Gross Plant Size (MW)	580	730
Net Plant Size (MW)	550	550
Annual Capacity Factor (%)	85	85

Total Overnight Cost	**$1,712,718,000**	**$2,370,951,000**
Total O&M Cost	**$166,888,000**	**$229,444,000**
Annualized Total Overnight Cost	$49/MWh	$72/MWh
Total O&M Cost	$41/MWh	$56/MWh
Total Cost of Electricity w/o TS&M	**$90/MWh**	**$128/MWh**
Differential	**BASE**	**$38/MWh**
Total Cost of Electricity with TS&M	**$90/MWh**	**$137/MWh**
Differential	**BASE**	**$47/MWh**

***Note: The capital and O&M costs for the Equivalent BBS Case 11 were adjusted as described in Sections 0 and 0, respectively.**

Based on this comparison, the incremental COE of CO_2 capture, based on ION's proprietary solvent technology, for a 550 MW_{net} plant is $38/MWh before transportation, storage, and monitoring of the CO_2 and approximately $47/MWh with TS&M included (based on the DOE/NETL Report basis).

The incremental COE of the ION proprietary solvent technology is lower than the incremental COE of CO_2 capture as defined in the DOE/NETL Report by a comparison between BBS Cases 11 and 12, summarized in Table 15.

Table 15: DOE/NETL BBS Lifecycle Costs and Cost of Electricity Analysis

Description	**DOE/NETL BBS Case 11 (June 2011 dollars)**	**DOE/NETL BBS Case 12 (June 2011 dollars)**
Gross Plant Size (MW)	580	802
Net Plant Size (MW)	550	550
Annual Capacity Factor (%)	85	85
Total Overnight Cost	**$1,348,445,000**	**$2,414,734,000**
Total O&M Cost	**$175,107,995**	**$262,730,838**
Annualized Total Overnight Cost	$38.36/MWh	$73.29/MWh
Total O&M Cost	$42.76/MWh	$64.15/MWh
Total Cost of Electricity w/o TS&M	**$81/MWh**	**$137/MWh**
Differential	**BASE**	**$56/MWh**

Description	**DOE/NETL BBS Case 11 (June 2011 dollars)**	**DOE/NETL BBS Case 12 (June 2011 dollars)**
Total Cost of Electricity with TS&M	**$81/MWh**	**$147/MWh**
Differential	**BASE**	**$66/MWh**

As part of the DOE/NETL Report, the economics were compared on a \$/tonne-CO_2-captured basis as well; this comparison between the DOE/NETL values and those developed for the TEA are included in Table 16; all costs are presented in 2011 dollars. This value is calculated based on the differential cost to incorporate CO_2 capture.

Table 16: Costs of CO_2 Capture Analysis

Description	**DOE/NETL BBS Case 11**	**DOE/NETL BBS Case 12**	**Equivalent BBS Case 11***	**ION w/ CO_2 Capture**
Annualized TOC (\$/year)	\$157,093,843	\$300,151,436	\$199,532,000	\$294,709,000
Differential	\$143,057,593		\$95,177,000	
Total Annual O&M Cost (\$/year)	\$175,107,995	\$262,730,838	\$166,888,000	\$229,444,000
Differential	\$87,622,843		\$62,556,000	
Incremental Cost of Capture (\$/year)	\$230,680,437		\$157,732,000	
CO_2 Captured (tonne/year)	4,086,702		3,669,128	
CO_2 Capture Cost	**\$56/tonne**		**\$43/tonne**	
TS&M (\$/year)	\$40,912,047		\$36,677,000	
Total Cost of Capture with TS&M	**\$66/tonne**		**\$53/tonne**	

The CO_2 Capture Cost in the TEA is approximately \$13/tonne less than the CO_2 Capture Cost as defined in the DOE/NETL Report by a comparison between BBS Cases 11 and 12.

Final TEA (2017) Summary

ION engaged Sargent & Lundy, L.L.C. (S&L) to develop a TEA to evaluate the economics of building a new green-field supercritical coal-fired power plant equipped with a carbon capture system using ION's advanced solvent. The purpose of the TEA was to develop capital costs, operation & maintenance (O&M) costs, and cost of electricity (COE) for installing a new green-field power plant equipped with CO_2 capture following the design methodology established by the DOE/NETL BBS Case 12.

In 2016 and 2017 ION performed additional parametric testing and long-term steady-state testing at the Technology Centre Mongstad (TCM) in Norway. ION engaged S&L to update the TEA with the results from the TCM testing campaign, specifically to evaluate the economics of several sensitivity cases developed as a result of the testing at TCM.

S&L's vast experience in the power industry, specifically related to implementing new power generation projects, was relied upon to develop the preliminary design for the base plant using reference information available from DOE/NETL BBS Case 12 and typical industry information or engineering judgment. S&L proprietary programs were utilized to develop steam-cycle heat balances, process flow diagrams and material balances to determine a design basis for the base plant equipment. Data was provided by ION from the ProTreat® simulation model for the CO_2 capture process, where ION successfully validated their solvent specific ProTreat® simulation models with good convergence throughout numerous parametric and steady state testing conditions during pilot scale testing at the PSTU (0.5 MWe) and TCM (12 MWe). This modeling capability was used by ION to establish target test conditions and operational set points while empirical results were used to evaluate simulation accuracy.

The capital cost, O&M cost, and COE were developed for a new green-field power plant capable of providing a net power output of 550 MW and designed to achieve ≥ 90% capture of the CO_2 with a ≥ 95% CO_2 purity generated by the base plant. The costs developed for the TEA were compared to an Equivalent BBS Case 11, estimated to represent an equivalent $550MW_{net}$ boiler without CO_2 capture technology, in order to evaluate the incremental cost associated with applying ION's advanced solvent technology for CO_2 capture to meet the Department of Energy's goal for second generation solvent technology.

The results of this analysis including the total overnight capital cost, annual O&M cost, and COE and incremental costs associated with the CO_2 capture system are included in Table 17. In comparing ION's technology to the DOE/NETL BBS Case 12, which integrates a highly optimized and commercially available CO_2 capture technology, ION's technology shows:

- 38% incremental reduction in capital cost of CO_2 capture;
- 28% incremental reduction in annual operating and maintenance costs of CO_2 capture; and
- $35-44 per tonne of CO_2 capture, which is a 20% to 40% reduction in cost of CO_2 capture.

The 2017-TEA addressed the following sensitivity cases:

- Solvent Make-up Rate - To understand the effect that the solvent makeup rate has on the O&M costs and subsequently the COE, a sensitivity case was performed. The changes to the COE are determined based on the various make up rates relative to ION's base-case: 10-200%.
- Quantity of CO_2 Capture Trains - A sensitivity was performed to determine the impact on the overall capital cost and COE associated with utilizing a single train instead of two trains. For this sensitivity, it was assumed that the entire flue gas volume would be able to pass through one train of equipment, where the amount of equipment is halved, and

the volume or capacity is doubled. The costs were adjusted using a typical industry standard that the cost of redundant equipment can be scaled at a ratio of two-thirds.

- Relocation of the Booster ID Fan - In this sensitivity, the booster ID fan is relocated from upstream of the CO_2 Island to downstream of the DCC. The flue gas volumetric flowrate downstream of the quencher is approximately 10% smaller than upstream; therefore, relocating the booster ID fan results in a slightly smaller fan and motor. As the booster fan is currently located in a wet and corrosive environment, the materials of construction selected are suitable for these conditions and would be the same for a fan located downstream of the quencher. The design pressure rise of the fan would be the same as the base cost estimate.
- Split Injection to the Stripper - ION has proposed to split the stream of cool/rich solvent, with a portion of the solvent passing through the solvent-to-solvent heat exchanger (per the base design) and the remainder bypassing the heat exchanger and being introduced to the stripper without pre-heating. ION has estimated the following process impacts associated with this sensitivity case:
    - Reduced heat duty on the reboiler
    - Elimination of one of the two-stage heat exchangers for the solvent heat transfer.
    - Reduced flowrate of amine from absorber to stripper column
    - Significant increase in the cooling duty of the stripper recycle heat exchanger
    - Minor increases and decreases in the cooling duty of the other heat exchangers.
- Reduced Process Equipment Sizes - ION has proposed that potential reductions in equipment sizing (vessel diameters) may be achievable with their solvent. In order to evaluate the impact to the capital cost of reduced vessels, two sensitivity cases were evaluated where the DCC, ABS and STR were reduced by various percentages (5-25%)
- Internal Packing Types - The base design includes Sulzer Mellapak Type Packing. For this sensitivity, ION proposed to evaluate using an alternate structured packing for all three absorber columns supplied by Koch-Glitsch.
- Removal of Intercooling in Absorber Vessel - ION has proposed to remove the intercooling in the absorber column, as part of this sensitivity the intercooler pump recycle and heat exchanger are removed. In addition, ION has proposed to consolidate the absorber packing into one segment, requiring only one spray level and liquid distribution/collection devise in the absorber column.

The results of this analysis including the incremental change, for each sensitivity, to the total overnight capital cost, annual O&M cost and COE from the base case are included in Table 11. The majority of these sensitivity cases could be combined to demonstrate additional cost savings in an optimized design. The sensitivity cases have been developed to show the impact of each change to the economics of the CO_2 capture system; if pursued each would need to be fully vetted in conceptual design and demonstration.

ION is currently working with national and international partners to further demonstrate its CO_2 capture technology in real-world applications. ION anticipates that the results from this report, as well as future projects, will directly impact the state-of-the-art of CO_2 solvent technologies and facilitate advancement of CO_2 capture towards commercialization and implementation of ION technology.

Table 17 - 2017-TEA Lifecycle Costs and Cost of Electricity Analysis

Description	**DOE/NETL BBS Case 11**	**DOE/NETL BBS Case 12**	**Equivalent BBS Case 11**[1]	**ION 2017-TEA w/ CO_2 Capture**	**ION vs. Case 12 (% Change from BBS)**
Total Overnight Capital Cost	\$1,348,445,000 \$2,450/kW_{net}	\$2,414,734,000 \$4,390/kW_{net}	\$1,712,718,000 \$3,115/kW_{net}	\$2,370,951,000 \$4,310/kW_{net}	- 2%
Incremental Capital Cost of CO_2 Capture	BASE	\$1,066,289,000 \$1,940/kW_{net}	BASE	\$658,233,000 \$1,195/kW_{net}	- 38%
Total Annual O&M Cost	\$175,107,995 \$318/kW_{net}	\$262,730,838 \$478/kW_{net}	\$166,888,000 \$303/kW_{net}	\$229,444,000 \$417/kW_{net}	- 13%
Incremental Annual O&M Cost of CO_2 Capture	BASE	\$87,622,843 \$159/kW_{net}	BASE	\$62,556,000 \$114/kW_{net}	- 29%
Total COE without Transportation Storage & Monitoring (TS&M)	\$81/MWh	\$137/MWh	\$90/MWh	\$128/MWh	- 7%
Differential COE	BASE	\$56/MWh	BASE	\$38/MWh	- 32%
Total Cost of Capture w/o TS&M (DOE method)[2]	**N/A**	**\$56/tonne**	**N/A**	**\$43/tonne**	**- 23%**
Sensitivity Range of Cost of CO_2 Capture w/o TS&M[3]	**N/A**	**\$56/tonne**[4]	**N/A**	**\$35-44/tonne**[5]	**- 21-38%**

Notes:

1. Equivalent BBS Case 11 was developed to provide a representative basis for comparing the 2017-TEA power plant to an equivalent plant which does not include the carbon capture island and is incrementally smaller in size due to the lack of steam and auxiliary power consumption. This is similar to the methodology used by the DOE/NETL in Case 11. The capital and O&M costs for the Equivalent BBS Case 11 were adjusted as described in Sections 0 and 0, respectively.
2. COE increases by \$10/tonne when Transport, Storage & Monitoring is included. This number, however, depends on many factors, including transport distance, location and quality of storage site, and the cost can differ. To be consistent with the DOE/NETL, \$10/tonne was used.
3. The range provided includes sensitivities based on adjusted solvent make-up rates and constructing the CO_2 island in a single train, instead of two trains.
4. Sensitivity is not taken into account for DOE/NETL BBS Case 12.
5. Lowest cost achieved with smallest makeup rate, single train, split injection to stripper, minor reduction in vessel sizes and removal of intercooling.

Project Milestones

#	BP	Task	Milestone Title / Description	Original Completion Date	Revised Completion Date	Actual Completion Date
M1	1	1.6	Updated PMP	11/30/13	6/30/14	7/25/2014 Rev 1 11/7/2014 Rev 2 11/14/2014 Rev 3 12/8/2014 Rev 4 12/12/2014 Rev 5 3/6/2015 Rev 6 6/24/2015 Rev 7 7/17/2015 Rev 8
M2	1	1.7	Kickoff Meeting	12/31/13	N/A	12/19/2013
M3	1	2.1	Initial Economic Assessment	12/30/13	10/17/14	6/2/2014 Rev 1 12/5/2014 Rev 2
M4	1	2.2	Initial EH&S Assessment	12/31/13	6/13/14	6/13/2014
M5	1	1.2	Initial NEPA Documentation	12/31/13	N/A	10/1/2013
M6	1	3.1	Final Host Site Selection	10/31/13	6/30/14	6/9/2014
M7	1	3.2	Pilot Host Site Permit	9/30/14	N/A	6/9/2014
M8	1	4.7	Final Pilot System Design Pkg	12/31/14	N/A	10/31/2014 ISTU 10/31/2014 PSTU
M9	1	4.8	DOE BP 1 Review Complete	12/31/14	N/A	2/10/2015
M10	2	5.1	PSTU Modifications Complete	5/15/2015	N/A	6/15/2015
M11	2	5.2	ION Proprietary Solvent Delivery	5/29/2015	N/A	4/29/2015
M12	2	6.7	Pre-Startup Safety Review	5/29/2015	N/A	6/1/2015
M13	2	6.8	Pilot System Shakedown Complete	6/12/2015	N/A	6/22/2015
M14	2	7.0	ION Solvent Testing Complete	9/30/2015	N/A	8/10/2015
M15	2	8.3	Final TEA and EH&S Risk Assessment	2/26/2016	2/26/2016 (EHS) 7/31/2016 (TEA)	2/26/2016 (EHS) 9/6/2016 (TEA)
M16	2	8.5	Solvent Stability Assessment	2/26/2016	N/A	2/26/2016 Rev 0 1/31/2017 Rev 1
M17	2	9.0	Decommission & Dismantle	11/27/2015	N/A	8/31/2015
M18	2	10.0	Final DOE Report & Presentation	3/31/2016	N/A	4/1/2016

#	BP	Task	Milestone Title / Description	Original Completion Date	Revised Completion Date	Actual Completion Date
M19	3	11.2	ION Proprietary Solvent Delivery	5/31/2016	9/30/2016	9/26/2016
M20	3	12.8	Pilot System Shakedown Complete	10/31/2016	N/A	10/21/2016
M21	3	13.0	ION Solvent Testing Complete	2/28/2017	4/28/2017	4/28/2017
M23	3	15.0	Updated TEA	5/31/2017	12/29/2017	12/28/2017
M24	3	15.0	Final DOE Report & Presentation	6/30/2017	3/31/2017	TCM Results Presentation to DOE: 9/13/17 Final Report Submitted: 3/31/18

Abbreviation

AP	Amine Plant
CCGT	Combined Cycle Gas Turbine
CCS	Carbon Capture and Storage
CE	Capture Efficiency
CHP	Combined Heat and Power
CH_2O	Formaldehyde
DCC	Direct Contact Cooler
FTIR	Fourier Transform Infrared spectroscopy
GC	Gas Chromatography
GC-FID	Gas Chromatography-Flame Ionization Detection
HEX	Heat Exchange
HP	High Pressure
HSS	Heat-Stable Salts
IBC	Individual Bulk Container
IC	Ion Chromatography
ICP-OES	Inductively coupled plasma-optical emission spectrometry
KF	Karl Fischer water content measurement
L/G	Liquid-Gas Ratio
LC/MS	Liquid Chromatography/Mass Spectrometry
NCCC PSTU	National Carbon Capture Center’s Pilot Solvent Test Unit
RBT	Reboiler Temperature
RCC	Residue Catalytic Cracking
SINTEF	The Foundation for Scientific and Industrial Research at the Norwegian Institute of Technology
SRD	Specific Reboiler Duty
SST	Stripper Sump Temperature
TCM	Technology Centre Mongstad
UWW	Upper Water Wash
VLE	Vapor Liquid Equilibrium
WP	Work Package

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