CANSOLV TECHNOLOGIES INC.

TESTING OF CANSOLV DC-201 CO2 CAPTURE SYSTEM

AT THE NATIONAL CARBON CAPTURE CENTER

SUMMER 2014

Final Report for NCCC Campaign 2014 Piloting,

Campaign at Simulated CCGT Conditions, Hot Climate Conditions

REVISION STATUS			Sign-Offs		
Rev.	**Date**	**Description (Implemented/Issued for Review/Complete)**	**Approved**	**Reviewed**	**Custodian**
R0	April 16th, 2015	Final Report for NCCC Campaign (Simulated CCGT Conditions)	Paul-Emmanuel Just	Melina Infantino	Rouzbeh Jafari
R0NC	March 29th , 2017	Non Confidential Version			Paul-Emmanuel Just

1. BACKGROUND

Cansolv Technologies Inc. (CTI) was formed in 1997 to commercialize the Cansolv SO_2 Scrubbing System. At this time twenty commercial Cansolv Scrubbing Systems are in operation and several more are in the detailed engineering, construction or procurement phase. Driving from its expertise in re-generable amine technologies, Cansolv has developed an ingenious CO_2 Capture process. Numerous Cansolv CO_2 Capture demonstration units are currently being engineered and are well positioned to serve the evolving greenhouse gas abatement market.

On November 30th of 2008, ***Shell Global Solutions International B.V. (SGSI)*** purchased 100% of the shares of CTI. The company now operates as a wholly owned subsidiary of SGSI.

It is CTI's mission to be a leading global provider of high efficiency air pollution control and capture solutions. We want our patented technology to serve as the benchmark for stationary source air emission abatement around the world. Our commitment is to provide custom designed economic solutions to our clients' environmental problems.

Shell-Cansolv is an innovative, technology-centered company. The company continues to leverage its knowledge base to develop new and enhance existing applications for specific pollution abatement based on the Cansolv System platform. Through strategic partnerships and R&D, Cansolv strives to expand its product and service offering in the following areas:

- Multi-emission technology for control of CO_2, SO_x and mercury.
- Valuable material recovery from emission control processes.

The benefits of the Cansolv absorbent include (but not limited to):

- The elimination of the high cost of consumable absorbents and associated transportation costs;
- No environmental legacy obligations and costs;
- Reduced capital costs due to its high capacity and selectivity reduce; and minimal emission of effluents from the process.

Learn more at:
http://www.shell.com/global/products-services/solutions-for-businesses/globalsolutions/shell-cansolv.html

2. TECHNOLOGY SUMMARY

2.1. Simplified Process Flow Diagram

The Cansolv CO_2 Capture System process comprises the following major components: CO_2 absorber including inter-stage cooling and a water-wash section, regeneration tower and Amine Purification Unit (APU).

The diagram below represents the Cansolv CO_2 Capture System:

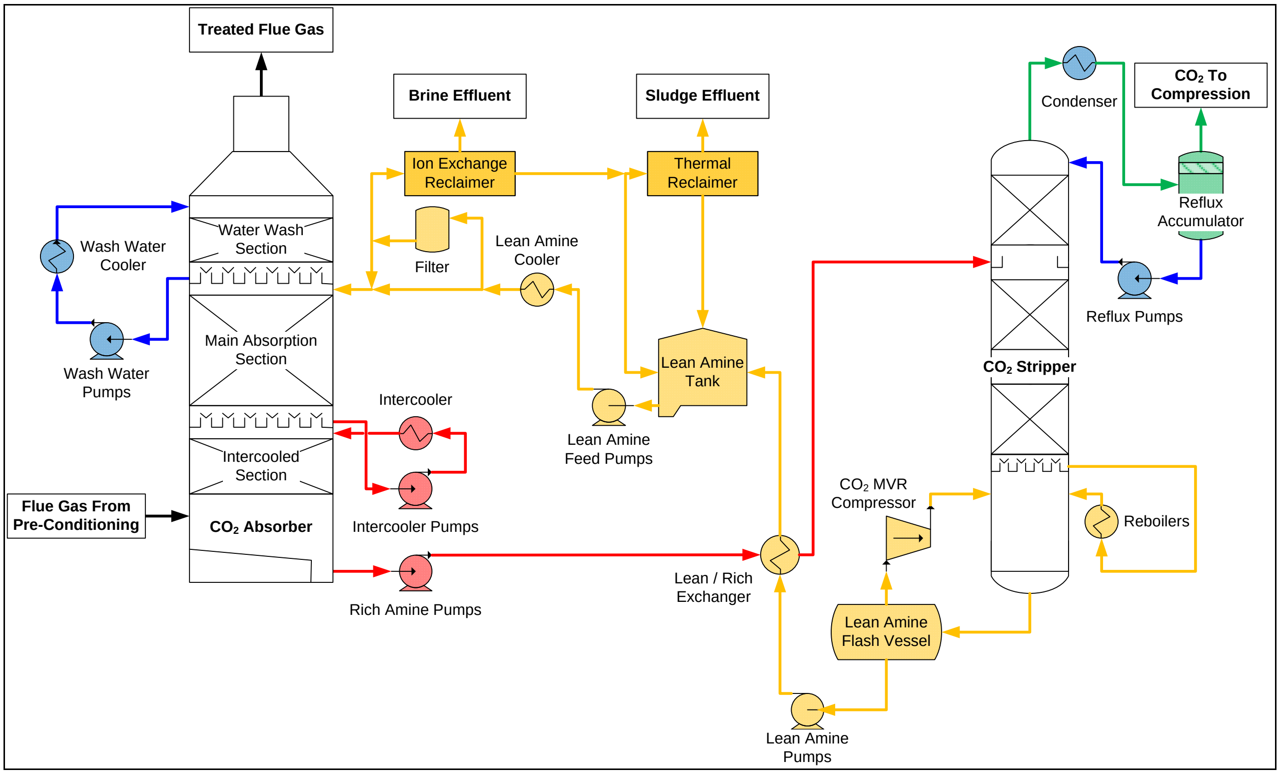

Figure 1: Cansolv CO_2 Capture Process- Simplified Block Flow Diagram

The Cansolv CO_2 Capture System is very similar to the well-known amine treating process for removal of H_2S and CO_2 from refinery streams and natural gas. The Cansolv process employs similar engineering methods, equipment selection and process control.

2.2. Upstream Gas Management

2.2.1. Pressure Drop

The pressure drop across the Cansolv system is expected to be about 4 inches water column (.01 bar) for the Quench/Pre-scrubber device (as described below) and about 13 inches water column (.032 bar) for the Cansolv absorber. A booster fan is expected to be required to provide this driving force and has been assumed for the purposes of this evaluation.

2.2.2. Particulate Management

Generally, Cansolv process can accept up to ~20 mg/Nm^3 of dust into the system before upstream abatement needs to be considered.

2.2.3. Pre-scrubber

Before the gas can be contacted with the Cansolv absorbent, it must be quenched to its adiabatic saturation temperature. This is required to limit evaporation of water from the solvent within the CO_2 absorber tower, which would result in an over concentration of amine. This equipment is assumed to be provided by others and would be outside the scope of Cansolv Process Design Package (PDP). It is assumed that the pre-scrubber would be a packed tower, which would provide enough surface area for both mass transfer and heat transfer purposes; mass transfer for caustic scrubbing of SO_2 and NO_2, heat transfer to sub-cool the flue gas. It is assumed that the caustic pre-scrubber will achieve 90% removal of both SO_2 and NO_2.

2.3. Cansolv CO_2 Absorber

The CO_2 in the flue gas is absorbed in the Cansolv absorber tower using the Cansolv absorbent. Since the Cansolv absorbent reacts reversibly with CO_2, multi-stage counter current contacting is used to achieve maximum loading of the carbon dioxide into the absorbent solution. Lean cool amine is fed to the top of absorption section. As the solvent flows down the column counter current to the feed gas, CO_2 is absorbed into the amine solvent, which then exits the column as rich amine.

The lean amine solution will be controlled and fed into the top of the column and only modest discharge pressures are expected to be required. The simplicity of this design ensures minimum maintenance and operating costs while providing maximum reliability.

In cases where the flowrates are extremely large, the absorber is expected to be constructed out of concrete and lined with an acid-resistant lining; which is consistent with our past projects in the power industry and of similar large scale. This arrangement is expected to yield significant savings in terms of CAPEX compared to a stainless steel option.

2.3.1. Inter-stage Cooling

As the amine flows down the absorption tower, it heats up due to the heat of reaction of the CO_2 with the amine. At the bottom of the column, the rich amine is cooled by the feed gas, resulting in a high temperature "bulge" partway up the column. The magnitude and location of the bulge is determined by the interplay between the feed gas and lean amine temperatures as well as the heat capacities and the heat of reaction.

In order to decrease the size of the temperature bulge and maintain our desired loading level, we have incorporated a cooled rich amine recirculation loop ("inter-stage cooling") into the lower section of each absorber tower. This design will withdraw partially loaded hot amine using a pump, cool it using a heat exchanger and re-inject the cooler amine in the absorber tower, just above a lower section of absorber packing.

2.3.2. Water-Wash Section

After CO_2 removal, the treated gas exits the absorption section through a chimney tray, and enters the water-wash section. Here the gas is contacted counter currently with water in a packed bed. During the counter current contacting in the absorber and due to the high heat of reaction of the CO_2 capture, small amount of absorbent may be vaporized and entrained by the gas. The water wash section serves to capture this entrained absorbent and return it to the solvent solution. Depending on case specific design considerations, this wash-water may or may not be cooled.

2.4. Solvent Regeneration

The regeneration section (or "Stripping") of this system would consist of four main components: lean-rich heat cross-exchanger, regeneration column, reboiler and condenser.

The rich CO_2 absorbent from the absorption tower(s) is pumped by the rich solvent pump(s) to the regeneration tower(s) via the lean/rich heat exchanger, where sensible heat is recovered from the lean amine.

The regeneration tower is filled with structured packing in order to achieve high mass transfer efficiency and a low pressure drop. A reboiler is used to generate stripping steam in the columns.

Rich solvent is fed to the regenerator tower below a short rectification section, in which reflux water is used to partially condense and remove amine solvent vapor from the upward flowing steam. As the absorbent flows down the column, the CO_2 is stripped from the liquid, carried overhead and cooled in the overhead condensers where most of the steam condenses. Water-saturated CO_2 vapor and condensed steam are separated in a reflux accumulator; the reflux water is returned to the top of the regeneration tower by a reflux pump. The gaseous, water saturated carbon dioxide leaves the reflux accumulator at positive pressure for downstream use or disposal.

Since the Cansolv absorbent does have some low volatility, the product CO_2 will be washed with reflux water to ensure that losses of amine into the product CO_2 are as minimal as possible.

2.5. Amine Purification Unit

Depending on the flue gas composition, the solvent in the Cansolv CO_2 Capture System can accumulate non-regenerable salts (also called Heat Stable Salts) as well as various degradation products over time. These contaminants must be removed from the solvent in order to maintain the guaranteed system performance. During the design stage of the project, Cansolv engineers will design for the removal of these contaminants by circulating a small fraction of the lean solvent flow to an amine purification unit (APU). The APU can be a simple Ion-Exchange system designed to remove ionic species, or may be a thermal reclaiming stage, or a combination thereof. Validation and confirmation of this requirement is an optimization step to be done during an engineering phase of a project.

2.6. Typical Capture Plant Battery Limits

Typical battery limits of a Cansolv technology Process Design Package (PDP) of a CO_2 capture plant, is as follows:

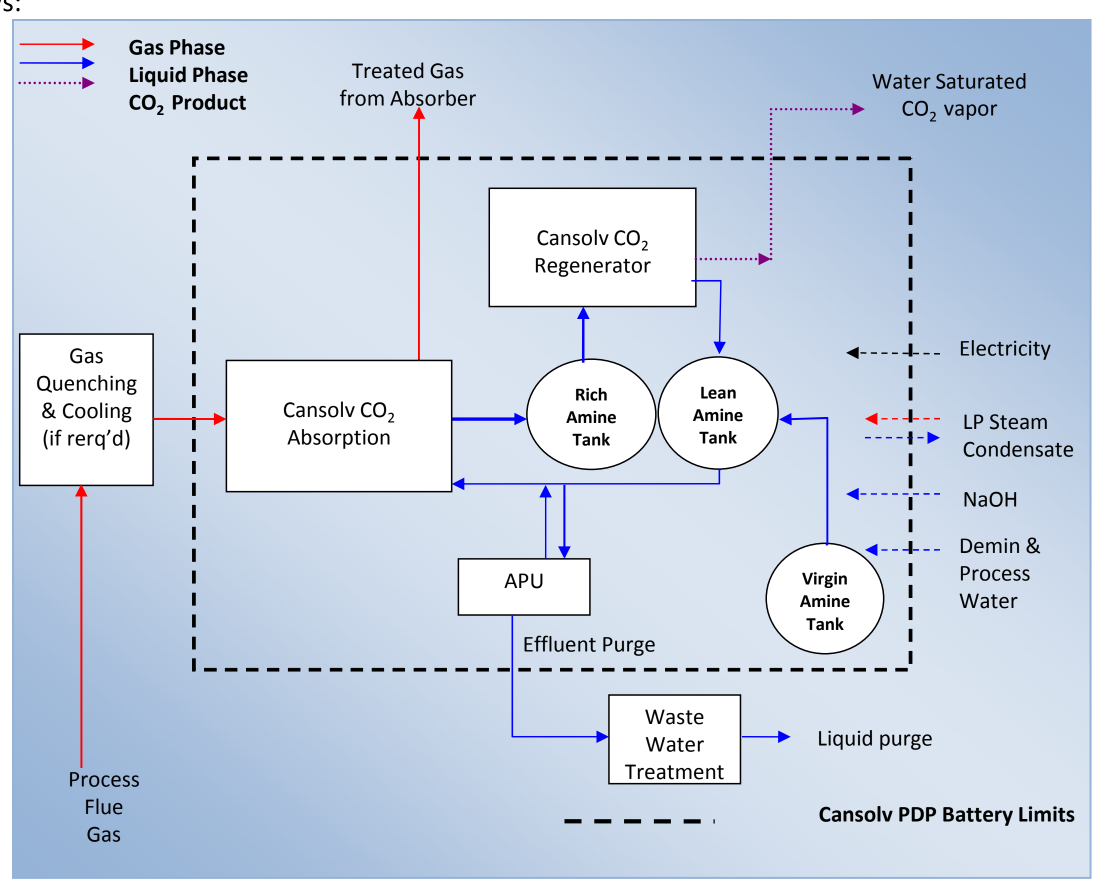

Figure 2: Typical PDP Battery Limits

3. TECHNOLOGY HISTORY

3.1. Previous Test Results

3.1.1. Past Piloting Experience - Cansolv CO_2 Capture Process

CTI has completed several pilot campaigns for the Cansolv CO_2 Capture process, described in T**able 1** below.

Table 1: Previous Test Campaigns

Application	Dates	Description
Natural Gas Fired Boiler	March 04 – June 04	Pilot tests at Paprican's* Headquarters. The CO2 concentration in the inlet gas was 12%vol and the recovery rate was 75%. The recovered CO2 was produced as water-saturated gas from the solvent stripper and was dried before compression and storage in a CO2 accumulator. * Paprican: Pulp & Paper Research Institute of Canada
Coal Fired Boiler	November 2005	Pilot tests at Smurfit-Stone's West Point Pulp & Paper Mill. The coal-fired boiler was equipped with an effective ESP, which removed most of the particulate matter. The pilot prescrubber quenched the gases and removed parts of the remaining particulates. The SO2 was also removed before the gas entered the absorber for CO2 absorption. It was confirmed that coal fired applications can be dealt with properly without creating any adverse effects on the Cansolv process. The CO2 concentration in the inlet and treated gas were 12%vol 5%vol.
Coal Fired Boiler	Feb. 06	Pilot tests at NSC (Nippon Steel Corporation). Inlet concentration was 22%, and recovery rate was 65%.
Coal Fired Power Plant	July 06 - Sept. 06	Pilot tests at Saskpower's Poplar River Power Plant (Saskatchewan, Canada). The inlet gas concentration was 12% and the recovery rate was 90%.
Natural Gas Fired Cogeneratio n	May 07 - Sept 07	The CANSOLV CO2 Capture process has been retained by a Shell-Statoil joint venture as one of the three leading CO2 capture technologies in the world. Cansolv solvent was be tested during extensive pilot plant trials in Risavika (Norway), as part of the technology selection process for one of the largest offshore CO2-EOR projects to date.
Blast Furnace	April 07	Pilot tests at NSC (Nippon Steel Corporation). Inlet concentration was 22%, and recovery rate was 90%.
Cement Kiln	Jan 08-Feb 08	Pilot tests at a Cement plant. Inlet concentration was 22%, and recovery rate was varied from 45% to 90%.

3.1.2. Development of 2nd Generation Solvents for CO_2 Post Combustion Capture (2009-2012)

Cansolv has established a comprehensive framework to steer development of 2nd generation solvents. Any new solvents are required to highlight the following improvements when compared to DC-103:

- Increased CO_2 loading capacity
- Lower regeneration energy requirement
- Increased stability

Table 2 below presents the technical objectives set for the new solvents and the resulting business value.

Development of new CANSOLV DC-201

The first development stage comprises of testing new candidates at the lab scale mimicking the Cansolv CO_2 capture system. During this "screening", the following solvent characteristics were studied:

- Loading-stripping capacity under different CO_2 partial pressures.
- Regeneration energy,
- Carbamate/bicarbonate equilibrium and ease of regeneration (using Nuclear Magnetic Resonance),

Table 2: Aimed technical objectives and expected business value

Technical Objectives (vs. DC-103)	Business Value
30% more CO_2 loading in the solvent	Reduction in solvent circulation rate leading to: • reduced CAPEX • reduced space requirements • less inventory
20% less steam requirement for steam regeneration	• reduced operating costs • lowered CO_2 footprint per ton CO_2 captured

One of the solvents, tested in 2010, demonstrated potential to meet the technical and business objectives and thus warranted further consideration and testing. Upon further testing of this new solvent, CANSOLV DC-201, it was recognized that the loading capacity increased by more than 50% over DC-103. This, in turn, led to a reduction in liquid circulation rate, and hence to a lower contribution of the sensible heat and latent heat components in the regenerator. Furthermore, the optimization of the

DC-201 formulation showed a 15% reduction in required regeneration energy over DC-103 on the Cansolv lab scale unit.

The second stage of the development consisted of testing DC-201 under real flue gas conditions at the 'pilot' size. Several piloting campaigns were performed where some of the studied parameters were:

- Effect of gas temperature and inter-cooling on solvent loading;
- Effect of packing height and type on approach to equilibrium (gas and liquid sides);
- Effect of lean-rich temperature approach on stripper performance;
- Emission measurements (with or without the use of a water-wash section).

Table 3, Recent Test Campaigns

Blast Furnace	Nov 11	Pilot tests at NSC (Nippon Steel Corporation). Two gas conditions were studied: 22.5% CO_2 (flue gas from Blast Furnace) and 13.5% CO_2 (diluted gas). Optimum regeneration energy at 90% CO_2 capture was 2.7 GJ/ton CO_2 (without any heat loss correction) for both cases with the use of two of the three Intercooling sections.
Natural Gas Fired	May 12	SINTEF 1 ton/day Tiller pilot facility (Trondheim, Norway).The optimal lean flow reboiler duty was 3.3 MJ/kg CO_2 captured for the natural gas case (4.5 vol% CO_2) and 3.1 MJ/kg for the recirculation case (13.5 vol% CO_2).
Coal Fired Boiler	Aug 12-Oct 12	NCCC Power Plant in Wilsonville, Alabama under standard coal combustion conditions. The flue gas composition was ~13.0% CO_2 and the total CO_2 capture was ~ 8 Ton CO_2/day. Optimum regeneration energy at 90% CO_2 capture was 2.3 GJ/ton CO_2 (without any heat loss correction).
Diluted gas from Coal Fired Boiler	July 13 – Oct 13	NCCC Power Plant in Wilsonville, Alabama under diluted coal combustion conditions. The flue gas composition was ~4.0% CO_2 and the total CO_2 capture was ~ 5 Ton CO_2/day. Optimum regeneration energy at 90% CO_2 capture was 3.3 GJ/ton CO_2 (without any heat loss correction).
Natural Gas Fired Cogeneration	Oct 14-	Demonstration test at TCM, Mongstad, Norway. Inlet concentration is 4%, and recovery rate is 90%. Start-up in Oct 14.

3.1.3. Expected performance for Gas Turbine Design

We have been working through the rigorous steps of making DC-201 a successful and commercial solvent. Based on the data and on the results gathered to date, it is possible to estimate the potential performance of the DC-201 solvent if it is to be used for a gas-turbine project compared to the DC-103 solvent.

Reduction in solvent circulation rate, steam consumption and cooling requirements will lead to smaller regenerating equipment size and piping, and exchangers and pumps with lower capacity. Therefore, capex savings are projected. Also, Solvent will be commercially available from qualified suppliers and should be cheaper than the current DC-103 market price.

Table 4: DC103 design performances and DC-201 expected performances for a gas-turbine project (270 MWe, 132 ton CO_2 captured per hour).

Main parameters	unit	DC-103	DC-201	DC-201 vs. DC-103 (% relative)
Solvent circulation	m^3/hr	2,083	1,327	-36%
Steam consumption	GJ / ton CO_2 captured	2.92	2.33	-20%
Cooling water	m^3/hr	5,856	4,262	-27%

3.2. Pathway to Commercialization

3.2.1. Scale-up Philosophy

It is widely understood that the emerging field of Carbon Capture and Storage (CCS) brings with it many new challenges in the legislative and engineering world, not the least of which is the concern of scale-up. Undeniably, when projects of this magnitude and cost are coupled with the challenges inherent in rolling out new technologies, risk mitigation is of the utmost importance and as such, the approach to scale-up must be clearly examined, defined and understood.

Cansolv has been in the business of providing large scale commercial amine plants for these types of applications since its foundation. In fact, Cansolv is the first company to employ an amine in an oxidative, post-combustion environment to selectively scrub a pollutant from the stream; through its world leading re-generable SO_2 scrubbing technology.

Cansolv has extensive experience in designing and rolling out commercial scale amine plants operating on oxidative flue gases in industrial applications worldwide. Many of the Cansolv units in fact operate on challenging applications such as refinery cockers and heavy fuel combustion boilers.

Designing a high performance amine plant for units where solid or liquid fuel (such as coal, coke, or oil) is combusted requires intricate considerations. Solvent protection, proper equipment line-up selection and often peripheral treatment units are among main challenges.

The particulate matter and potential carry-over of contaminants (heavy metals, mercury, trace chlorides or fluorides, etc) often associated with these fuel sources demand particular attention in the basic design and selection stage. Cansolv's robust design, born to perform in these environments, has evolved over time to adapt and meet guaranteed performance in these environments.

When it comes to treatment of post-combustion natural gas; many of the challenging elements are in fact no longer a consideration due to the relatively clean nature of the application.
The issue of "Scale-Up Risk" can be broken down into 3 distinct but critical categories:

1) Process Performance (chemistry)
2) Engineering and Design
3) Construction and Operability

The sections to follow highlight Cansolv's scale-up philosophy and pathway to success in scaling up technologies to commercial reality.

3.2.2. Process Performance

When scaling up a technology, an in-depth understanding of the chemistry is required to properly prepare for the design and engineering of the plant. This means ensuring the process you have prepared for at smaller scale acts the same at larger scales.

CTI's experience in taking the SO_2 scrubbing technology from conception, to laboratory, to pilot testing and to ultimate commercialization provided the confidence in the scalability of the chemistry. This was further confirmed by exceeding design expectations and warranted performance predicted from smaller scale testing and piloting (see figure 3 below) in hydraulics, energy consumption and capture performance.

Having succeeded in full scale commercialization of SO_2, it was an obvious choice to follow the same process development for the Cansolv CO_2 capture solvent. Ultimate solvent selection (DC-103) was based on the same decisions and philosophies cemented in development of CANSOLV DS for SO_2 scrubbing.

		Sulfur Recovery Unit, Belgium			Sulfuric Acid Plant, USA			FCCU, USA		
		Pilot (1999)	Design	Commercial (2002)	Pilot (2000)	Design	Commercial (2002)	Pilot (2003)	Design	Commercial (2006)
Gas Flow	SCFM	35	6,300	6,000	70	25,000	25,000	50	470,000	430,000
[SO2]in	vol %	1.2%	1.4%	1.0%	0.4 %	0.4 %	0.4%	900 ppmv	850 ppmv	800 ppmv
[SO2]out	ppmv	<100	75	50	<20	20	15	20	25	15
L/G	gal/kscf	8.9	10.7	7.1	5.4	3.2	2.7	6.0	4.2	3.5
Steam	lb / gal	3.8	3.6	2.1	3.4	2.9	1.9	3.3	2.8	2.5
absorber DxH	ft x ft	0.5 x 14 ft	4.6 x 30 ft	4.6 x 30 ft	0.5 x 14 ft	10 x 35 ft	10 x 35 ft	0.5 x 14 ft	32 x 120 ft	32 x 120 ft
stripper DxH	ft x ft	0.3 x 16 ft	4.3 x 50 ft	4.3 x 50 ft	0.3 x 16 ft	3 x 40 ft	3 x 40 ft	0.3 x 16 ft	12 x 64 ft	12 x 64 ft

x200 x700 X10,000

Figure 3: Scaling the Cansolv Chemistry

Therefore the confidence in the chemistry of the CANSOLV CO_2 solvent is not purely based on historical success; but rather on the fact that the solvents are purposely of the same molecule family and the chemistry of the process is essentially identical. Figure 3 below illustrates why the success of the scaled-up SO_2 scrubbing technology is relevant to predict the same for the scaled-up CO_2 process.

3.2.3. Engineering and Design

In addition to the obvious selection of a good solvent, there are several other critical factors related to successful scale-up of an amine based technology - not the least of which is engineering and design. It is Cansolv's philosophy in every design, to go 'back to the basics' to ensure each design starts from the same sound basics that have been successful in the past.

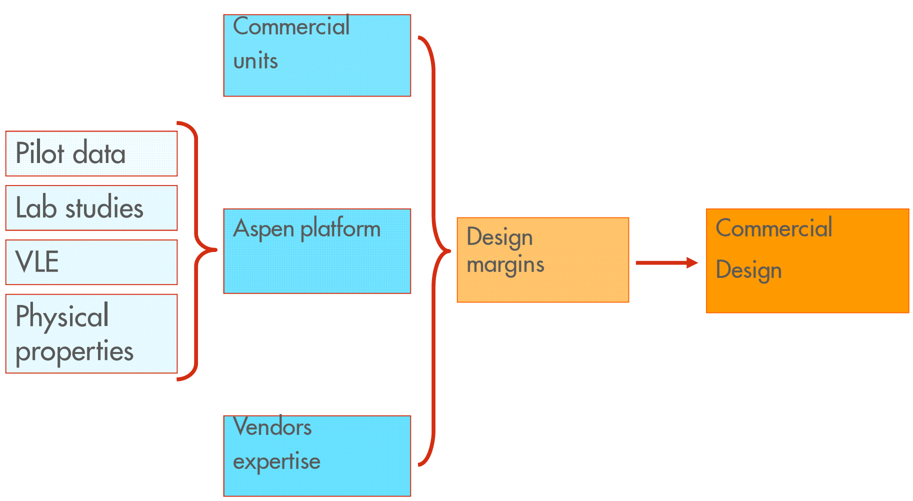

Figure 5: Commercial Design Philosophy

The mechanical efficiency of a carbon capture plant is based on the mass transfer surface area being sufficiently designed to enable the amine to fully interact with the flue gasses. In order to address this, CCS amine based CO_2 capture systems require the use of large vessels that incorporate sophisticated internals to ensure efficient capture of CO_2 by the amine. The mechanical and process design of the tower is complex. It requires intense collaboration between the client, process designer, internals vendor and the vessel mechanical designer to ensure that all design considerations are carried into the final vessel design. As such, during the Frond End Engineering Design (FEED), Cansolv will ensure among others at least the following key parameters are confirmed:

- Flow profiles are properly considered and that sufficient baffles and flow distributors are provided.
- Essential Computational Fluid Dynamic (CFD) studies are carried out to ensure proper gas flow distribution throughout the tower and equal distribution of liquid and vapour streams from each of the multiple reboiler bundles used in the solvent regenerator.
- Factory acceptance tests are conducted to confirm liquid distribution performance of key liquid distributors in the large vessel
- Structural systems are designed carefully to ensure internals are not subjected to excessive flex, expansion or bending during operation
- Modern 3D-CAD depictions of the large towers will also likely be performed to enable the designers to properly visualize the designs and ensure elevations and orientations of nozzles and internals are correct.

When concerned with issues such as scale-up risk, it is important to consider the historical scale-up pathway. Figure 6 below illustrates the scale-up history of Cansolv design and engineering for operating units.

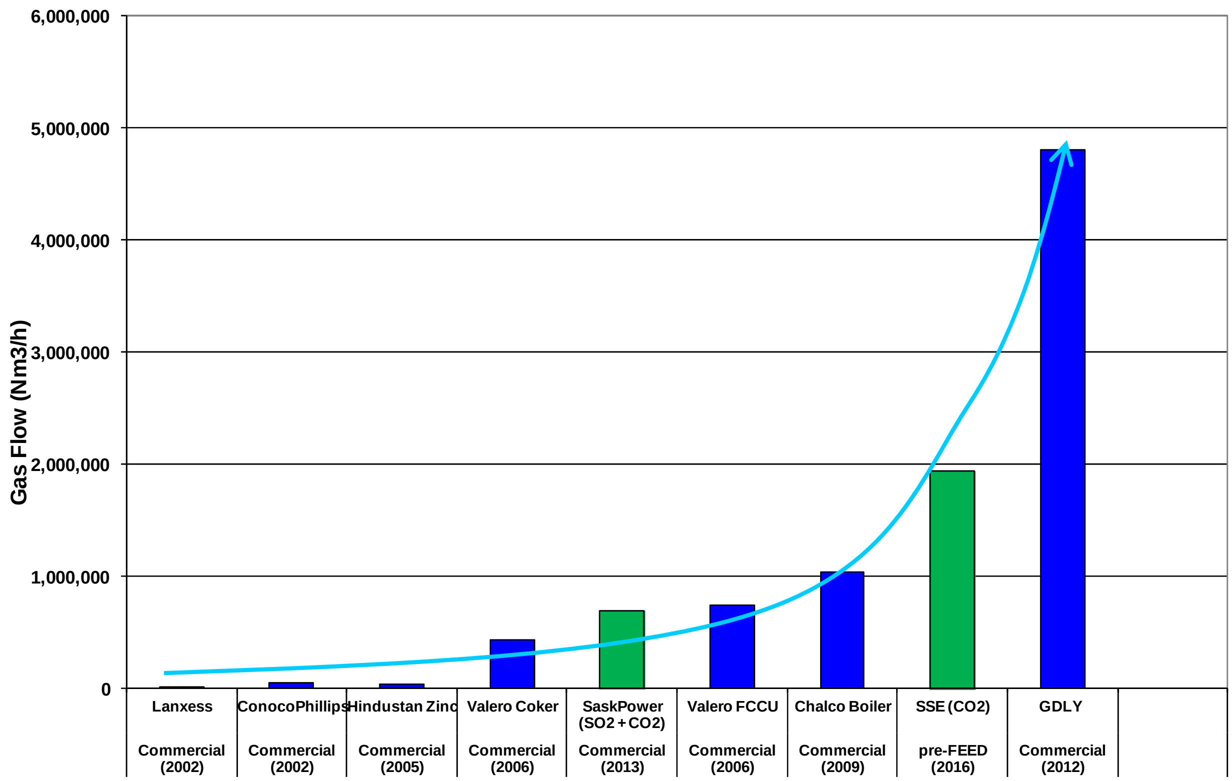

Figure 6: Commercial Scale-Up Pathway

3.2.4. SaskPower Boundary Dam CCS Demonstration Project

The Cansolv experience and proven success in the area using amines provides the experience and confidence to be successful in CO_2 applications such as the SaskPower project, which is highlighted below. It is the continued evolution and learnings from this construction project that assures us that our concerns related to scale-up are appropriately mitigated and do not in fact represent risks. All of the learnings available at the SaskPower project will be directly relevant and available for the SSE project from FEED through Engineering Procurement and Construction (EPC) completion. The SaskPower Boundary Dam project is the largest CO_2 capture project in the world today.

Project Description

The Boundary Dam Power Station is an aging asset in the SaskPower fleet, and the intent is to extend its life rather than replace the plant. The current projection is that the upgrades to the plant will extend its useful power production life by 30 years.

As part of this plant retrofit effort, a requirement to perform a steam turbine generator replacement was imminent; by integrating the overall retrofit requirements with SO_2 and CO_2 capture implementation, savings will emerge versus an uncoordinated approach that would require significant rework if sulfur and carbon capture were implemented separately.

For this project, the resulting captured CO_2 emissions will be compressed and transported through pipelines with the intent of selling it for Enhanced Oil Recovery (EOR). When completed, the SaskPower integrated carbon capture plant will capture over one million metric tons of CO_2 per year, reflecting a 90% CO_2 capture rate for the 150 MW coal-fired unit. Additional benefits of the project include integration of an SO_2 capture process that will provide feedstock for a 50 ton per day sulfuric acid plant.

Project Status Update

Table 5 below presents the status of the SaskPower Boundary Dam CCS Demonstration Project.

Table 5: Project milestones

Milestone	Milestone Date	Notes
FEED complete	November 2009	Completed
Project Award	March 2010	Completed
Detailed Design	December 2010	Completed
Long Lead item Procurement	December 2010	Completed
Financial Investment Decision	May 2011	Completed
Start of Construction	May 2011	Completed
Construction Completion	May 2013	Completed
Warranty Test Run	August 2014	On Target
Hand-Over to Client	August 2014	On Target

Figure 7: 3D Model of the SaskPower Capture Island

Figure 8: Completed Capture Plant Integrated with Power Plant

Detailed engineering of the Cansolv Integrated SO_2/CO_2 Capture Plant was executed by SNC-Lavalin Inc.

(SLI). The engineering was conducted using the SmartPlant suite of design tools. P&IDs have been developed using SmartPlant's intelligent P&IDs. A ll engineering lists have been in continual sync with the 3D model. This approach was taken right from the start of the FEED. This allowed SLI to save precious time when the project was finally awarded. Without this approach, it would have been difficult to meet the tight schedule required. Balance of Plant is under the responsibility of Stantec Consulting Ltd, SaskPower's engineering firm. Figure 7 shows the completed 3D model while Figure 8 illustrates the completed construction of the Capture Plant and integration with the Power Plant.

Project Challenges and Lessons Learned

There are always risks associated with first-of-a-kind projects, for example:

a) Process performance risks (Related to CO_2 capture efficiency and energy requirements);
b) Scale-up risks (ex.: Uncertainties associated to fluid dynamics of large absorption and regeneration towers);
c) Application specific risks (ex.: Absorbent contamination by traces components present in the flue gas leading to increased amine degradation);
d) Economical risks (ex.: Impact on Cost of Electricity);

In this case, all risks were addressed at each step of the project and moreover during the initial phase of the FEED. For example, at the beginning of the FEED, in June 2009, a process performance risk analysis was conducted, involving representatives from all major stakeholders. Mitigation and recovery measures were listed and developed around process performance risk items.

a) The reliability of the process modelling tools was consolidated by detailed measurement of kinetic and thermodynamic properties and validated via more than 6,000 hours of pilot plant testing. Uncertainties associated to all key design parameters were quantified and engineering design margin were specified accordingly;
b) Computational Fluid Dynamic (CFD) simulations were conducted to ensure appropriate fluid distribution across the main towers;
c) Design improvements were included to reduce the likelihood of absorbent contamination and to enhance the capabilities of the absorbent reclaiming systems;
d) Optimization studies were carried out to minimize the parasitic load of Capture Plant on the Power Plant.

These are only examples taken from a vast list of mitigation and recovery measures.

The SaskPower BD3 CCS project should serve as an example in terms of transparency and collaboration between stakeholders. Risk items were always openly discussed to promote a clear understanding of what is at stake and to lead the decision making process towards the wise verdict.

4. PROJECTED BENEFITS OF TECHNOLOGY

1. Provides superior capture kinetics and higher loading capacity compared to conventional amines,
2. Requires lower re-generation energy,
3. Minimizes losses through low volatility in comparison to conventional amines
4. Ensures lower corrosivity compared to conventional amines
5. Delivers advanced technology development
    a. Years of experience
        i. Designing and operating large scale amine plants for Post Combustion Applications
        ii. Handling amine exposure to harsh oxidative post combustion environments,
        iii. Developing, integrating and operating advanced process line-ups that will minimize the penalty attributed to the post-combustion capture plants
    b. Integrated learnings from operating Cansolv plants installed at power facilities,
    c. Tailored ion exchange and thermal reclaiming technologies for superior amine purification

5. TESTING OF CANSOLV DC-201 AT NCCC (Simulated Natural Gas Tests –Hot Climate Conditions) – SUMMER 2014

5.1. Description of the pilot unit at NCCC (Simulated Natural Gas)

The unit is sized to achieve a capture rate of 5 tons CO_2/day (at 90% capture) and being operated 24/7. That is when the plant is operated for simulated natural gas testing, where the inlet flue gas CO_2 concentration is 4 %vol. (coal flue gas diluted with air). Based on the specifications below, the unit at NCCC is deemed to be adequate to reach the technical objectives of the piloting campaign.

Absorber

Overall dimensions: 115' tall by 26" OD/25.25" ID diameter

Number of packing sections and height of each: 3 sections, 20' each

Number of intercooling stages and temperature return: 2 stages, between 1st and 2nd beds/2nd and 3rd beds. One HX in each loop with independent temperature control

Packing type: Sulzer Mellapak Plus 252Y

Sampling on Absorber

Liquid sampling ports:

Only inlet and outlet sampling only. Also have sampling on intercooler loops.

Gas sampling ports:

One on absorber, manual port at top of absorber.

One at absorber inlet,

One at wash tower outlet,

Thermal reclaimer

Processing flow:

About 3-5% of hot lean solution,

Operating temperature range:

Reclaimer designed for 500F mechanically. Steam (max 420 psig) is used to provide heat,

Operating pressure range:

Regeneration system is designed for max 200 psig operating pressure.

Flows

Type of flowmeter for amine:

Coriolis meters supplied by Micromotion

Allowable recirculation rate (minimum and maximum amine flows

15-75 gpm

Type of flowmeter for gas:

V Cone flowmeters supplied by McCrometer

Allowable gas flowrate (minimum and maximum gas flows):

Minimum controllable flow seems to be 2500-3000 pph.

Max design gas flow is 5,000 lb/hr, but can be increased to the extent of pressure drop limitation

Type of flowmeter for steam:

V Cone flowmeters supplied by McCrometer,

Allowable steam flow rate (minimum and maximum steam flows):

Max steam flow rate to Reboiler is 3,200 lb/hr

Pre-scrubber and Quench

Incoming gas composition (including ash load and characterization):

Varies with power plant load.

Typically (vol%, wet) 10-12% CO_2, 5-6% O_2, 12-15% H_2O, about 25 ppm SO_2.

Gas composition after pre-scrubber:

At absorber inlet, typically (vol%, wet): 11-13% CO_2, 5-7% O_2, 6-8% H_2O, 0 ppm SO_2.

Gas saturation temperature after pre-scrubber:

Temperature after pre-scrubber but before blower is almost the same as the incoming gas temperature. After the cooler/condenser, the temperature usually is 110F

Stripper and Reboiler

Overall stripper dimensions:

75' tall by 24"OD/23.25"ID diameter

Number of packing sections and height of each:

2 sections, 20' each

Packing type (incl. specific area):

Sulzer Mellapak Plus 252Y

Operating pressure:

200 psig max

Heat loss:

Under evaluation

Rich line pressure:

According to solvent operating condition, usually operated at 50-120 psi above regeneration pressure to minimize two phase flow

Filtration

FCF:

Particulate filter/carbon bed filter/particulate filter. It is a 3 stage filtration loop

5.2. Operation & Results

Since the development of the second generation of CO_2 capture solvent by Shell Cansolv, it has been tested in several pilot test facilities as listed in Table 3. In 2013, CANSOLV DC201 was successfully tested under simulated CCGT flue gas conditions for 1715 hours of operation at the NCCC piloting facility in Wilsonville, AL, US. 90 (+/- 5) % CO_2 capture was achieved and energy consumption requirements have not deteriorated before 1200 hours of operation, where the concentration of degradation products in the solvent hindered its performances (no bleed-and-feed or reclamation technology was used during the test). For 2014 a series of piloting campaigns envisioned to provide information needed to understand the contributions to amine losses for clean gas applications. As an example, CANSOLV DC-201 has been tested with real CCGT flue gas at TCM and at NCCC.

The 2014 piloting campaign at NCCC was from July 23rd to August 15th 2014. A total of 500 stable hours of testing were envisioned, according to the testing plan submitted to NCCC (Document: R0002-R40EX-002-R-01)

The objectives of this campaign were:

1) Operate under hot climate conditions while monitoring CO_2 capture performance and degradation rate,
2) Measure emissions with virgin solvent,
    a. no CO_2 in flue gas, i.e. no carbamate/bicarbonate/carbonate interaction
3) Measure emissions under coal conditions,
    a. Investigate impact of amine volatility on entrainment rate in presence of acid mist,
    b. Evaluate performance of new mist eliminator compared to previously used items, i.e. previous DC-201 piloting campaign,

Only 322 hours of operation were achievable due to flue gas supply short come. Table 6 summarizes source of inlet gas to the absorber and duration of stable operations.

Table 6: Flue gas source and duration of steady state operation

Inlet gas source	Start	End	Duration (hrs:min)
Pure air	7/23/2014 at 17:00	7/24/2017 at 14:43	21:43
Dilute CCGT	7/25/2014 at 14:50	8/6/2014 at 0:14	273:24
Pure air	8/6/2014 at 0:14	8/8/2014 at 23:35	71:21
Dilute CCGT	8/8/2014 at 23:35	8/11/2014 at 0:28	48:53
Coal fired	8/11/2014 at 18:36	8/12/2014 at 21:00	26:24
Coal fired	8/14/2014 at 8:45	8/15/2014 at 14:53	29:59
Total			**322:17**

As mentioned before, Cansolv process is being designed based on specific level of contamination in flue gas. Thus, a pre-treatment unit, up-stream of the absorber, is considered typically. At NCCC pre-scrubber unit treated flue gas before entering the absorber. Presence of SO_2 in flue gas causes side reactions which result in amine transformation. NOx can have similar effect however transformation products, involving NOx, may introduce environmental issues.

Table 7: Flue gas composition before and after pre-scrubber

Parameter	Before scrubber	After scrubber
Average flue gas temperature (^oC)	75.1	53.9
Average O_2 concentration (% vol).	7.4	16.7
Average CO_2 concentration (% vol)	11.7	4.7
Average SO_2 concentration (ppmv)	32.1	0.4
Average NOx composition (ppmv)	92.4	36.2

As summarized in Table 7, Pre-scrubber did well by cooling down the flue gas to hot climate condition and removed significant amount of SO_2 and NOx. Differences in CO_2 and O_2 concentration is due to dilution of flue gas to achieve CCGT conditions after pre-scrubber.

The CO_2 removal versus time is shown in Figure 9. 90 (+/- 5) % CO_2 capture target was achieved and maintained for 200 hrs. Throughout the campaign CO_2 capture performance has not deteriorated and was stable.

In general, in an amine-based post combustion CO_2 capture process, with no make-up added, it is expected that CO_2 capture declines over time. This is due to transformation of the main amine component to product(s) which do not have any CO_2 capture capacity. This deterioration was not observed during NCCC 2014 campaign. One reason was the length of the test, which was not long enough to build significant amounts of degradation products and/or contaminants and then not long enough to loose significant amount of amine. In addition, CANSOLV DC-201 transformation product maintains certain capacity for CO_2 capture.

The stripping factor, as shown in Figure 10, was also stable and not worsen during the test period. Optimized energy consumption under hot climate conditions (Figure 11) is about 6% higher than colder conditions (described in Table 8). This is expected since the CO_2 equilibrium loading is lower at higher absorbent temperature and hence a higher circulation rate and steam rate are required per unit mass of CO_2 capture.

Table 8: operating conditions, cold and hot environment

	NCCC campaign 2013 Cold condition	NCCC campaign 2014 Hot condition
Lean solvent temperature (^oC)	40	54
Flue gas temperature (^oC)	35-40	45-50

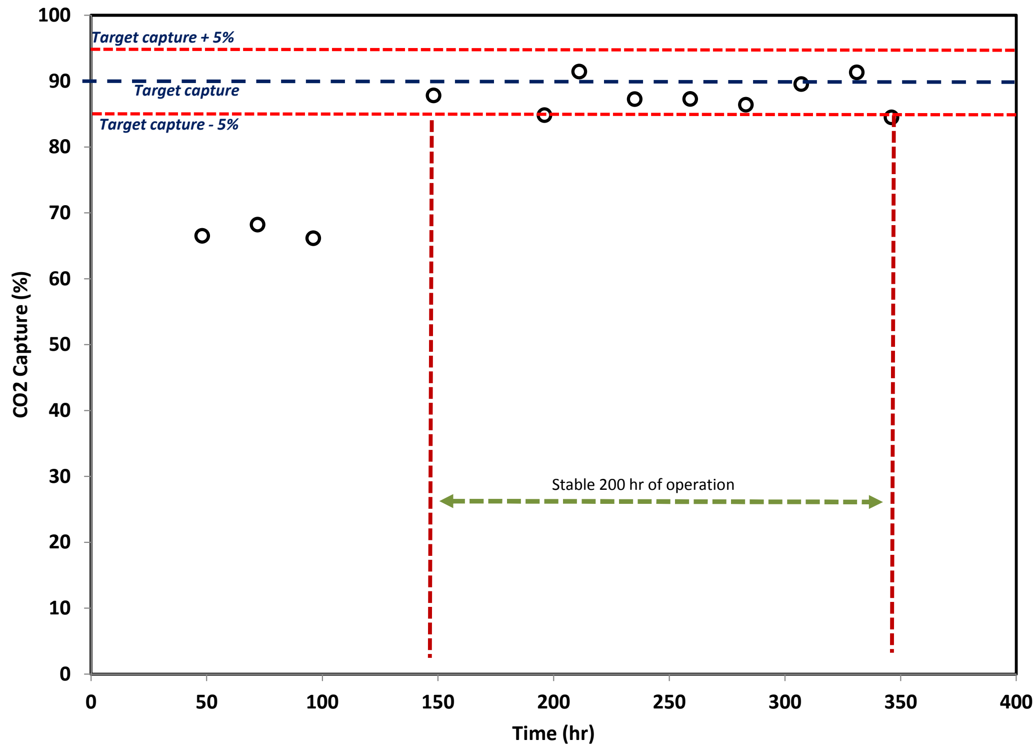

Figure 9: CO_2 removal versus time for hot climate conditions

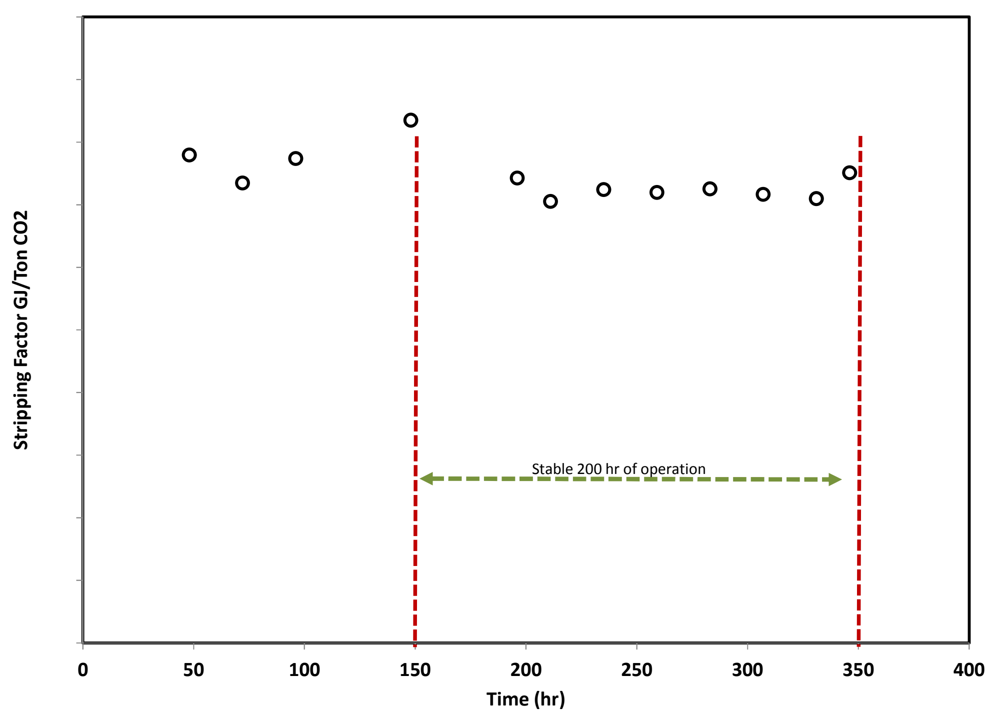

Figure 10: Stripping factor versus time for hot climate conditions

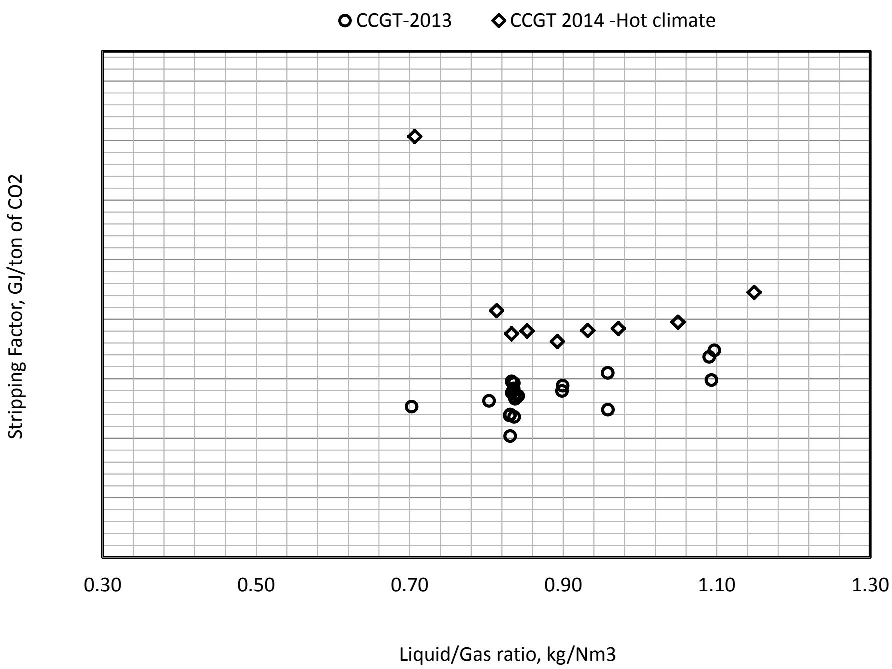

Figure 11: Comparison between stripping factor for cold climate and hot climate

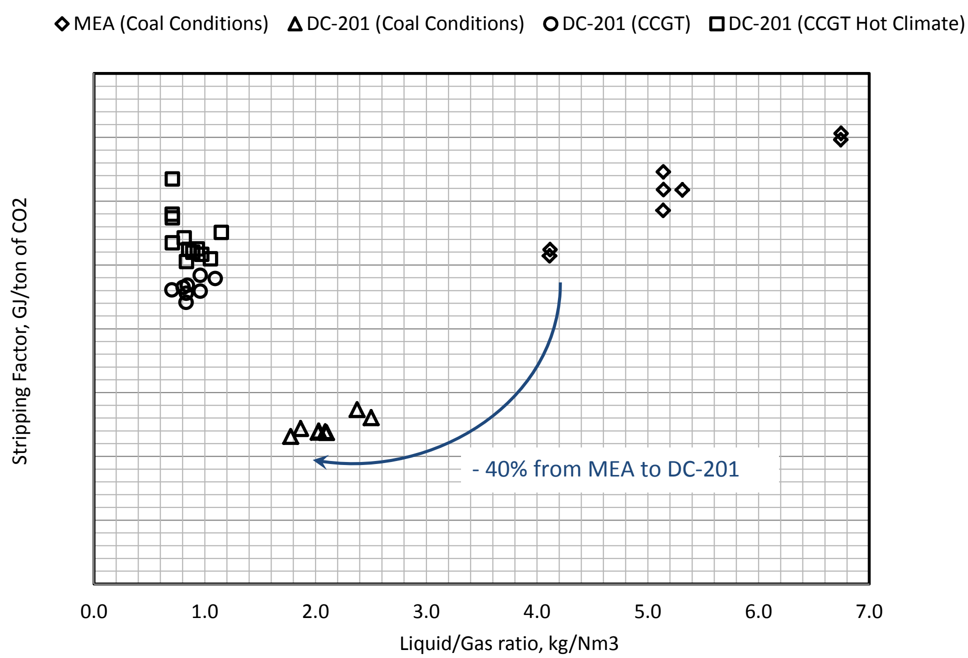

Figure 12: Stripping factor for 90% CO2 capture for different operating conditions and flue gas composition

Figure 12 summarizes the energy requirements for different conditions, i.e. for CO_2 capture with MEA, with DC-201 in coal conditions, with DC-201 in simulated CCGT conditions and with DC-201 in simulated CCTG conditions at hot climate. CO_2 capture with DC-201 is significantly advantageous compare to MEA. It shows lower energy requirements to achieve same level of CO_2 removal and additionally considerably lower amine circulation rate.

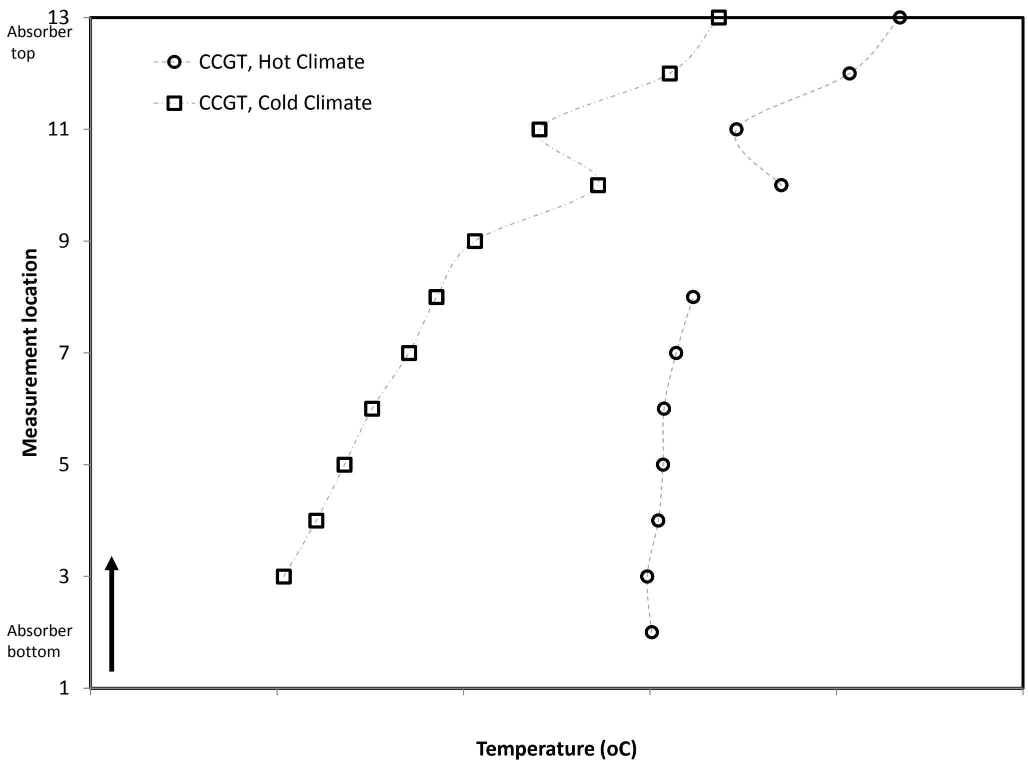

Figure 13: Absorber temperature profile for hot and cold climate test condition

Figure 13 illustrates the temperature profile in the absorber for both cold and hot climate tests. At cold conditions, the solvent enters the absorber at lower temperature and has higher capacity for CO_2 absorption. Accordingly, a higher temperature rise and a broader variation were observed. However, at hot conditions, the solvent with higher temperature has lower capacity for CO_2 absorption thus temperature variation was narrow. Both tests have been done with same CO_2 capture target and two profiles can be almost super-imposed,

In terms of degradation rate, it was not possible to make any meaningful observation since the continuous hours of operation under CCGT were not long enough to get a clear trend. Additionally, challenges with sampling and material analysis prevented from achieving reliable data acquisition. The internal strontium standard that was used to standardize degradation product accumulation showed to be ineffective due to solubility problem.

To evaluate emission, gas sampling using an impinger train was performed. The same sample system which was developed and used during 2013 campaign at the NCCC was used here. Schematic of sampling system is shown in the Figure 14. The gas is extracted iso-kinetically to obtain a representative gas sample. An ice bath removes both droplets and condensable liquids in a Modified EPA Method 5 (MM5) sample system. After the ice bath there is a manifold section where smaller gas flows can be drawn through sample systems. The collected samples were sent to Shell Cansolv Laboratories for analysis of amine and degradation products.

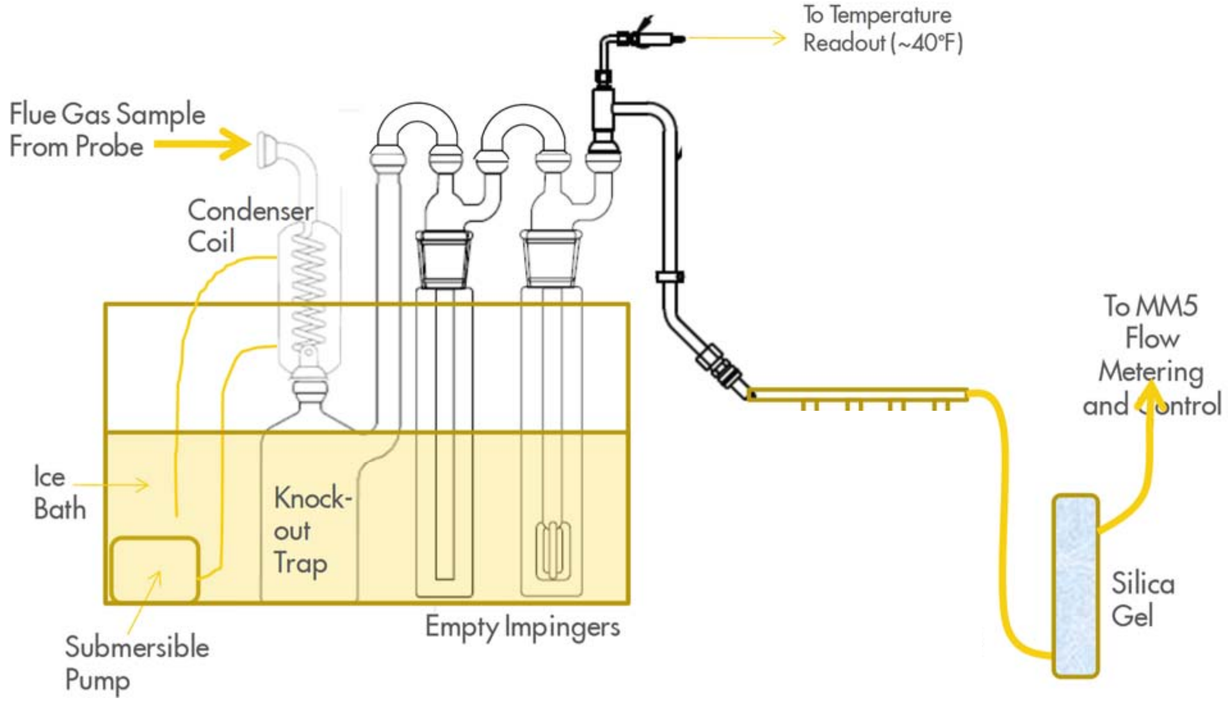

Figure 14: Gas sampling train

Amine emission and its components can occur by means of 1) vapour emission due to volatility, 2) carry over as a result of mechanical entrainment and 3) aerosols. These emissions can lead to environmental hazards and solvent losses which in turn can increase operating costs.

During the amine emission surveys performed at NCCC, it has been proven that amine emissions are considerably influenced by the composition of the flue gas. In other words, the more contaminated the flue gas entering the CO_2 capture system, the greater the resulting amine emissions will be. SO_3 is known to be in coal fired power plant flue gas. It may convert to H_2SO_4 in presence of water (vapour) in gas phase and condenses as temperature of flue gas crosses H_2SO_4 dew point and makes sulfuric acid aerosols. In addition, particulate matters in flue gas (soot, fly ash, …) can act as nuclei and contribute in aerosol formation. That is, the concentration of acid mist (SO_3), particulate and other flue gas contaminants significantly affect amine emissions.

To investigate DC-201 emission two different flue gas streams were tested:

(1) Standard Coal Combustion Flue Gas – this is the flue gas with no dilution after the dry ESP, SCR and FGD

(2) Clean Air – this is atmospheric air around the plant that was used as a benchmark. Saturated air was sent at appropriate flowrates through the CO_2 Absorber.

As summarize in Table 9, Fresh virgin amine solution tends to emit less than used amine solution, in which degradation products have built up. A value of 6.25 times less has been measured during this campaign. The contaminants present in the flue gas, from coal fired plant, causes higher emission. A value of 26.2 times has been measured during this campaign. The internal standard which was supposed to help assessing individual contribution of volatility and liquid entrainment was found to be ineffective both for DC-201 and DC-103.

Table 9: Amine emission under different conditions

Inlet gas type	Amine type	Emission ration compared to test with air
Air	Used amine*	1.00
Air	Virgin amine	0.16
Coal condition	Used amine*	26.20

*: Used amine: Amine + degradation products

Level of amine emission is an important parameter to manage to prevent any operational, environmental, health and safety issues. Using demister is a general technology to apply. Table 10 summarizes experimental data comparing standard demister (Sulzer K9033) and high efficiency demister (Sulzer K9797). Changing demister (to high efficiency from standard) did not have significant impact in terms of emission control. Based on the test done by Laborelec, aerosel/PM size was smaller than 0.8 micron. No difference between size and concentration of aerosol/PM was observed before and after two types of demister.

Table 10: comparing standard and high efficiency demister to control amine emission from DC-103

Test description	DC- 103 emission – NCCC lab.(ratio)
Outlet of standard demister	1
Outlet of high efficiency demister	0.8

6. Conclusions

1) Successful CANSOLV DC-201 testing under simulated CCGT flue gas conditions for 322 hours of operation was achieved.

2) Process performance was maintained near 90 % CO_2 removal for the duration of the testing. It has been shown that the influence of transformation product concentration on CO_2 removal is limited in the narrow tested range.

3) The overall energy consumption (stripping factor) for hot climate is 6% higher than the one for cold climate. Since the rich CO_2 operating loading is lower at higher absorbent temperature, a higher circulation rate and steam rate was required per unit mass of CO_2 captured.

4) Fresh virgin amine solution (with degradation products) tends to emit less than the used amine solution, in which degradation products have built up. A value of 6.25 times less has been measured during this campaign.

5) The contaminants present in the flue gas, from coal fired plant, causes higher emission. A value of 26.2 times has been measured for coal flue gas during this campaign.

7 Future works

Shell Cansolv has been testing DC-201 for post combustion CO_2 capture at several pilot facilities for both coal and natural gas fired power plants to advance its technology.

Comprehensive understanding on amine stability and mitigation measures for emission will help to reduce design margins and in time decreasing capital and operating cost. By reducing capital and operating cost, Cansolv's post combustion emission removal technology, will become even more attractive for the power industry to deal with new environmental protection legislations. ,

To achieve these, evaluating new demister to control amine (and degradation product) emission would be of interest. Due to the very small size of the aerosol particulates found in the gas from NCCC, the Sulzer high efficiency 9797 demister was not capable of reducing significantly the level of amine emissions during this past test. Brownian type demister have recently been reported to give very significant results in these cases. It would be very interesting to qualify this type of demister for coal application, considering any beneficial effect (reduction in aerosol concentration) and detrimental effect (higher pressure drop in absorber and potential fouling by fly ash).