



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

20th -24th October 2024 Calgary, Canada

## Bench Scale Development of a High-Performance Drop-in Solvent for Flue Gas CO<sub>2</sub> Capture

Sujay Someshwar,<sup>a</sup> Aravind V. Rayer Rabindran,<sup>a\*</sup> S. James Zhou,<sup>a</sup> Sukanta Kumar Dash,<sup>b</sup> and Raghbir Gupta<sup>a</sup>

<sup>a</sup> Susteon Inc., 215 Southport Drive Suite 1400, Morrisville, NC 27560, <sup>b</sup> Pandit Deendayal Energy University (PDEU)

---

### Abstract

Susteon has developed a drop-in high performance, water-lean, mixed amine solvent (trademarked as Sustenol<sup>TM</sup>) with fast absorption and desorption kinetics for significantly improved CO<sub>2</sub> capture efficiency for flue gas streams with a low CO<sub>2</sub> concentration (~4 vol%) such as flue gas from natural gas combined cycle (NGCC) power plants. Amine-based solvent absorption technology is the most mature and reliable technology for CO<sub>2</sub> capture at a large scale such as from a power plant flue gas; however, the amine absorption process requires large absorption columns which result in high capital costs and energy requirements (typically >3.0 GJ/tonne of CO<sub>2</sub>). Using a design of experiments methodology, Sustenol<sup>TM</sup> solvent was optimized for a significantly lower energy for regeneration. Furthermore, the solvent exhibits significantly lower sensible heat in addition to having three times higher absorption kinetics compared to 30 wt% monoethanolamine (MEA) solvent. The optimized Sustenol<sup>TM</sup> also shows a higher dynamic CO<sub>2</sub> absorption capacity of ~0.5 mol<sub>CO<sub>2</sub></sub>/mol<sub>amine</sub> compared to 0.25 mol<sub>CO<sub>2</sub></sub>/mol<sub>amine</sub> for 30 wt% MEA. Additionally, the solvent exhibits high oxidative, thermal and hydrothermal stability leading to lower solvent loss and emissions compared to the current leading solvents. These advancements have resulted in a solvent regeneration energy of 2.16 GJ/tonne of CO<sub>2</sub> which is >30% lower than current state-of-the-art commercial and emerging solvents. A rate-based thermodynamic process model developed in Aspen Plus<sup>TM</sup> was experimentally validated with bench and pilot-scale testing results. This process model was used to develop a high-fidelity techno-economic analysis (TEA) for post-combustion CO<sub>2</sub> capture from a 687 MW<sub>e</sub> NGCC power plant. This TEA indicated the cost of CO<sub>2</sub> capture by Sustenol<sup>TM</sup> for 97% CO<sub>2</sub> removal at \$54/tonne and for 90% removal at \$49/tonne, with a pathway to achieve \$45/tonne of CO<sub>2</sub> with continued process and solvent advancements.

**Keywords:** water-lean solvent; NGCC flue gas; CO<sub>2</sub> capture; absorber efficiency; CO<sub>2</sub> desorption, specific regeneration duty, thermal and oxidative stability.

---

### 1. Introduction

Amine-based solvent CO<sub>2</sub> capture is one of the most practiced point source capture methods with its roots tracing back to the 1930s when monoethanolamine (MEA) was first used to treat acid gases from refineries [1]. Despite its maturity and ongoing governmental incentives for CO<sub>2</sub> capture and sequestration, such as the United States Section 45Q tax credit, widespread adoption remains limited due to overall high CO<sub>2</sub> capture costs for flue gas streams. These costs

---

\* Corresponding author. Tel.: +1-984-400-0094, E-mail address: [avr@susteon.com](mailto:avr@susteon.com)

stem from high capital cost primarily due to large column diameter and height requirements dictated by lower CO<sub>2</sub> absorption rates and from high operating costs due to high energy requirements for solvent regeneration and significant solvent degradation resulting into high solvent make up rates [2,3].

Due to the technology maturity, the amine solvent-based CO<sub>2</sub> capture process has become well optimized through advancements such as intercooling the solvent in the absorption column to maintain high absorption rates and new stripping column designs to allow for integrated heat recovery from the exiting CO<sub>2</sub> stream to minimize the heat energy requirements of the system [2,4,5]. Furthermore, entirely new designs of the capture process have been proposed such as the use of a rotating packed bed reactor which employs centripetal acceleration of the solvent through a packed bed to minimize column height requirements resulting in significantly lower capital costs [6]. Despite these advancements, the high CO<sub>2</sub> capture costs persist, leading much of the current research to focus on further solvent development.

To address the cost issues in amine-based CO<sub>2</sub> capture, solvent development and optimization need to focus on several key properties: (1) CO<sub>2</sub> working capacity of the solvent, (2) rate of absorption of CO<sub>2</sub>, (3) solvent degradation rate, and (4) enthalpy of CO<sub>2</sub> absorption [7]. The CO<sub>2</sub> absorption rate determines the height of packing required and size of the absorber columns. The oxidative, thermal, and hydrothermal degradation rates of the solvent directly determine solvent make up rate. For a conventional reboiler design, a lower enthalpy of CO<sub>2</sub> absorption is critical in reducing the amount of steam needed for solvent regeneration [5,8]. Furthermore, CO<sub>2</sub> working capacity of the solvent determines the circulation rate in the capture process. Key attributes of an optimal solvent include a lower water percent for increased CO<sub>2</sub> working capacity while maintaining low viscosity, avoiding precipitation, and low degradation rates.

Amine moieties are the most salient CO<sub>2</sub> capture agents in solvents due to the nitrogen group's high reactivity towards CO<sub>2</sub> while being regenerable at relatively low regeneration temperatures (<150°C) compared to other CO<sub>2</sub> capture agents such as metal hydroxide salts [9]. The chemical structure of amine moiety results in differing CO<sub>2</sub> capture properties among a wide variety of amines. Primary amines (such as MEA) capture CO<sub>2</sub> through carbamate formation leading to their characteristically high CO<sub>2</sub> absorption rates which makes them the most used CO<sub>2</sub> capture solvents [9]. However, they require high energy regeneration, have a lower working capacity, and generally exhibit high degradation and corrosion rates. Secondary amines also capture CO<sub>2</sub> through carbamate formation with a lower absorption rate and working capacity than primary amines but exhibit stronger stability compared to primary amines; however, they suffer from NO<sub>x</sub>-induced (present in most of the combustion flue gases) oxidative degradation and carcinogenic nitrosamine formation. Tertiary amines, such as methyl diethanolamine (MDEA) and triethanolamine (TEA), capture CO<sub>2</sub> through bicarbonate formation, offering high stability and high working capacity with low heat of absorption, but suffer from very slow CO<sub>2</sub> absorption rates [9].

CESAR-1 solvent developed by SINTEF in Norway is currently a leading amine-based CO<sub>2</sub> capture solvent formulated using a blend of 2-amino-2-methyl-1-propanol (AMP) and piperazine (PZ) in an aqueous solution. Initially designed to displace 30 wt% MEA-based CO<sub>2</sub> capture in pilot systems, it exhibits high working capacity and reaction kinetics; however, both AMP and PZ have been observed to precipitate out at high concentrations. The resulting solution is dilute and leads to less efficient CO<sub>2</sub> capture and requires higher regeneration energy (~3 GJ/tonne of CO<sub>2</sub>) [10].

To address the costs associated with the current amine-based solvents for point source CO<sub>2</sub> capture, Sustenol has been developing a novel solvent, Sustenol™ since 2021. This mixed amine solvent blend takes advantage of the high CO<sub>2</sub> capture rates of primary and secondary amines, while leveraging the higher working capacity, high oxidative and thermal stability, and lower regeneration energy requirement that tertiary amines bring.

## 2. Bench-Scale Experimental Testing

To develop and screen various solvent compositions, a 15 kg CO<sub>2</sub>/day bench-scale absorber and stripping system was designed and built as shown in Figure 1.

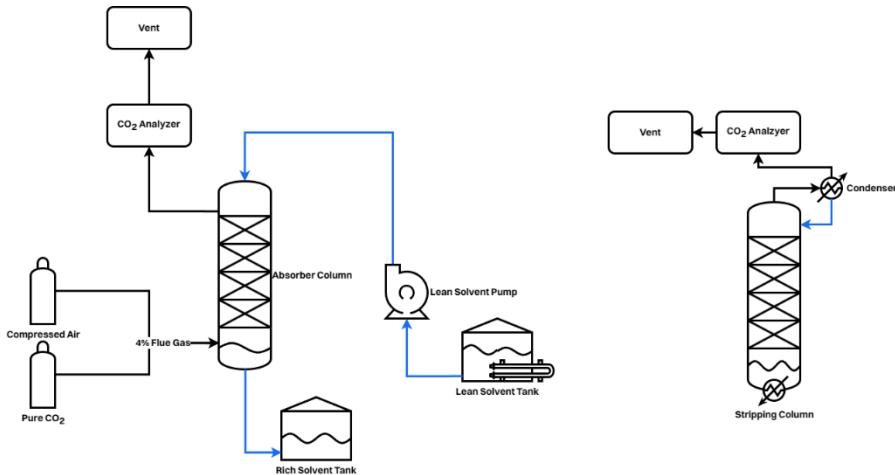


Fig. 1. Susteon Bench-Scale Solvent Test System. Left: Semi-batch Absorber Column. Right: Batch Stripping Column

A 5-foot tall, 1.5-inch inner diameter Schedule 80 PVC pipe was used as the absorber column with 4 feet of KUBER wire structured packing filling the column to increase the contact area between the solvent and the incoming flue gas. Mass flow controllers were used to mix compressed air and ultra-pure CO<sub>2</sub> to get the desired ~4.3% inlet CO<sub>2</sub> concentration and a total flowrate of 35-47 SLPM of the simulated flue gas was fed to the column for CO<sub>2</sub> capture testing. The lean solvent was heated to 40°C to simulate a commercial amine plant. It was pumped into the column in a countercurrent fashion to the flue gas flow at varying flowrates to vary the mass of liquid / mass of flue gas (L/G) ratio. A Quantek NDIR CO<sub>2</sub> gas analyzer was used for absorber effluent gas to determine the CO<sub>2</sub> concentration to calculate percent CO<sub>2</sub> capture. To test thermal stability and the cyclic performance of the solvent, a stripping column was designed and constructed from a stainless-steel kettle with an 1800 W heater. The kettle was connected to an overhead condenser to maintain the water concentration of the solvent while releasing the CO<sub>2</sub> from the rich solvent.

Extensive physiochemical property measurements were conducted on the lean and rich solvents from the bench testing. In addition to viscosity and density measurements which were performed using a 10 mL pycnometer and NDJ-8S viscometer, respectively, a gas evolution titration system was used to determine CO<sub>2</sub> working capacity of the solvent. The heat of absorption of the solvent was measured using a THT  $\mu$ RC micro-reaction calorimeter with a gas injection port.

To perform vapor pressure and rate measurements, a stirred tank reactor was designed to allow the vessel to be closed and for pressure to be measured at elevated temperatures. Additionally, gas injection ports allowed CO<sub>2</sub> injection into the solvent tank, and the partial pressure of CO<sub>2</sub> was measured with respect to time and temperature to determine the rate of CO<sub>2</sub> absorption. The reactor was operated at a stirring speed of 1800 rpm and at temperatures up to 30°C using tandem magnetic coupling stirring and modular electrical heating.

A water-lean amine solvent for CO<sub>2</sub> capture was developed by using a blend of proprietary tertiary, primary, secondary, and hindered amines. Through iterative testing via a nested design of experiment matrix using the bench-scale absorber and stripping reactor, key properties such as CO<sub>2</sub> capture efficiency at various L/G ratios, solvent viscosity, heat of absorption, density, absorption rate, and regeneration energy were determined to optimize the concentration of each component in the solvent formulation. The facilities at the Pandit Deendayal Energy University (PDEU) in Gandhinagar, India were used to validate the bench-scale testing results in their one (1) tonne/day CO<sub>2</sub> pilot unit with a 40 kW reboiler capacity with simulated flue gas composition. Additional testing was conducted to measure CO<sub>2</sub> capture and regeneration energy requirements as well as performance stability over time.

### 3. Results

Figure 2 shows a comparison of the performance of Sustenol™ with the 30 wt% MEA solvent which was used as a baseline. Higher CO<sub>2</sub> capture efficiencies were observed for Sustenol™ solvent at the same L/G ratio.

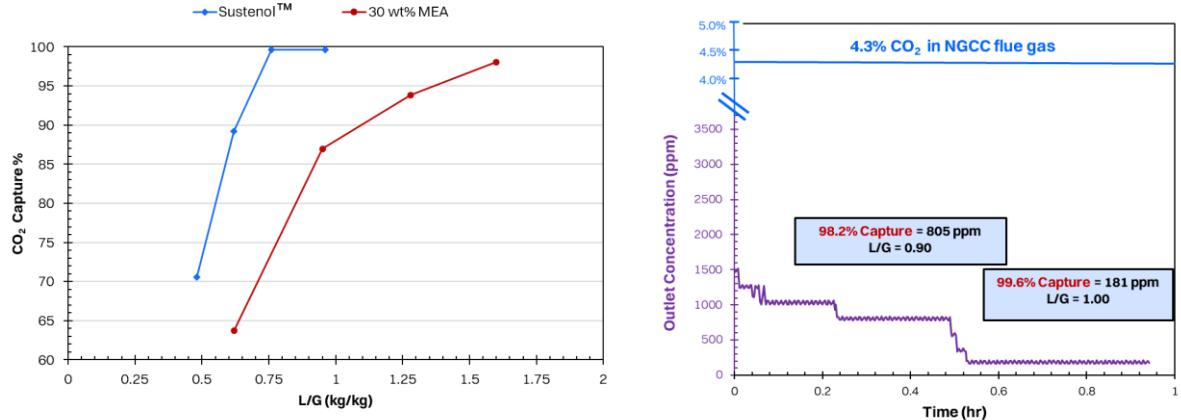


Fig. 2(a) CO<sub>2</sub> Capture Efficiency of 30 wt% MEA vs Sustenol™ at various L/G Ratios  
 (b) PPM Level Capture of CO<sub>2</sub> using Sustenol™ from NGCC Flue Gas

From Figure 2(a), at the same solvent circulation rate at L/G of 0.6, Sustenol™ captures almost 90% of the CO<sub>2</sub> from a simulated NGCC flue gas (~4.3% CO<sub>2</sub>) while 30 wt% MEA captures <65% CO<sub>2</sub>. Furthermore, at an L/G ratio of 0.7, Sustenol™ captures ~97% CO<sub>2</sub> from this flue gas. As shown in Figure 2(b), Sustenol™ can capture 98.2% of CO<sub>2</sub> (with 805 ppmv CO<sub>2</sub> in the effluent) at an L/G ratio of 0.9 and 99.6% CO<sub>2</sub> capture at an L/G ratio of 1.0 producing an effluent with 181 ppmv of CO<sub>2</sub> which is lower than the CO<sub>2</sub> concentration in the ambient air (~420 ppmv). Therefore, it is possible to achieve net-zero or negative CO<sub>2</sub> emissions from NGCC plants with Sustenol™, clearly demonstrating its fast kinetics and high working capacity for CO<sub>2</sub> capture even with low (~4%) CO<sub>2</sub> concentration in the flue gas.

The significantly reduced regeneration energy of Sustenol™ solvent was validated by lower heat capacity (kJ/kg/K) and heat of absorption (kJ/mol CO<sub>2</sub>) that was observed during testing. Lower heat capacity in both the lean and rich conditions manifests into lower sensible heat which, in conjunction with the lower heat of absorption, resulted in a lower reboiler duty (GJ/tonne CO<sub>2</sub>). These results are shown in Figure 3.

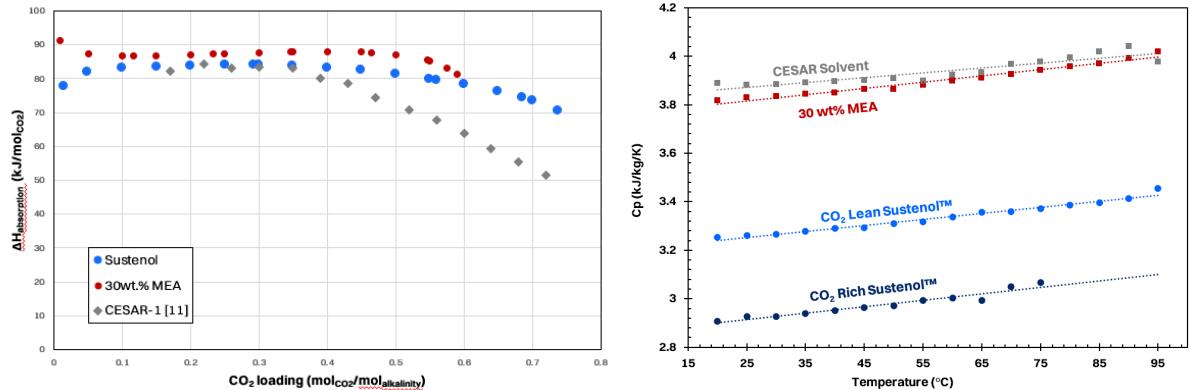


Fig. 3(a) Heat of Absorption of 30 wt% MEA and CESAR-1 vs Sustenol™ at various CO<sub>2</sub> Loadings  
 (b) Heat Capacity of Sustenol™ vs. 30 wt% MEA and CESAR-1 [11].

At 75°C, Sustenol™ has lower heat of absorption across all tested CO<sub>2</sub> loadings compared to both CESAR-1 and 30 wt% MEA solvent formulations. Data from the micro-reaction calorimeter showed a 17% decrease in heat capacity for Sustenol™ over the temperature range from 15-95°C. The heat of absorption and heat capacity results obtained were used to estimate the overall regeneration energy/reboiler duty from Equation 1 and plotted in Figure 4 [10].

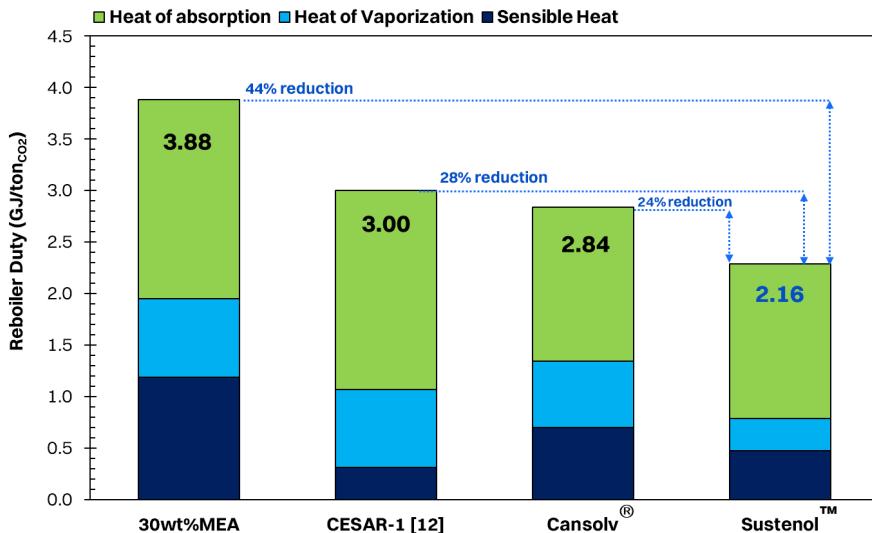


Fig. 4. Estimated Regeneration Energy for NGCC Flue Gas CO<sub>2</sub> Capture [12].

A comparison was made to current CO<sub>2</sub> capture solvents, including 30 wt% MEA, CESAR-1, and Cansolv® to estimate reduction in the regeneration energy with Sustenol™. The reboiler duty was reduced from 3.88 GJ/tonne CO<sub>2</sub> for the 30 wt% MEA to 2.16 GJ/tonne CO<sub>2</sub> with Sustenol™ indicating a 44% reduction. Similarly, as shown In Figure 4, the reboiler duty for Sustenol™ is >20% lower than the Cansolv® and CESAR-1 solvents.

In addition to high working capacity and lower heat of regeneration, second order absorption reaction kinetics were measured for the 30 wt% MEA, CESAR-1, and Sustenol<sup>TM</sup> solvents and are shown in Figure 5(b). Solvent kinetics were determined from the vapor-liquid equilibria (VLE) data and associated rate constants along the length of the absorber packing. From the VLE data, the estimated working capacity of Sustenol<sup>TM</sup> was 0.44 mol<sub>CO<sub>2</sub></sub>/mol<sub>amine</sub> as shown in Figure 5 (a). From the results presented in Figure 5(b), Sustenol<sup>TM</sup> exhibits nearly triple the reaction kinetics that of 30 wt% MEA solvent at 25°C. CESAR-1 appears to have a higher reaction rate than both 30 wt% MEA and Sustenol<sup>TM</sup> primarily due to its high piperazine content, but it suffers from high reboiler duty as shown in Figure 4.

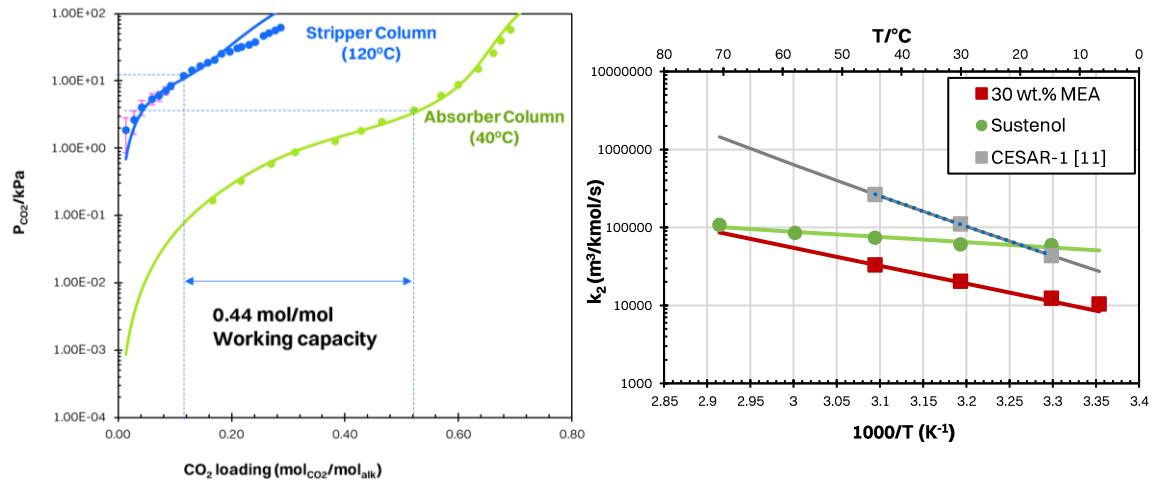


Fig. 5(a) Sustenol™ VLE from Data taken from Absorber and Stripper Columns  
 (b) Sustenol™ Reaction Kinetics vs 30 wt% MEA and CESAR-1 [13].

Following the in-house laboratory evaluation of Sustenol™ at Susteon at 15 kg/day  $\text{CO}_2$  at bench-scale, pilot-scale testing of 30 wt% MEA and Sustenol™ solvents was conducted at PDEU in their nominal 1 tonne/day  $\text{CO}_2$  continuous pilot plant. This 1 tonne/day capacity pilot plant was designed for a 13%  $\text{CO}_2$  concentration flue gas (coal combustion flue gas). This pilot unit has an absorber with 10-inch diameter and 13 feet height and a stripper with 10-inch diameter and 6 feet height. For a ~4%  $\text{CO}_2$  containing flue gas, the capacity of this pilot plant was about 350 kg/day. Simulated NGCC flue gas conditions used in the pilot scale testing are given in Table 1. These pilot plant tests were aimed to compare Sustenol™ solvent's  $\text{CO}_2$  capture performance at various L/G ratios and regeneration heat duty with the bench-scale test results obtained in Susteon laboratory.

Table 1. Test conditions used in the pilot scale

Flue gas flow rate	1000-4000 slpm
Flue gas $\text{CO}_2$ conc.	4.0 vol%
Flue gas inlet T	35-40°C
Flue gas inlet P	1.0 psig
Solvent inlet T	40°C
Liquid flow rate	3-10 lpm
Flue gas $\text{H}_2\text{O}$ conc.	5-7 vol%
Flue gas $\text{O}_2$ conc.	8-12 vol%
Flue gas $\text{N}_2$ conc.	70-80 vol%
L/G (kg/kg) range	0.7-4

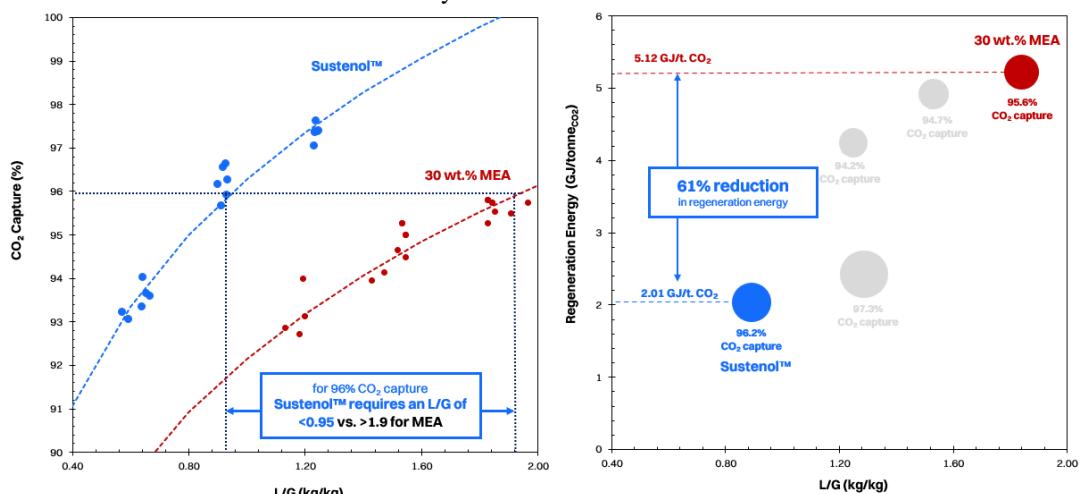


Fig. 6(a) CO<sub>2</sub> Capture Performance Comparison between 30 wt% MEA and Sustenol™ at various L/G Ratios  
 (b) Regeneration Heat Duty for Sustenol vs 30 wt% MEA.

As shown in Figure 6(a), Sustenol™ required an L/G ratio of ~0.95 to achieve 96% CO<sub>2</sub> capture from a simulated flue gas containing 4.3% CO<sub>2</sub>, compared to an L/G ratio of 1.9 for the 30 wt% MEA for the same 96% CO<sub>2</sub> capture. This finding validated the bench-scale test results, demonstrating that Sustenol™ is a more efficient solvent for CO<sub>2</sub> capture. Furthermore, the heat duty required to regenerate Sustenol™ was 2.01 GJ/tonne CO<sub>2</sub>, compared to 5.12 GJ/tonne CO<sub>2</sub> for 30 wt% MEA. This observed 61% reduction in regeneration heat duty is consistent with the bench-scale test results. This pilot-scale testing confirmed lower regeneration heat duty and higher CO<sub>2</sub> capture efficiency of Sustenol™.

Further testing was conducted at PDEU to evaluate solvent performance over a period of 7 hours continuous operation. Figure 7 shows the test results including inlet and outlet CO<sub>2</sub> concentrations as well as the percent CO<sub>2</sub> capture performance as a function of time. The inlet and outlet CO<sub>2</sub> concentrations and CO<sub>2</sub> capture efficiency remained relatively stable over the 7-hour period of continuous operation during the pilot testing. Notably, Sustenol™ consistently captured >97% CO<sub>2</sub> from the simulated flue gas, validating the bench-scale test results. Preliminary testing for thermal and oxidative stability was also conducted which showed no significant degradation. However, this testing was for a short period of time and further degradation/stability testing is planned for early 2025. Total accumulated bench-scale testing of the Sustenol™ solvent was >300 hours with no signs of degradation.

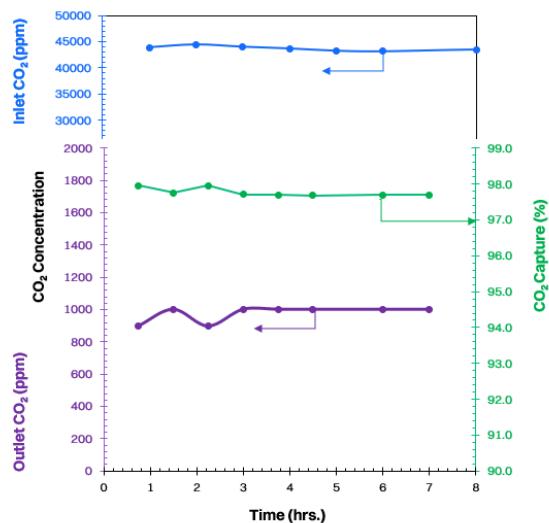


Fig. 7. CO<sub>2</sub> Capture Performance over 7 hrs. Continuous Operation at PDEU

#### 4. Modeling and Technoeconomic Analysis

A rate-based thermodynamic process model was built in Aspen Plus™ to estimate the CO<sub>2</sub> capture costs using Sustenol™ as a drop-in solvent in existing amine-based CO<sub>2</sub> capture systems. This model was rigorously validated with the experimental results obtained in bench-scale and pilot-scale test units as discussed above. This evaluation culminated in a techno-economic analysis (TEA) of Sustenol™ and its comparison with 30 wt% MEA and Cansolv® solvent systems. Basis of the TEA and CO<sub>2</sub> capture cost for various solvents were taken from the 2021 NETL report from the U.S. Department of Energy as well as studies published in the International Journal of Greenhouse Gas Control [14, 15, 16]. The overall costs of CO<sub>2</sub> capture using each solvent were calculated and are shown in Figure 8.

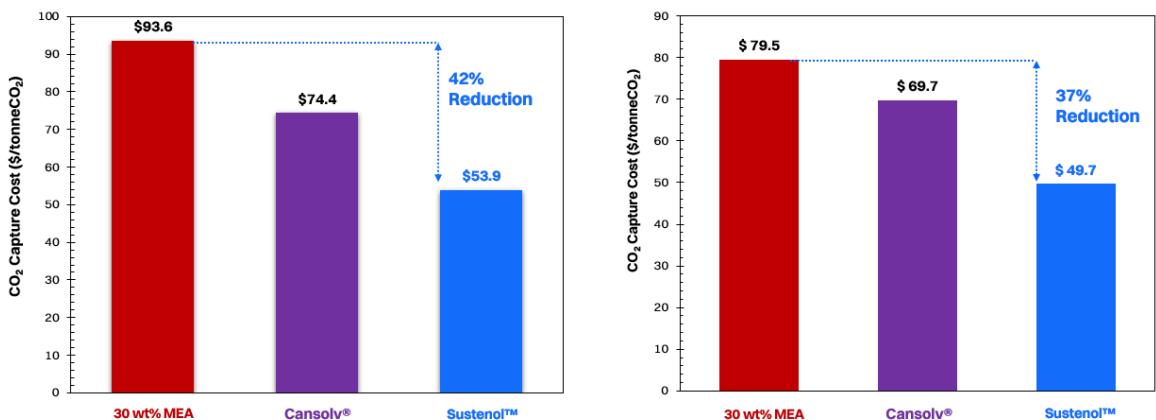


Fig. 8. (a) Capture costs for 97% CO<sub>2</sub> capture; (b) capture costs for 90% CO<sub>2</sub> capture [14,15,16].

Previous TEAs reported for 30 wt% MEA and Cansolv® showed that the costs for 97% CO<sub>2</sub> capture were \$93.00 and \$74.40 per tonne of CO<sub>2</sub>, respectively. For 90% capture, the costs decreased to \$79.50/tonne CO<sub>2</sub> for 30 wt% MEA and \$69.70 per tonne of CO<sub>2</sub> for Cansolv® [14, 15, 16]. The TEA conducted in this study using the experimentally validated process model showed lower CO<sub>2</sub> capture costs for both 90% and 97% capture using Sustenol™ compared to 30 wt% MEA and Cansolv® as shown in Figure 8. Specifically, the cost for 97% CO<sub>2</sub> capture estimated at \$53.90 per tonne of CO<sub>2</sub> is 42% lower than 30 wt% MEA. These TEA findings built upon the previous studies on commercial CO<sub>2</sub> capture solvents [14, 15, 16] demonstrate that Sustenol™ solvent's unique attributes can significantly reduce the cost of CO<sub>2</sub> capture from NGCC flue gas (~4% CO<sub>2</sub>). Additional TEA work done by Susteon for other higher CO<sub>2</sub> concentration flue gases (cement plants, coal combustion, recovery boiler in paper and pulp industry, etc.) indicates further reduction in the CO<sub>2</sub> capture cost below \$40 per tonne and in some cases as low as \$35 per tonne.

## 5. Technology Roadmap

As reported here, Sustenol™ solvent has been developed from the Technology Readiness Level (TRL) of 2 to current TRL 5 since 2021. Initial bench-scale and pilot-scale testing has demonstrated its superior properties and performance for CO<sub>2</sub> capture from a simulated NGCC flue gas. The development work is continuing to further de-risk this technology. A technology roadmap is shown in Figure 9. Susteon has signed a solvent manufacturing agreement with a major contract manufacturer who has successfully produced 5,000 liters of Sustenol™ solvent and is currently producing 10,000 liters for the testing at NCCC. Furthermore, Susteon has obtained a comprehensive U.S. patent on the composition of the Sustenol™ solvent with associated international filings.

The most important risk mitigation activities planned, include obtaining solvent testing data with actual flue gas for 1000s of hours of testing at large pilot and/or demonstration scale to: (1) demonstrate stable CO<sub>2</sub> capture performance at low L/G ratios, (2) validate regeneration heat duty (~2.2 GJ/tonne), (3) measure solvent emissions and any degradation products including formation of heat-stable salts, (4) determine its ecotoxicity and (5) determine corrosion with carbon and stainless steel and compatibility with the materials of construction. With these goals, Susteon has contracted with SINTEF (a Norwegian research institute which developed industry standard benchmarks for solvent degradation testing) to perform a comprehensive thermal and oxidative degradation testing of Sustenol™. In parallel, Susteon has contracted with an independent third-party to perform an environmental health and safety (EHS) certification using their standard protocols which were used for competing CO<sub>2</sub> capture solvents.

Additionally, Susteon is currently building a continuous 40 kg CO<sub>2</sub>/day solvent capture unit which should be operational in February 2025 and will use this unit to perform 1,000 hours of continuous testing with the Sustenol™ solvent with a simulated NGCC flue gas. During this testing, in addition to measuring CO<sub>2</sub> capture performance and regeneration heat duty, Susteon will also measure solvent emissions as well as effect of trace contaminants in the flue gas. Following this testing, the Sustenol™ solvent will be tested at the National Carbon Capture Center (NCCC) using their Pilot Solvent Test Unit (PSTU), which captures 5 tonnes of CO<sub>2</sub>/day from a slipstream (at 0.5 MWe) from the exhaust of the NGCC power plant for 6 months. This testing will be done to confirm the capture performance of Sustenol™ in real flue gas conditions and observe the emissions and solvent stability profile to de-risk the technology with an actual flue gas at 5 tonne/day scale. Following testing at NCCC, demonstration-scale testing is planned for 4 months at the Technology Centre Mongstad (TCM). This facility is a 100 tonne CO<sub>2</sub>/day capture plant with a 10 MW reboiler that will further validate the solvent performance and its stability at scale for commercial deployment [18].

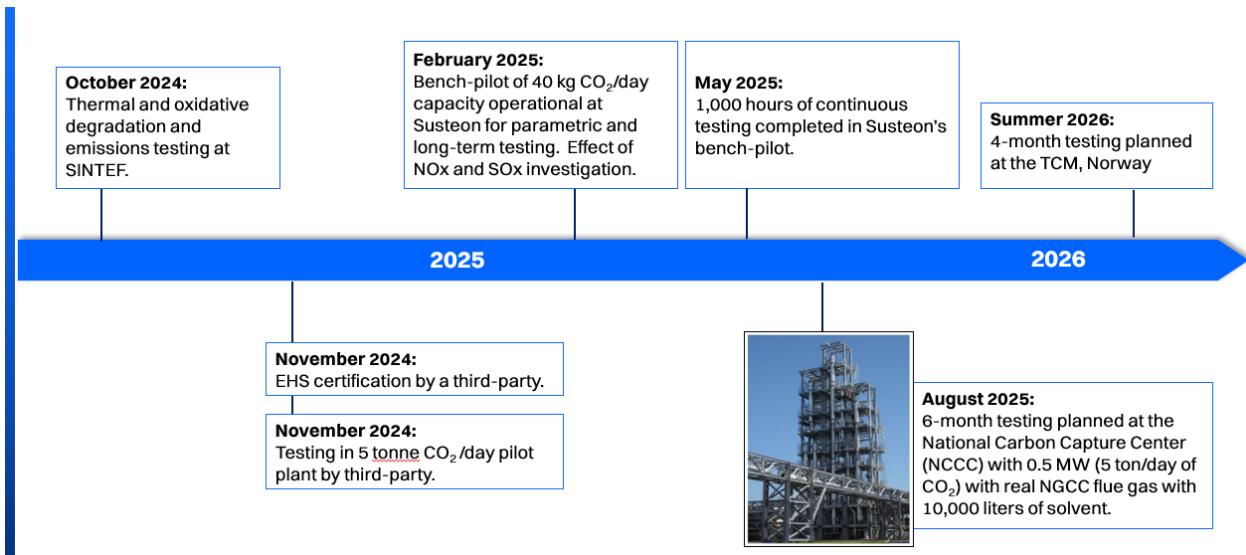


Fig. 9. Technology Advancement Plans for Sustenol™

## 6. Conclusions

Susteon has developed Sustenol™, a drop-in high performance, water-lean, mixed amine solvent with fast absorption and desorption kinetics for >95% CO<sub>2</sub> capture efficiency for an NGCC flue gas (4% CO<sub>2</sub>). The composition of the Sustenol™ solvent is optimized to reduce regeneration energy duty, to increase absorption reaction kinetics, enhance CO<sub>2</sub> absorption capacity and reduce thermal and oxidative degradation through a comprehensive design of experiment testing methodology. This optimization was achieved by conducting extensive testing in a bench-scale absorber column and characterization of physicochemical properties for both rich and lean solvent samples. Results obtained from the 15 kg/day CO<sub>2</sub> bench-scale column were then validated in a 1 tonne/day pilot plant at PDEU. At a low L/G ratio of 0.7, Sustenol™ exhibited >90% CO<sub>2</sub> removal from a simulated NGCC flue gas containing ~4% CO<sub>2</sub>. The regeneration heat duty for Sustenol™ in bench-scale tests was ~2.16 GJ/tonne of CO<sub>2</sub>, which was 44% lower than 30 wt% MEA. Pilot-scale testing at PDEU validated bench-scale testing results and demonstrated that Sustenol™ can achieve 96% CO<sub>2</sub> capture efficiency at half the L/G ratio than 30 wt% MEA. This PDEU testing also demonstrated a 61% reduction in regeneration energy using Sustenol™ compared to 30 wt% MEA in over 7 hours of continuous testing at >96% CO<sub>2</sub> capture from a simulated NGCC flue gas.

All results obtained from testing at bench and pilot scale were used to develop a comprehensive TEA for Sustenol™. This TEA showed an estimated 42% reduction in capture cost for 97% CO<sub>2</sub> removal from an NGCC flue gas and 37% reduction for 90% removal compared to the cost of capture using 30 wt% MEA. The TEA results demonstrated that CO<sub>2</sub> capture cost can be reduced to below \$50/tonne using Sustenol™. Susteon has developed a technology roadmap to bring the cost of CO<sub>2</sub> capture to <\$45/tonne for the NGCC flue gas with further advancements in the technology.

Susteon has developed a detailed technology roadmap to de-risk this technology for commercial deployment. These derisking activities include: comprehensive solvent degradation testing, long-term testing in pilot (5 tonne/day) and demonstration scale units (100 tonne/day) with actual NGCC flue gas and engineering design studies to qualify the Sustenol™ solvent as a drop-in solvent.

## Acknowledgements

Financial support for this work was provided by the United States Department of Energy's National Energy Technology Laboratory under cooperative agreements DE-FE0032216 and DE-FE0032461. Susteon gratefully acknowledges TotalEnergies' contribution for cost-sharing and technical support.

## References

- [1] Abotaleb, et.al., Chemical and physical systems of sour gas removal: An overview from reaction mechanisms to industrial implications. *Journal of Natural Gas Science and Engineering*, Vol 106, October 2022.
- [2] Bhattacharyya, D. et. al., post-combustion CO<sub>2</sub> capture technologies – a review of processes for solvent-based and sorbent-based CO<sub>2</sub> capture. *Current Opinion in Chemical Engineering*, 2017
- [3] Neerup, R. et. al., Solvent degradation and emissions from a CO<sub>2</sub> capture pilot at a waste-to-energy plant, *Journal of Environmental Chemical Engineering*, Vol 11, 2023.
- [4] Brandl, P. et. al., A century of re-exploring CO<sub>2</sub> capture solvents. *International Journal of Greenhouse Gas Control*. Vol 120, October 2022.
- [5] Yu-Jeng, et.al., Optimum heat of absorption for CO<sub>2</sub> capture using the advanced flash stripper. *International Journal of Greenhouse Gas Control*, Vol 53, August 2016.
- [6] Shukla, C. et. al., A review of process intensified CO<sub>2</sub> capture in RPB for sustainability and contribution to industrial net-zero. *Front. Energy Res.*, 2023.
- [7] Raksa, A. et. al., Solvent Development for Post-Combustion CO<sub>2</sub> Capture: Recent Development and Opportunities. *MATEC Web of Conferences*, Vol 156, 2018.
- [8] Neveux, T. et. al., Energy Performance of CO<sub>2</sub> Capture Processes: Interaction Between Process Design and Solvent. *Chemical Engineering Transactions*, Vol 35, 2013.
- [9] Vega, F., Cano, M., Camino, S., Fernández, L. M. G., Portillo, E., & Navarrete, B. (2018). Solvents for Carbon Dioxide Capture. InTech. doi: 10.5772/intechopen.71443
- [10] Feron, P. & Cousins, Ashleigh & Jiang, Kaiqi & Zhai, Rongrong & Garcia, Monica. *An update of the benchmark post-combustion CO<sub>2</sub>-capture technology*. Fuel. 273. (2020). 117776. 10.1016/j.fuel.2020.117776.
- [11] Notz, R., et. al., A shortcut method for assessing absorbents for post-combustion carbon dioxide capture, *International Journal of Greenhouse Gas Control*. Vol 5 (2011) 413-421
- [12] Brúder, P., Grimstvedt, A., Mejell, T., & Svendsen, H.F. (2011). CO<sub>2</sub> capture into aqueous solutions of piperazine activated 2-amino-2-methyl-1-propanol. *Chemical Engineering Science*, 66, 6193-6198.
- [13] Arunkumar Samanta, S.S. Bandyopadhyay, Absorption of carbon dioxide into aqueous solutions of piperazine activated 2-amino-2-methyl-1-propanol, *Chemical Engineering Science*, Volume 64, Issue 6 (2009) 1185-1194, ISSN 0009-2509, <https://doi.org/10.1016/j.ces.2008.10.049>.
- [14] Feron, P. & Cousins, Ashleigh & Jiang, Kaiqi & Zhai, Rongrong & Garcia, Monica. *An update of the benchmark post-combustion CO<sub>2</sub>-capture technology*. Fuel. 273. (2020). 117776. 10.1016/j.fuel.2020.117776.
- [15] Du et al., Zero-and negative emissions fossil-fired power plants using CO<sub>2</sub> capture by conventional aqueous amines. *International Journal Greenhouse Gas Control* 111 (2011)103473 (1-14).
- [16] Schmitt, T.S. Leptinsky, M. Turner, A. Zoelle, M. Woods, T. Shultz, and R. James, Fossil Energy Baseline Revision 4a,” National Energy Technology Laboratory, Pittsburgh, October 14, 2022.
- [17] Costs estimated using the NETL baseline 2021 costing methodology. Theis, J. Costing Estimation Methodology for NETL Assessments of Power Plant Performance. National Energy Technology Laboratory. U. S. Department of Energy, February 2021.
- [18] Kermani, S.H. Putta, K.R. Øi, L.E. “Optimum Conditions and Maximum Capacity of Amine-Based CO<sub>2</sub> Capture Plant at Technology Centre Mongstrand”, ChemEngineering 2024, 8, 114.