Development of a Novel Gas Pressurized Stripping Process-Based Technology for CO_2 Capture from Post-Combustion Flue Gases

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DISCLAIMER

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ABSTRACT

A novel Gas Pressurized Stripping (GPS) post-combustion carbon capture (PCC) process has been developed by Carbon Capture Scientific, LLC, CONSOL Energy Inc., Nexant Inc., and Western Kentucky University in this bench-scale project. The GPS-based process presents a unique approach that uses a gas pressurized technology for CO_2 stripping at an elevated pressure to overcome the energy use and other disadvantages associated with the benchmark monoethanolamine (MEA) process. The project was aimed at performing laboratory- and bench-scale experiments to prove its technical feasibility and generate process engineering and scale-up data, and conducting a techno-economic analysis (TEA) to demonstrate its energy use and cost competitiveness over the MEA process.

To meet project goals and objectives, a combination of experimental work, process simulation, and technical and economic analysis studies were applied. The project conducted individual unit lab-scale tests for major process components, including a first absorption column, a GPS column, a second absorption column, and a flasher. Computer simulations were carried out to study the GPS column behavior under different operating conditions, to optimize the column design and operation, and to optimize the GPS process for an existing and a new power plant. The vapor-liquid equilibrium data under high loading and high temperature for the selected amines were also measured. The thermal and oxidative stability of the selected solvents were also tested experimentally and presented. A bench-scale column-based unit capable of achieving at least 90% CO_2 capture from a nominal 500 SLPM coal-derived flue gas slipstream was designed and built. This integrated, continuous, skid-mounted GPS system was tested using real flue gas from a coal-fired boiler at the National Carbon Capture Center (NCCC).

The technical challenges of the GPS technology in stability, corrosion, and foaming of selected solvents, and environmental, health and safety risks have been addressed through experimental tests, consultation with vendors and engineering analysis. Multiple rounds of TEA were performed to improve the GPS-based PCC process design and operation, and to compare the energy use and cost performance of a nominal 550-MWe supercritical pulverized coal (PC) plant among the DOE/NETL report Case 11 (the PC plant without CO_2 capture), the DOE/NETL report Case 12 (the PC plant with benchmark MEA-based PCC), and the PC plant using GPS-based PCC. The results reveal that the net power produced in the PC plant with GPS-based PCC is 647 MWe, greater than that of the Case 12 (550 MWe). The 20-year LCOE for the PC plant with GPS-based PCC is 97.4 mills/kWh, or 152% of that of the Case 11, which is also 23% less than that of the Case 12. These results demonstrate that the GPS-based PCC process is energy-efficient and cost-effective compared with the benchmark MEA process.

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EXECUTIVE SUMMARY

Carbon Capture Scientific, LLC (CCS), CONSOL Energy Inc. (CONSOL), Nexant Inc. (NEXANT), and Western Kentucky University (WKU) have been working together to develop a novel Gas Pressurized Stripping (GPS) process for post-combustion CO_2 capture. Cooperative Agreement DE-FE0007567 was awarded on October 1, 2011 and ended on September 30, 2015.

The proposed GPS-based process is an absorption-based, post-combustion carbon capture (PCC) technology that uses a patented GPS technology for CO_2 stripping at an elevated pressure to overcome the energy use and other disadvantages associated with the benchmark monoethanolamine (MEA) process. The project objectives include performing laboratory- and bench-scale experiments to prove its technical feasibility and generate process engineering and scale-up data, and conducting a techno-economic analysis (TEA) to demonstrate its cost competitiveness over the MEA process, aimed at advancing the GPS-based technology to the pilot-scale demonstration level.

To meet these project objectives, a combination of experimental, process simulation, and technical and economic analysis studies were applied. The major work activities and the results of these studies are summarized below.

1. Simulation study and optimization of the GPS-based process.

GPS column behavior studies were conducted using ProTreat™ software through parametric simulation studies. Favorable configuration and operating conditions for the GPS column were identified, which shows that: 1) high heat efficiency can be achieved when the heating units are placed in the top half of the GPS column and maximum of four heating units is recommended; 2) high operating pressure is favorable for high thermal efficiency and high GPS effluent CO_2 pressure, but results in high capital and operational cost; 3) higher operating temperature is favorable for better GPS column performance, but subject to solvent thermal stability; and 4) GPS column thermal efficiency exceeds 60% for the selected commercial solvents.

Thermodynamic analysis of the GPS process shows that the absorption-based CO_2 capture process is not only a CO_2 separation process, but also a thermal compression process. Hence, GPS process optimization is, in fact, a thermal compression study. Optimization of the GPS process shows that thermal compression does not increase the heat efficiency of low-pressure steam applications comparing to that for direct power generation. Meanwhile, there is an optimal operating pressure range (20 bar or less) based on balancing CO_2 compression work, pumping work, and capital equipment costs.

For a modified GPS-based PCC process design with a split gaseous stream from the GPS column, this split gaseous stream includes 20% of the overall recovered CO_2 and goes through the second absorption cycle. The remaining 80% of the overall recovered CO_2 was compressed directly as part of CO_2 product. Simulation results show that the overall energy performance for this modified GPS-based process is less than 0.22 kWh/kg CO_2.

Another alternative separation method for the GPS column product stream was also developed, which integrates a compound compression/refrigeration process into the GPS-based PCC process. This process further improves energy efficiency, because its overall energy performance is 0.198 kWh/kg CO_2.

Because the above two configurations are more complex and would incur higher capital cost, the latest optimization of the GPS-based process is a simplified version without downstream GPS product stream separation, i.e., one absorption/desorption cycle with a GPS column operating pressure of about 6 bar. The performance of this latest GPS-based process design was investigated during bench-scale testing at the National Carbon Capture Center (NCCC) host site with real coal-derived flue gas and via a detailed TEA.

2. Solvent properties study at high temperature and high CO_2 loading.

An experimental apparatus for measuring the vapor-liquid equilibrium (VLE) of CO_2-aqueous amine systems was designed, procured, assembled, and validated based on a 970-mL autoclave. The VLE data were measured for various concentrations of the CO_2/piperazine (PZ)/methyl diethanolamine (MDEA)/H_2O system and compared with ProTreat simulation results. The experimental data exhibit reasonable agreement with the simulation results at low-to-moderate CO_2 loadings, indicating that use of the simulation results provides a reasonable representation of equilibrium behavior. Better agreement between the measured and predicted results is observed as the temperature is increased. At higher CO_2 loadings (i.e., greater than ~0.6 mol/mol amine), the measured equilibrium CO_2 partial pressures become markedly higher than those predicted by ProTreat software.

Solvent thermal stability studies demonstrated that the estimated solvent loss is significantly less than the control target of 3 kg solvent/ton CO_2 captured.

Solvent oxidative stability tests showed that the estimated solvent loss is significantly less than the control target of 3 kg solvent/ton CO_2 captured.

Solvent corrosion tests indicated that while the corrosion rate depends on the material type, the overall rates are relatively low. For all types of materials, corrosion rates are less than 1.0 mils/year for temperatures less than 100°C, thereby suggesting that carbon steel could be used in equipment components that do not exceed 100°C. In comparison, equipment components that exceed processing temperatures of 80°C may benefit from stainless steel fabrication. This type of design could assist in decreasing the overall capital cost.

3. Lab-Scale experimental testing of GPS process performance

A lab-scale, packed-bed absorption column of 9 feet in packing height and 4 inches in internal diameter with two inter-stage cooling zones was fabricated to test the performance of the selected solvents with simulated flue gas. Results show that 90% CO_2 capture can be achieved at gas flow rates of less than 20 liters/min, but the percentage of CO_2 capture decreases with increasing feed gas flow rate. When the lean loading exiting the stripper decreases from 3.8 to 3.3 wt%, the 90% capture target can be achieved at gas flow rates up to 30 L/min. Similarly, at flow rates less than 15 L/min, 90% capture can be achieved with solvent lean loadings up to 4.0 wt%.

A lab-scale, packed-bed GPS column of 6 feet in packing height and 1 inch in internal diameter was fabricated to test its performance with the selected solvents. The GPS column has multiple heating locations along the column depth. The nitrogen (N_2) stripping gas is measured and incorporated at the bottom of the column. Results show that: 1) at constant operating pressure of 6 bar, the target lean loading (4 wt%) was achievable over a large range of solvent flow rates, but the CO_2 purity reduces with increasing solvent flow rate as a flow rate of 150 g/min or less is required to achieve 95% CO_2 product purity; 2) to achieve target lean loading, the required N_2 stripping gas/solvent ratio increases with increasing column operating pressure, which also reduces CO_2 product purity; 3) introducing the slipstream still enables the GPS column to be operated at the anticipated CO_2 working capacity and CO_2 purity, which indicates that use of a slipstream from the GPS column can assist in maintaining the requisite CO_2 product purity; and 4) the thermal efficiency of the GPS column (ratio of the theoretical minimum heat duty to the actual heat duty) is 64%, which is much higher than that of a traditional packed-bed column with bottom reboiler (typically 20% or less).

The secondary absorption column in the original GPS process design was fabricated by modifying the GPS column, because both column have similar operating conditions. Results show that the CO_2 concentration in the outlet gas stream is much less than the target CO_2 concentration of less than 5% though the CO_2 concentration in the outlet gas stream increases slightly with increasing operating temperature at the top of the column. This good performance is a combination of the large driving force of mass transfer at the bottom of the column and the ability to achieve thermodynamic equilibrium at the top of the column.

Flasher tests using a modified 970-mL autoclave were conducted to verify the predictions from PreTreat simulations. The results measured experimentally agree well with the data collected at 10 and 20 bar. At operating pressure of 40 and 60 bar, however, the measure CO_2 pressure was greater than those by corresponding simulation, because of increased difficulty in accurately sampling.

To seek a low capital cost alternative, a lab-scale standard rotating packed bed (RPB) was evaluated at anticipated absorption and stripping operating conditions. The results indicate that the use of RPB could reduce effectively the equipment footprint by 20 times or more, hence greatly reducing capital costs of the columns.

4. Continuous skid testing of a bench-scale GPS based process

A nominal 500 SLPM skid-mounted, column-based GPS bench unit was evaluated at the NCCC host site. The skid has dimensions of 10'6" length and 8' width. The absorber has 8'' ID and 32' height and the GPS column has 6" ID and 30' height. The skid was equipped with PLC control system and able to run without manual intervention. Parametric test results showed that:

- With increase of total flue gas flow rate, the CO_2 removal rate in the absorber is reduced while CO_2 purity from the stripper is reduced slightly;
- With increase of G/L volume ratio, the CO_2 removal rate is reduced and CO_2 purity was not affected;
- With the increase of stripper operating pressure, both the CO_2 product purity from the stripper and CO_2 removal rate in the absorber are reduced; and
- With the increase of N_2 flow rate, the CO_2 product purity is reduced but CO_2 removal rate increased.

These results agree with those obtained from the lab-scale individual unit tests and the computer simulation. After the parametric tests, the skid was transitioned to the long-term test and 24-hour operation mode. The operating conditions were maintained at which 90% CO_2 removal rate from flue gas in the absorber is achieved and CO_2 product with 95% purity from the stripper product stream (dry base) is produced. These operating conditions were determined from the parametric tests, including the operating pressure of about 6 bar and operating temperature of 120°C in the stripper. The long-term test started from late May and ended in early August 2015 and operation was fairly stable.

During the long-term tests, solvent loss was also measured. However, since the bench-scale skid system was not equipped with a solvent recovery system, the solvent loss was high at an estimated net loss rate range of 2.9-3.2 kg/day.

Energy consumption tests were conducted to evaluate the performance of the GPS technology. Excluding the sensible heat, the total reaction and stripping heat averaged 1,586 kJ/kg CO_2 captured, which is in close agreement with the computer simulation result of 1,570 kJ/kg. The sensible heat of the solvent can be estimated based on the working capacity and specific heat of the rich and lean solutions. The estimated sensible heat was in the range of 250 to 500 kJ/kg CO_2 captured.

Both parametric and long-term tests at NCCC have demonstrated that the GPS process is able to achieve 90% CO_2 removal from typical coal-derived flue gas. GPS process is also able to produce high-pressure CO_2 product with required purity. Additionally, the energy consumption of the GPS process is much lower than that of the DOE MEA baseline case.

5. Techno-economic study of GPS technology for post-combustion flue gas CO_2 capture

Comparison of the power outputs, capital and O&M cost estimates and LCOE was conducted among the DOE/NETL report Case 11 supercritical PC plant without CO_2 capture, the DOE/NETL report Case 12 supercritical PC plant with benchmark MEA-based PCC, and the nominal 550 MWe supercritical PC plant using GPS-based PCC. The results show that the net power produced in the supercritical PC plant with GPS-based PCC is 647 MW, greater than the MEA-based design. This higher efficiency is mainly due to the GPS process' much lower steam requirement and smaller CO_2 compression auxiliary power consumption. The 20-year LCOE for the supercritical PC plant with GPS-based PCC, ***not considering*** CO_2 TS&M, is 97.4 mills/kWh, or 152% of the Case 11 supercritical PC plant without CO_2 capture, which is also 23% less than that with benchmark MEA-based PCC.

A sensitivity analysis was conducted on the supercritical PC plant with GPS-based PCC to determine the impact of amine degradation on its LCOE. The base assumption is that the DFGD reduces the SOx level in the flue gas to < 1 ppmv before it enters the CO_2 absorber, minimizing amine degradation due to SOx. However, the MDEA losses are assumed to be 0.4 lb/ton of CO_2 removed due to its molecular weight being twice as high as MEA. The total amine loss could be as high as 4 to 6 lbs/ton of CO_2 recovered, as losses due to thermal, NOx and oxygen degradation are further considered on top of amine degradation due to SOx. The LCOE varies linearly with amine degradation rates of up to 8 lbs/ton of CO_2. It is estimated that the GPS LCOE increases by about 1.2 mill/kWh for every amine degradation increment of 1 lb/ton CO_2 recovered.

6. Preliminary Environmental, Health and Safety Risk Assessment

Results from engineering analysis and engineering control for the full-scale GPS-based PCC process show that: 1) the gaseous emission control system of the GPS-based process does not increase the current emissions of the power plant regulated matters, such as SO_2, NOx, particulate matter, and mercury; 2) the maximum concentration of amines emitted with the flue gas through the stack of the power plant would be below 1 ppmv; 3) the wastewater from the PCC plant can be collected and treated by an onsite water treatment facility to within the U.S. EPA standards; 4) the waste liquid of the PCC plant is heat stable salts, volatile acids and iron products from the circulating solvent solution from the solvent reclaimer; and 5) the estimated maximum waste stream is below 10 metric ton/day, which can be appropriately disposed by the power plant onsite facilities, or by an outside waste handling facility.

The potential risks of the GPS-based process effluent streams for the major EH&S issues arising from operating the process are identified and corresponding mitigation approaches and actions are summarized, which satisfy all existing EH&S regulations and guidelines related to the GPS-based CO_2 capture process design, operation and maintenance. The properties and toxicological effects of the blended amine solvent solution of MDEA, PZ and water are also summarized.

7. Major conclusions and recommendations

The major conclusions of the project are: 1) a combination of experimental, computer simulation, and techno-economic analysis was effective to identify optimal process configurations and operating conditions for the GPS technology; and 2) the GPS-based PCC process is energy-efficient and cost-effective compared with the benchmark MEA process. For integration of the GPS process into a 550-MWe PC-fired power plant, the increase in cost of electricity (COE) is approximately 23% lower than that for the benchmark MEA process.

For future work, a scale-up study of an integrated GPS-based PCC plant at a pilot-scale using a slipstream of actual flue gas is recommended. The plant is recommended to install water wash solvent recovery unit at top of absorber to avoid solvent loss and emission to atmosphere, to install a condenser or an equivalent heat recovery unit for the GPS product stream to recover solvent, and to install a flue gas scrubber to reduce amine solvent degradation.

1. INTRODUCTION

1.1 Background

Absorption by liquid solvents is the most mature technology for CO_2 capture from post-combustion flue gas. Amine-based absorption is a well-established and proven process in the chemical industry[1]. However, high energy consumption in solvent-based CO_2 capture continues to be a major hurdle for commercialization. The U.S. Department of Energy's National Energy Technology Laboratory (DOE/NETL)[2] estimates that the deployment of current post-combustion CO_2 capture technology, aqueous monoethanolamine (MEA) solution-based chemical absorption process as shown in Figure 1.1, in a new pulverized-coal power plant would decrease the plant power production by 30%.

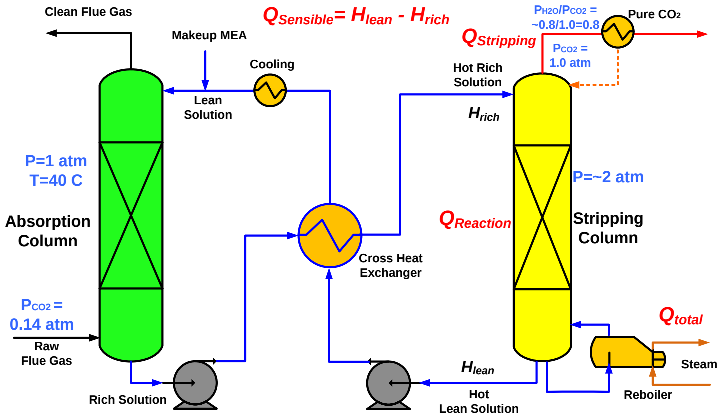

Figure 1.1. Flow diagram of conventional MEA-based absorption/stripping process

Among the energy required for CO_2 capture, steam is usually the largest to supply the heat demand for CO_2 desorption; compression work is the energy required to compress CO_2 from the operating pressure in the stripper (1.5 to 2 atm in the benchmark MEA process) to the sequestration-ready pressure (2,215 psia/152 atm); and auxiliary power uses include electricity consumption by pumps and fans. The total parasitic power loss of the baseline MEA process is 0.37 kWh/kg of CO_2 captured. Among these sources of power loss, 0.25, 0.08 and 0.04 kWh/kg of CO_2 are attributed to steam extraction, CO_2 compression, and auxiliary power use, respectively. Obviously, steam extraction to the stripper is the main cause of the total parasitic power loss.

The steam used to desorb CO_2 is extracted from the steam turbine system of the power plant. Steam extraction reduces the plant's electricity output. The resultant electricity loss depends not only on the amount, but also on the quality of steam extracted. In the stripper, the total heat consumption (Q_T) includes three components: heat of reaction or heat of absorption (Q_R), sensible heat (Q_S), and stripping heat (Q_W):

$$Q_T = Q_R + Q_S + Q_W \tag{1.1}$$

The heat of reaction is the energy used to desorb the CO_2 from the CO_2-rich solvent. The sensible heat is the energy to heat the CO_2-rich solution entering the stripper to a designated temperature. The stripping heat is the energy consumed to generate the amount of water vapor leaving the top of the stripper (per unit mass or mole of CO_2). For the baseline MEA process, Q_R, Q_S, and Q_W are approximately 1870, 990 and 690 kJ/kg of CO_2 (3,550 kJ/kg of CO_2 in total), respectively.

The high energy consumption in the baseline MEA process results mainly from the following factors: 1) the heat of reaction itself is high; 2) the limited solvent working capacity leads to a high solvent recirculation rate, which increases the sensible heat and electricity consumption by the circulation pump; 3) the low operating pressure (usually <2 atm) of the stripper results in higher CO_2 compression work; and 4) the low operating pressure of the stripper results in a high stripping heat, because the water vapor pressure in the gas stream leaving the stripper accounts for a significant portion of the total pressure at the top of the stripper.

This project aimed to develop a novel Gas Pressurized Stripping (GPS) based technology to overcome the above adverse factors associated with the baseline MEA process.

1.2 Description of the GPS technology

The cornerstone of the GPS-based technology is the GPS column. Two innovations introduced into the design of the GPS column (schematic of tray-type column is shown in Figure 1.2) overcomes the adverse factors associated with the baseline MEA process. The first innovation is that a high-pressure stripping gas is introduced into the stripping column to replace water vapor and pressurize (and hence the gas pressurized stripping) the column. Due to the introduction of a high-pressure stripping gas, the operating pressure of the column is now decoupled from the water vapor pressure and can be changed independently by changing the pressure of the stripping gas. In principle, any inert and harmless gas can be used as stripping gas. However, for CO_2 capture from power plant, nitrogen (N_2) is preferred. The impact of this innovation is that the operating pressure of the stripper can be increased well beyond approximately 2 atm. The second innovation is that heat is provided through multiple locations along the stripping column. Heat could be provided internally, as shown on the left side of Figure 1.2, where heating coils are installed on each or some trays, or externally, as shown on the right side of Figure 1.2, where liquid is extracted, heated and then pumped back to the column. Multiple heating locations eliminate temperature gradients in the stripping column. These two improvements enable the GPS column to be more thermally-efficient than conventional columns.

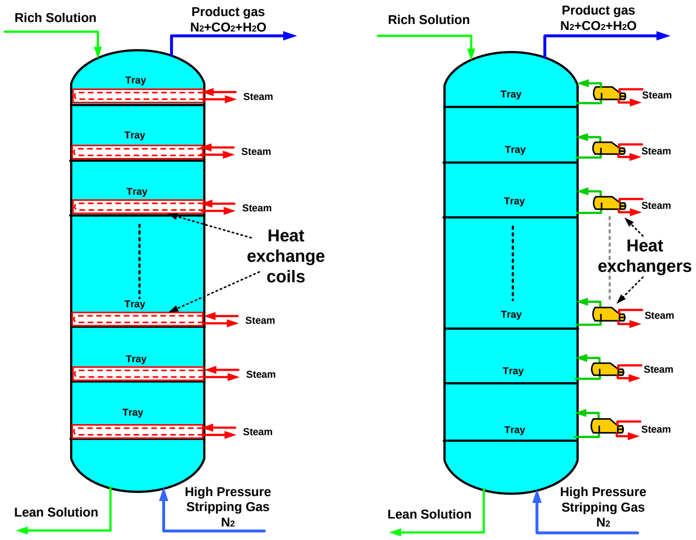

Figure 1.2. Schematic Diagram of a Tray-type GPS Column

The product gas stream from the GPS column is similar to the original flue gas in that it is a mixture of CO_2, N_2, and water vapor. The difference between the product stream of the GPS column and original flue gas is that the total pressure of the product gas stream and the partial pressure of CO_2 in it are significantly greater than those in original flue gas. A further separation method may be needed to separate CO_2 from the product gas stream. This separation can be accomplished by an additional absorption/stripping cycle, a membrane separation unit or a compression/refrigeration process to separate CO_2 from the GPS product stream. However, the GPS process has evolved greatly during the project from its original (see Figure 2.9) to the latest process configuration. Figure 1.3 illustrates the latest configuration of a GPS process, which is quite similar to a conventional MEA-based separation process shown in Figure 1.1 except that the conventional stripping column is replaced by a GPS column. Our bench-scale experimental study and computer simulation have demonstrated that with a CCS proprietary solvent the product gas can easily achieve 95% CO_2 purity, as required by DOE, at an operating pressure around 6 atm. Figure 1.4 demonstrates how the purity and operation pressure is correlated. Clearly, CO_2 purity higher than 95% product gas can be easily achieved when the operating pressure is lower than 6 atm.

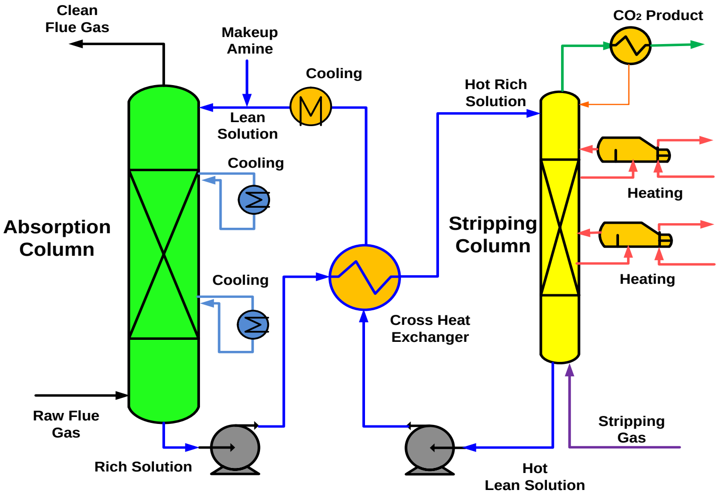

Figure 1.3. Flow diagram of GPS absorption/stripping process

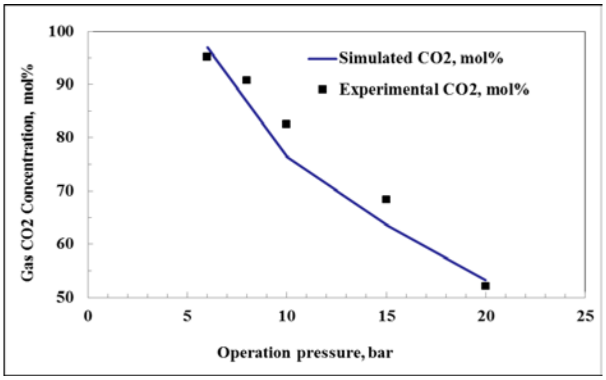

Figure 1.4. Effect of GPS column operating pressure on CO_2 product purity

The GPS process is robust and since it is a process it can be applied to a variety of solvents. Through bench-scale testing of commercially-available solvents, thermodynamic analyses and computer simulations, a piperazine (PZ) promoted N-methyldiethanolamine (MDEA) aqueous solution was identified as the current best solvent. The performance of the GPS process using this blended solvent is compared to the baseline MEA process. Table 1.1 compares the thermal efficiency among a conventional stripper (used in Case 12 Baseline Case) to both simulation and experimental data collected during bench-scale studies for the GPS column. The thermal efficiency of the GPS column is much higher than that of a conventional stripping column. Using MEA as the solvent, the conventional stripper only has a thermal efficiency of 41% - a value that excludes the sensible heat. (Sensible heat is excluded because it is not part of the stripper properties, but is related to heat exchanger technology and capital cost). In contrast, the GPS column achieves a thermal efficiency above 80% - nearly two times that of the conventional stripper used in Case 12. It is also important to note that the simulation data is comparable with experimental results.

Table 1.1. Thermal efficiency of GPS Column and conventional stripper

Items	Conventional Stripper (MEA)	GPS Column Simulation	GPS Column Experiment
Reaction Heat kJ/kgCO_2	1,870	1,400	1,336
Stripping Heat kJ/kgCO_2	690	170	149
Stripping Column Total Heat kJ/kgCO_2	2,560**	1,570**	1,485**
Minimum Heat Required kJ/kgCO_2	1,047	1,377	1,189
Stripping Column Efficiency (%)	41	87	80

** Does not include sensible heat

1.3 Technical challenges to be addressed

One of the advantages of the GPS process is that it uses conventional absorption/stripping steps, hence off-the-shelf equipment is modified in order to implement the process. This aspect mitigates some of the technical risk of implementing the process in a power plant environment. Since the solvent used in the process is based on commercial amine solvents, technical risks associated with amines can be anticipated. As a result of the decision to perform testing of the GPS system at the National Carbon Capture Center (NCCC), additional technical risks have been identified. A summary of the technical risks and their status are outlined in Table 1.2.

Table 1.2 Technical Risk Register

Description of Risk	Probability	Impact	Risk Management (Mitigation and Response Strategies)	Status
Stability of solvent at GPS operating conditions	Moderate	Low	• Lower operating temperature of the flashers to reduce solvent loss • Reduce operating temperature of the GPS column • Add stabilization agents to solvents	Addressed in BP1 and mitigated
Solvent induced corrosion	Moderate	Low	• Select more resistant materials of construction for flashers • Add corrosion inhibitors	Addressed in BP2 and mitigated
Foaming of the solvent	Moderate	Low	• Add anti-foaming chemicals	Addressed in BP2 and mitigated
Economics of the GPS process is not favorable	Low	High	• Identify the process units which are critical to the process economics • Analyze the issues related to the high capital cost	Examined in BP1, resulted in revisions to BP2 and BP3 to improve economics
Environmental, health and safety (EH&S) risk (e.g. nitrosamines)	Moderate	Moderate	• Identify the issues and propose mitigation pathways • Change solvent formulation • Replace solvent	Addressed in BP2 and BP3
Logistics related to NCCC testing of GPS system	High	High	• Schedule long lead time items • Prepare spare parts and materials that are most likely needed during system commissioning and maintenance • Interact closely with NCCC on CCS's test plan, and NCCC's facility schedule	Addressed in BP2 and BP3

The first technical risk was evaluated in BP1. Results demonstrated that the solvent was stable at GPS operating conditions. The second technical risk, corrosiveness of the solvent, was addressed in BP2. The corrosiveness of amine solutions under the planned operational conditions is well understood and methods to mitigate corrosion have been developed. If the corrosiveness of the solvent is too high, then the proper materials of construction will be selected to reduce this effect, i.e., specifying a more corrosion-resistant material. The downside of this approach is that it could increase the capital cost, but based on preliminary techno-economic analysis, the potential increase in capital cost would be minimal. Another measure to mitigate the corrosion issue is to add a corrosion preventing agent in the solvent. The third risk was related to the foaming of the solvent. Experiments with the selected solvents demonstrated that the foaming risk was minimal.

The fourth risk is the unfavorable economic performance of the GPS process. Through comprehensive efforts from computer simulation as well as experiments, CCS has identified optimal GPS-based process configurations as well as their operation conditions. And this risk has been mitigated. The fifth risk related to GPS process is the environmental, health and safety (EH&S) risk. Since the blended solvent is based on commercially-available amine solvents, it is expected that their EH&S risk profile should be well understood and contained. The potential for the formation of nitrosamines has been acknowledged by both the team and the NCCC. The NCCC took measurements to test for the potential formation of nitrosamines during testing at their facility.

The last risk was addressed through project planning (i.e., ordering of long lead time items), contracting with an external engineering firm (to assist in the design and construction of the unit to be tested at the NCCC), and close communication and cooperation with the NCCC. Specifically, CCS engineers prepared detailed test plans to fit into the NCCC operation schedule, so that as much as possible work related to commissioning, parametric testing and long-term testing could be performed during the time period when NCCC testing facility was available.

1.4 Primary goals and technical objectives

The primary goal of the project is to develop a breakthrough GPS-based technology for CO_2 capture from post-combustion flue gases. Through a comprehensive series of computer simulations, experimental work, and techno-economic analyses, the project will acquire all of the information required to advance the technology into pilot-scale.

The main objectives of the project include: 1) lab-scale tests of individual process units to document experimental results and obtain necessary information to progress the technology to the pilot-scale; 2) computer simulations to maximize the benefit of the GPS technology for existing power plants; 3) experimental investigation of selected solvents to minimize the economic risk of the proposed technology; 4) lab-scale testing of a rotating packed bed (RPB) at anticipated absorption and stripping operating conditions to evaluate performance and the potential to reduce GPS system capital costs; and 5) design, fabrication, and operating a bench-scale unit capable of processing about 500 standard liters of actual coal-derived flue gas per minute (SLPM) in conventional column-based GPS system at the NCCC host site.

The project team includes Carbon Capture Scientific, LLC. (CCS LLC), CONSOL Energy Inc. (CONSOL), Nexant Inc. (NEXANT) and Western Kentucky University (WKU). CCS LLC provides the GPS technology, CONSOL assists in the engineering and testing and provides the R&D facilities, NEXANT performs the techno-economic analysis (TEA), while WKU is a consultant on corrosion testing.

1.5 Technical approach

The proposed GPS process was a combination of two absorption/stripping cycles. The major process units include two absorption columns, one GPS column, and a series of flashers. Each of the four major process units was tested individually at lab-scale to obtain the required first-hand process design data. Two lab-scale packed columns (low and high pressure) were set up to simulate the three columns involved in the

GPS process. The low-pressure column, equipped with inter-stage cooling capability, was used to simulate the first absorption column. The high-pressure column was used to simulate the GPS column. Stainless steel was used to fabricate the high-pressure column. Inter-stage heating capability was added to the high-pressure column. Since the GPS column and second absorption column operate at identical pressure, the high-pressure packed column was also used to simulate the second absorption column with necessary modification. The flashers were tested by the same equipment (autoclave) as that used for phase equilibrium data measurement. When the autoclave was used to measure phase equilibrium data it was operated as a closed system at equilibrium state. Whereas when it was used to simulate the flashers it operated as a flow system and at a steady-state.

An absorption/stripping process involves a solvent. Certain process design data, such as solvent physical properties and phase equilibrium data, vary depending on the solvent being used. A blended PZ/MDEA solution was identified as the candidate solvent for the GPS process. Blended PZ/MDEA solution is a commercial solvent, and a great deal of its physical properties and phase equilibrium data are available in literatures or from solvent vendors. However, the operating conditions for the GPS process extend into a range (CO_2 pressure > 10 atm and T > 100°C), which may be beyond those for the conventional processes. The data in computer simulation software packages are usually extrapolated and may not be accurate enough for process design. In the project, these data were measured for the candidate solvent (blended PZ/MDEA) at GPS process operating conditions. Additionally, there are other risks that have to be managed as well. For example, stability and corrosiveness of the solvent used in the GPS process can impact the economics of the GPS process. To minimize this technical risk, the stability and corrosiveness of the blended PZ/MDEA solvent were also studied at GPS process operating conditions.

To meet the project goals and objectives, a combination of process simulation, experimental testing, and technical and economic analysis studies was applied for this project. The GPS technology has been progressively tested through computer simulation first, then experiments with each major individual unit operations in a laboratory setting at Carbon Capture Scientific's facilities, and finally at bench-scale with an integrated, continuous, skid-mounted GPS system using real flue gas from a coal-fired boiler at the NCCC. The superior energy performance of the GPS technology as predicted by computer simulations and confirmed by bench-scale GPS system tests provide a sound basis to advance the GPS technology to the next step.

1.6 Scope of the work

To meet the project objectives, a combination of computer simulations, experimental work, slipstream testing, and technical and economic analysis studies was performed. The project conducted individual unit lab-scale tests for four major process components, including a first absorption column, a GPS column, a second absorption column, and a flasher. Lab-scale testing of a RPB at anticipated absorption conditions was conducted to evaluate performance and the potential to reduce GPS system capital costs. A computer simulation task was carried out to study the GPS column behavior under different operating conditions and finally optimize the column design and operation. Two additional computer simulation tasks were then performed to optimize the GPS process for an existing and a new power plant. The vapor-liquid equilibrium data under high loading and temperature for the selected amines were measured in this project. A solvent stability study collected information on the solvent operating cost when the novel amine-based solvent was used in the GPS process. A bench-scale unit capable of achieving at least 90% CO_2 capture from a nominal 500 SLPM coal-derived flue gas slipstream was designed and built by CCS LLC for testing in a conventional GPS system operating mode at the NCCC. Lastly, the project team updated the techno-economic study and completed the EH&S risk assessment.

2. SIMULATION STUDY AND OPTIMIZATION OF THE GPS PROCESS

2.1 GPS column study and optimization

2.1.1 GPS column behavior study

GPS column is the key unit operation in the GPS-based process. Compared to conventional strippers, the GPS column is operated at higher pressure by the introduction of high pressure N_2 (with a small portion of CO_2) as the stripping gas. The use of this stripping gas simultaneously eliminates the need to use water as a stripping gas and enables high operating pressures. The use of multiple heaters along the column eliminates the need to use water vapor as a heat carrier and, most importantly, reduces the temperature gradient in the stripper. The net impact of these design changes is that the product gas is a mixture of stripping gas, CO_2, and water vapor. This results in an increased CO_2 partial pressure, but may require another separation unit downstream from the GPS column to separate CO_2 from the mixture.

The goal of GPS column behavior study is to identify favorable heating configurations and operating conditions to achieve optimal energy performance. ProTreat™,[3] a software package specifically-designed for industrial gas treating, was used in this study. Simulation results have illustrated that parameters, including the number and location of side-heating, gas/liquid ratio, operating pressure, operating temperature and CO_2 concentration in the lean stripping gas, affect the energy performance of the GPS column. Conditions were optimized through parametric studies and the original testing scheme from the Statement of Project Objectives (SOPO) is shown in Table 2.1.

Table 2.1. Variable ranges for GPS column behavior study

Variable	Concentration range (weight %)	Data point
Number of heating locations	3~15	7
Gas/liquid ratio	5~15	5
Operating pressure	20~50	5
Operating temperature	80~140ºC	7
CO_2 % in lean stripping gas	1~5%	5

The GPS column system used in the parametric simulation studies is depicted in Figure 2.1. The inflow and compositions of the rich solvent from the 1st absorption column and CO_2 concentration of effluent lean solvent to the 2nd absorption column are assumed fixed for the GPS column study. (All compositions are reported on a WEIGHT percentage). The influent solvent composition is 20% piperazine (PZ) and 30% MDEA water solution loaded with 8.35% CO_2. A criterion of the GPS column study is to keep the CO_2 concentration at 5.10% in the effluent lean solvent in order to achieve the desired CO_2 removal.

A. Placement of side-heating units. The effect of side-heating location on GPS column heat performance was investigated by four different schemes to place the four heating units in the GPS column. Scheme A places the four units evenly distributed along the GPS column depth. Scheme B places all the units evenly in top half of the GPS column. Scheme C places the heating units evenly in middle section of the GPS column. Scheme D places the units evenly in bottom half of the GPS column. These designs can be examined by maintaining the CO_2 removal, rich solvent condition, and heating temperature constant, while varying the side-heating location. The critical factor to explore is the impact of heating unit placement on the heat requirement of the GPS column for each scheme. To reach a desired CO_2 removal, the stripping gas inflow rate was adjusted with each scheme. As shown in Figure 2.2 and Figure 2.3, scheme B (heating in top half) has the maximum effluent gas CO_2 pressure and the minimum heat requirement while scheme D (heating in bottom half) has minimum effluent gas CO_2 pressure and the maximum heat requirement. These results illustrate that high heat efficiency can be achieved when the heating units are placed in the top half of the GPS column. Therefore, placement of side-heating units in the top section of the GPS column is the most favorable to improve GPS column performance.

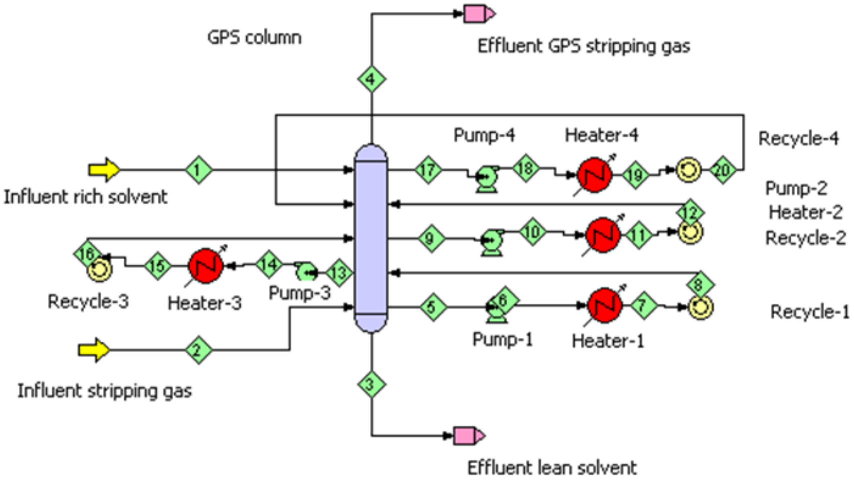

Figure 2.1. Flow-diagram for GPS column study

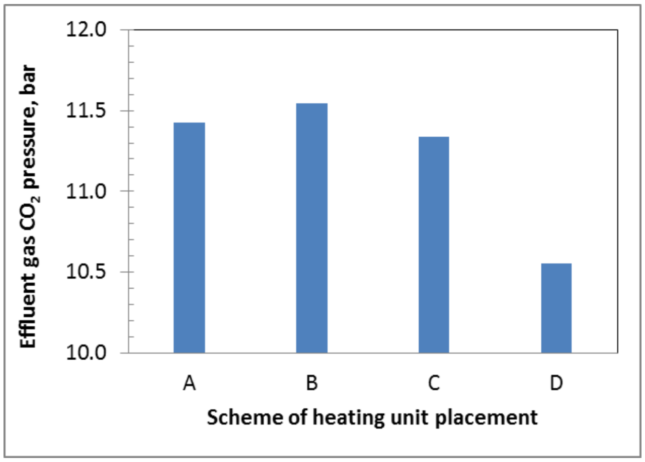

Figure 2.2. Effect of heating location on GPS column performance

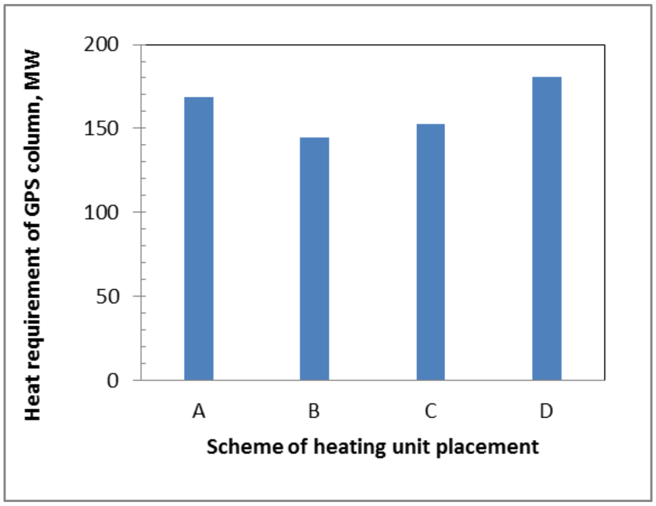

Figure 2.3. Effect of heating location on heat requirement of GPS column

B. Number of side-heating units. The impact of the number of heating units on GPS column performance was also studied using a methodology similar to the one described previously for heating unit placement. Based on previous results, all side-heating units are placed in the top half section of the GPS column. Figure 2.4 demonstrates that increasing of number of side-heating units is favorable to reduce the stripping gas usage thereby increasing the CO_2 partial pressure in the effluent stripping gas. Additionally, increasing the number of side-heaters improves operation conditions of the GPS column from a thermodynamic point of view. This may reduce the packing depth thus reducing the capital cost of the GPS column. On the other hand, increasing of number of side-heating units also increases their own capital and operation cost. Therefore, the selection of the number of side-heaters is a trade-off between capital cost, operation cost and GPS column performance. As shown in Figure 2.4, the increase of effluent gas CO_2 pressure is reduced when the number of heating units is four or more. In addition, for a given number of side-heating units, the heat duty of a heating unit decreases when the unit is placed away from the top of the GPS column. In other words, a heating unit becomes less important when it is placed lower than other units. Therefore, a maximum of four heating units is recommended based on the simulation results.

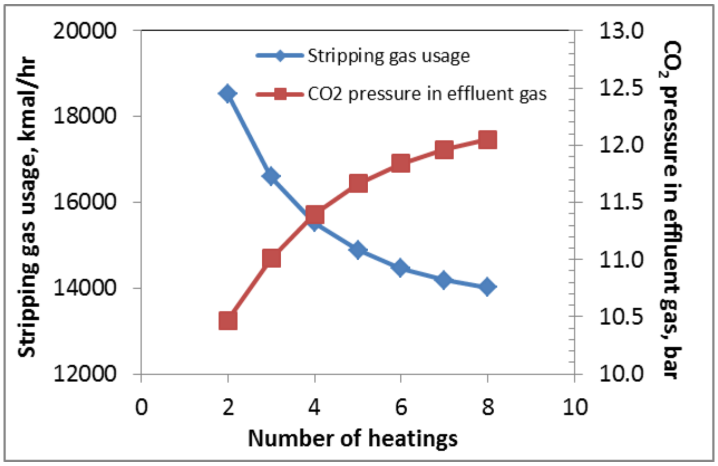

Figure 2.4. Effect of number of side-heating units on GPS column performance

C. GPS operating pressure. Figure 2.5 illustrates the effect of GPS operating pressure on effluent CO_2 partial pressure and gas/liquid (G/L) ratio under operating temperature of 120°C. The G/L ratio increases linearly with increasing operating pressure, because more stripping gas is required to maintain a higher operating pressure. It is expected that the CO_2 partial pressure of the effluent stripping gas increases with increasing operating pressure. However, the rate of this increase appears to slow down, thus resulting in the partial pressure approaching an asymptotic value. On the other hand, increasing operating pressure increases the power duty of the solvent circulation pumps and capital cost for the equipment due to high operating pressure. This behavior indicates that an optimal operating pressure range exists based on a trade-off between the GPS column performance and capital and operation costs.

D. GPS operating temperature. The GPS column operating temperature has a great impact on the column operation and performance. Figure 2.6 shows that the influent stripping gas usage required for the desired CO_2 removal rate decreases rapidly with increasing operating temperature, which results in a significant increase of effluent CO_2 partial pressure from 0.9 bar at 80°C to 19.6 bar at 140°C. Although the stripping heat represented by effluent water vapor flow rate decreases rapidly with increasing operating temperature, the overall heat requirement of GPS column increases by 11.9% with operating temperature from 80°C to 140°C owing to the increase of heat capacity and reaction heat of the amine solvent, as illustrated in Figure 2.7. Comparing to the great increase of product CO_2 gas pressure, higher operating temperature is favorable for better GPS column performance. Unfortunately, the amine solution is subject to rapid degradation when operating temperature is above 120°C, as discussed subsequently in Section 4.

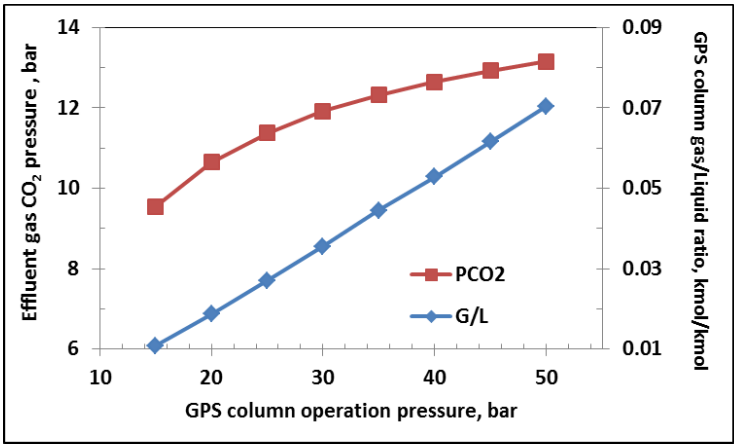

Figure 2.5. Effect of operation pressure on GPS performance

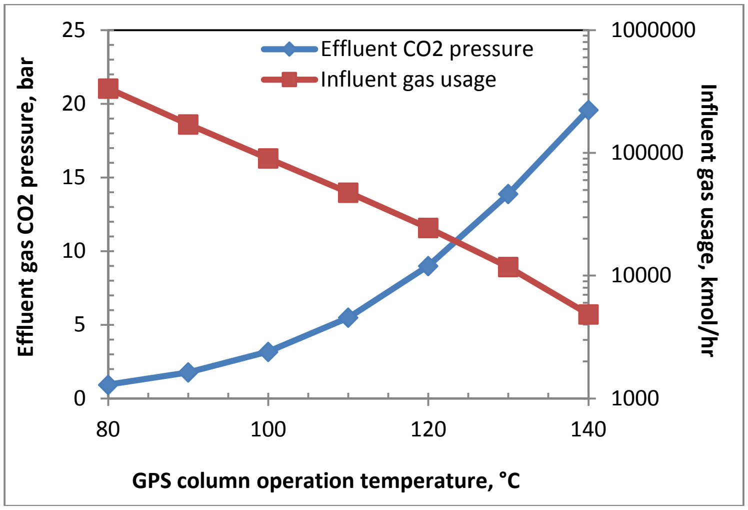

Figure 2.6. Effect of operation temperature on GPS column product performance

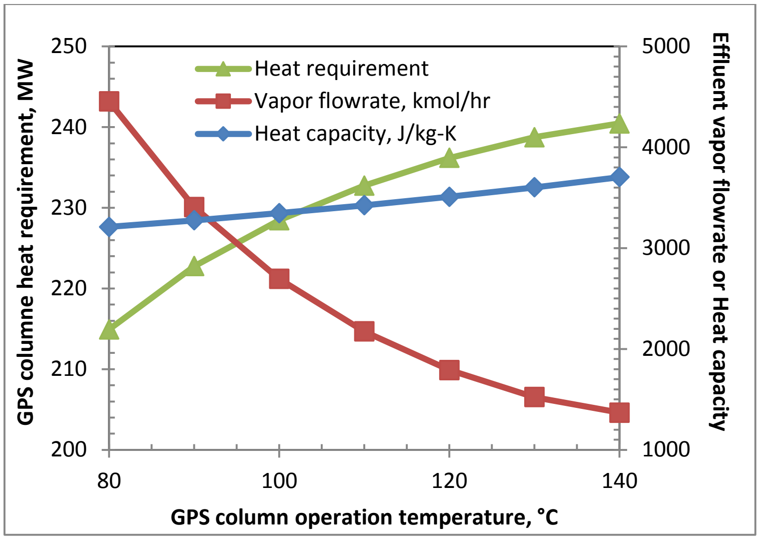

Figure 2.7. Effect of operation temperature on GPS column energy performance

E. CO_2 concentration in stripping gas. Figure 2.8 demonstrates the effect of CO_2 concentration in stripping gas on effluent CO_2 partial pressure and G/L ratio under an operating pressure of 30 bar and temperature of 120°C. With increasing CO_2 concentration in influent stripping gas, more influent stripping gas is required to reach the criterion of CO_2 concentration in lean solvent, which results in rapid increase of G/L ratio and decrease of CO_2 partial pressure in effluent stripping gas. The CO_2 concentration in stripping gas of the GPS column also depends on the performance of the 2nd absorption column. An optimal CO_2 concentration in stripping gas was investigated in subsequent optimization of overall GPS process discussed in next subsection.

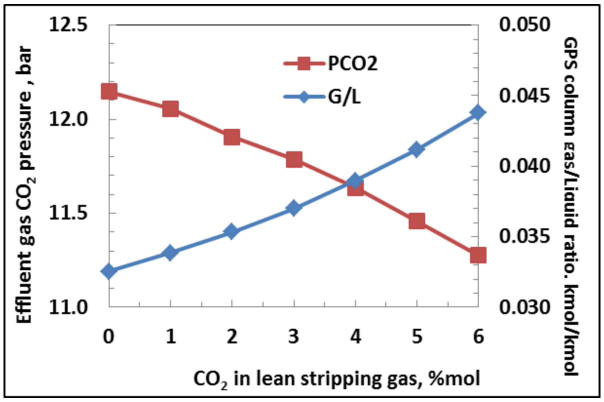

Figure 2.8. Effect of lean solvent CO_2 concentration on GPS performance

Based on the evaluating parameters and ranges outlined in Table 2.1, it has been determined that the best design to this point is up to four side-heating units in the top half section of the GPS. For G/L ratio, it cannot be investigated independently as it depends on given operating conditions and a desired CO_2 removal. In other words, it is used as an adjusted parameter to achieve a desired CO_2 removal under given conditions. For the effect of operating pressure, high operating pressure is favorable for high thermal efficiency and GPS effluent CO_2 pressure, but results in high capital and operational cost. Therefore, there is an optimal operating pressure, which is discussed in next subsection. For operating temperature, high operation temperature is beneficial for high GPS effluent CO_2 pressure, but depends on the solvent properties. For the CO_2 concentration in the inlet stripping gas, increasing the CO_2 concentration in stripping gas reduces the GPS column performance by decreasing CO_2 partial pressure in effluent stripping gas. Because the CO_2 concentration in stripping gas is also affected by the performance of 2nd absorption column, an optimal CO_2 concentration in the stripping gas was investigated in subsequent optimization of the overall GPS process.

2.1.2 GPS Column Optimization and Thermal Efficiency Estimation

Optimization of the GPS column depends on the overall GPS technology-based processes, because any changes of operating condition in the GPS column would impact other unit operations, including the 1st and 2nd absorption columns as well as subsequent flashers. Optimization of the GPS process is based on Case 12 in the DOE/NETL report (NETL, August 2007)[4] as the base case. The difference of this optimization study from Case 12 is that the MEA-based CO_2 absorption system is replaced by the GPS process. The baseline Case 12 is a nominal 550 MWe supercritical PC power plant with 90% CO_2 capture. The properties of this flue gas are listed in Table 2.2.

The flow diagram for the original GPS process for CO_2 capture from flue gas is shown in Figure 2.9. Two types of blended amine-water solution were tested respectively in optimization simulation: 20%/30%/50% and 15%/35%/50% (PZ/MDEA/H_2O). Nitrogen gas was used as stripping gas. The goals of the GPS process optimization are to minimize the energy use and to remove 90% of CO_2 from the flue gas.

Table 2.2. Flue gas composition and conditions.

Parameter	Unit	Value
Flow rate	kg/hr	3,122,000
Temperature	°C	57
Pressure	kPa	104
Flue gas composition		
N_2	vol%	67.71
O_2	vol%	2.35
CO_2	vol%	13.26
H_2O	vol%	16.68

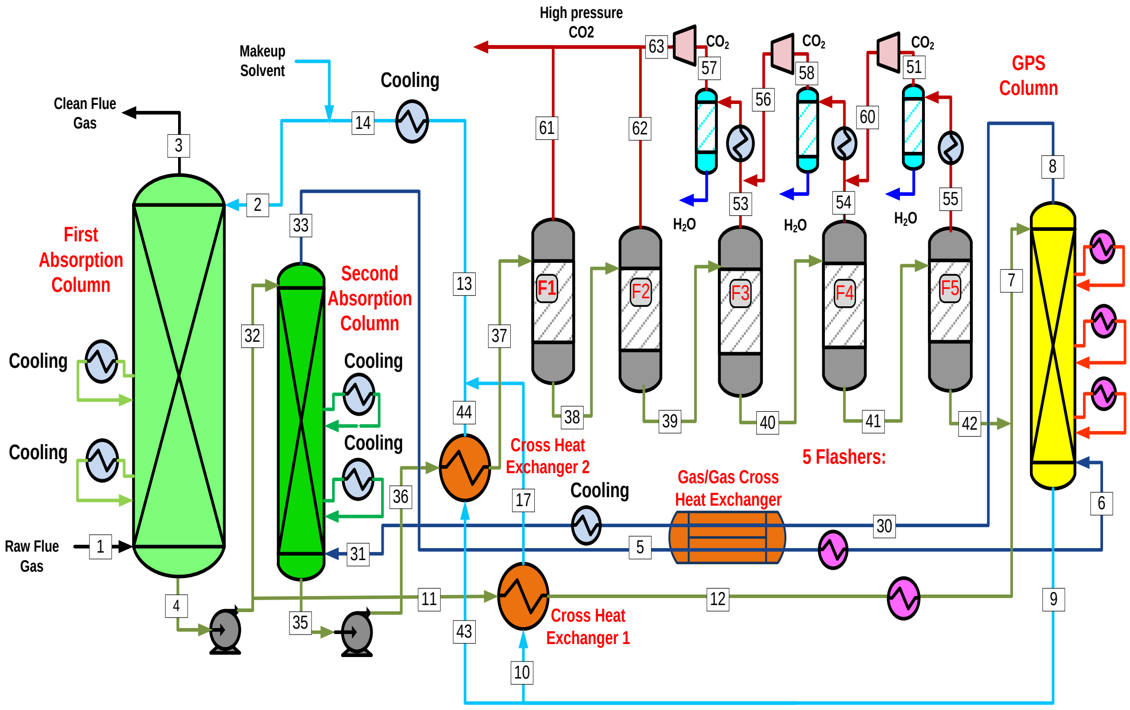

Figure 2.9. Flow diagram of multi-cycle GPS process for CO_2 capture from flue gas

Design and operation parameters for the GPS process for the two types of blended solvent are shown in Table 2.3. In GPS process design, packed-bed columns were used for the 1st and 2nd absorption columns and the GPS (stripping) column owing to their low pressure drop. Structured packing (Mellapak 170 Y) was selected for all packing columns. There are two external cooling units to remove reaction heat for both 1st and 2nd absorption columns. The side-cooling not only increases the solvent working capacity (i.e., reduces sensible heat), but also increases the CO_2 loading of the rich solution (i.e., increases the CO_2 partial pressure). There is no reboiler in the GPS column, instead, there are three sets of external heating units to supply the heat for CO_2 stripping. The temperature of the inlet rich solution stream is 120°C. Five flashers were used to release CO_2 from the second rich solution. During the simulation, the CO_2 concentration in the effluent gas and the CO_2 concentration in the influent stripping gas are maintained at the same values. Also, the CO_2 concentration in the flasher effluent is maintained at the same value as the CO_2 concentration in the influent rich solvent.

Table 2.3. Design and operation parameters for optimization of the GPS process at a 30 bar operation pressure

Equipment	Parameter	15%/35%/50% solvent	20%/30%/50% solvent
1st absorption	Packing depth, m	45	35
	Diameter, m	21.7	21.4
	Percent flooding, %	50	50
	1st cooling location, m	24	18
	2nd cooling location, m	36	30
	Packing	M170.Y	M170.Y
GPS	Packing depth, m	25	25
	Diameter, m	11.8	11.5
	Percent flooding, %	50	50
	1st heating location, m	4	4
	2nd heating location, m	8	8
	3rd heating location, m	12	12
	Packing	M170.Y	M170.Y
2nd absorption	Packing depth, m	20	20
	Diameter, m	8.6	8.6
	Percent flooding, %	50	50
	1st cooling location, m	9	5
	2nd cooling location, m	15	15
	Packing	M170.Y	M170.Y
Gas feeding	Inflow, kmol/hr	24,500	24,000
	CO_2 composition, %mol	4.0	4.0
	N_2 composition, %mol	95.7	95.7
	H_2O composition, %mol	0.3	0.3
	Temperature, °C	43.25	43.25
	Pressure, psi	435.12	435.12
	Flow rate, kg/hr	12,800,000	12,050,000
Circulation flow (Lean)	CO_2 composition, %wt	3.79	4.54
	Piperazine, %wt	14.42	19.09
	MDEA, %wt	33.65	28.64
	Working capacity, %wt	4.10	4.30
	Temperature, °C	43.25	43.25
	Pressure, psi	435.12	435.12
	Make-up H_2O, kg/hr	54,021	52,135
	Make-up MDEA, kg/hr	398	322
	Make-up PZ, kg/hr	682	1,006
CO_2 capture	Capture rate, %	90.24	90.20
	Production rate, kmol/hr	12,965	12,952
	CO_2 composition, %mol	99.71	99.71
	H_2O composition, %mol	0.23	0.23
	Temperature, °C	78.25	78.25
	Pressure, psi	1305	1305

The heat balance for the GPS column is listed in Table 2.4. For the 15%/35%/50% solvent, 19.7%, 7.7% and 72.6% of overall external heat are consumed by sensible heat, stripping heat and reaction heat, respectively. Similar results were obtained for the 20%/30%/50% solvent, sensible heat, stripping heat and reaction heat take 18.7%, 7.6% and 73.7%, respectively.

Thermal Efficiency estimation of the GPS column. The analytical minimum heat requirement of the GPS column can be estimated based on the van't Hoff Equation as follows,

$$\Delta H = -R[\ln(P_2) - \ln(P_1)]\frac{T_1 T_2}{T_2 - T_1} \tag{2.1}$$

Where, P_1, P_2 are average CO_2 partial pressures in the 1st absorption column and GPS column, respectively; T_1, T_2 are the operation temperature in the 1st absorption column and GPS column.

The average CO_2 partial pressures can be estimated by integrating the CO_2 equilibrium curves generated with ProTreat™ for the 1st absorption column and GPS column. The estimated analytical minimum heat requirements for the 15%/35%/50% and 20%/30%/50% solvents are 1,277.6 kJ/kg CO_2 and 1,289.5 kJ/kg CO_2, which lead to the GPS column thermal efficiencies (percentage of the minimum heat requirement in the sum of heat of reaction and stripping heat) of 78.5% and 79.7%, respectively.

Sensible heat was not accounted in the total heat requirement since sensible heat is the property of a solvent rather than the GPS column. Optimization of GPS process is not able to impact the sensible heat requirement. It should be noted that even including the sensible heat, GPS column is still able to achieve thermal efficiency of 60%.

Milestone Achievement. The heat balance results shown in Table 2.4 demonstrate that the GPS column thermal efficiency can easily exceed 60% for the selected commercial solvents. This result meets one of the required milestones for Budget Period (BP) 1.

Table 2.4. Heat balance for GPS column

Heat category	**15%/35%/50% solvent**	**Percentage of Total Heat (%)**	**20%/30%/50% solvent**	**Percentage of Total Heat (%)**
Overall external heat, kJ/kg CO_2	2027.45	100	1982.76	100
Sensible heat, kJ/kg CO_2	398.98	19.7	371.80	18.7
Stripping heat, kJ/kg CO2	156.65	7.7	150.10	7.6
Heat of reaction by difference, kJ/kg CO_2	1471.82	72.6	1460.86	73.7
CO_2 average pressure in GPS column, psi	82.21		84.41	
CO_2 average pressure in 1st absorption, psi	0.72		0.70	
Analytical minimum heat requirement, kJ/kg	1277.6		1289.5	
GPS column heat efficiency, %	78.5		79.7	

2.2 Optimization of GPS Process for Existing PC Power Plant

2.2.1 Overview

Simulation results have shown that the GPS process extracts less steam than the baseline MEA process. However, it may still be at levels that decrease low-pressure (LP) turbine efficiency. On the other hand, using a refrigeration process to reduce absorption temperature can improve the performance of an absorption/stripping process and reduce its heat usage. If electricity usage due to refrigeration is less than the gain due to less steam usage in refrigerated absorption/stripping process, such a refrigerated absorption/stripping process may be favorable. Optimization of GPS process was used to identify the favorable conditions for absorption temperature and assess the impact of steam extraction on LP turbine.

A. Impact of absorption temperature on steam use. The variable to be examined in this subtask is the absorption temperature of the first and second absorption columns. The temperature range to be studied will be from 0 to 35ºC for both columns with 5ºC apart.

B. Impact of steam extraction on LP turbine. Typical performance data of steam turbines with respect to steam turbine loading was collected and examined. A relationship between the efficiency and the steam loading of an LP turbine was created based on the data collected. Such relationship obtained would be used to estimate electricity loss (or gain) due to more or less steam extraction.

The original objective of GPS process optimization was to identify a favorable low absorption temperature. A lower absorption temperature would increase the rich solvent CO_2 loading and thus reduce steam extraction owing to a relatively lower stripping temperature. Based on our thermodynamic analysis, it is possible that both lean and rich solvent loading may increase with reducing absorption temperature while the solvent working capacity may not necessarily increase. The favorable consequences of low temperature absorption can be seen by the van't Hoff equation for the estimation of product CO_2 equilibrium pressure:

$$\ln\left(\frac{P^{*}_{CO_2,T}}{P^{*}_{0}}\right)=\frac{\Delta H_R}{R}\left(\frac{1}{T}-\frac{1}{T_0}\right) \tag{2.2}$$

where, $\boldsymbol{T_0}$ is the target absorption temperature and $\boldsymbol{T}$ is the GPS stripping temperature. P_0= 0.14 atm as the CO_2 equilibrium pressure in flue gas. $P^{*}_{CO_2,T}$ is the product gas CO_2 equilibrium pressure from GPS column.

Equation 2.2 demonstrates that a high CO_2 equilibrium pressure product can be obtained if $\boldsymbol{T_0}$ can be reduced and $\boldsymbol{T}$ held constant. Or if $P^{*}_{CO_2,T} / P^{*}_{0}$ remains the same, the stripping temperature can be reduced as $\boldsymbol{T_0}$ decreases in order to reduce the steam extraction. As a result, the absorption-based CO_2 capture process is not only a CO_2 separation process, but also a thermal compression process. Hence, GPS process optimization is, in fact, a thermal compression study.

2.2.2 Thermal compression may not be advantageous

Absorption-based CO_2 capture processes use heat to separate CO_2 from flue gas and to compress CO_2 thermally. The heat is often provided by LP steam extracted from LP turbines. If the steam extracted were evaluated as equivalent electric power, its equivalent heat efficiency is listed in Table 2.5 as real efficiency. If the steam has not been extracted, but used for power generation, its Carnot cycle efficiency can be estimated by the saturated temperature at the extracted pressure. Table 2.5 compares the heat efficiency for Carnot cycle efficiency and thermal compression efficiency for both MEA-based and GPS-based processes. A key factor to be investigated is the ratio of real efficiency-to-Carnot efficiency. It is anticipated that the ratio of the GPS process would be greater than one if thermal compression is more efficient. In comparison, the ratio is very close to one for both the MEA and GPS processes, i.e., real and Carnot efficiencies are nearly identical. These results imply that using thermal compression (as by the GPS process) does not increase the heat efficiency. A critical consideration in the GPS process now becomes pumping power. Increasing the operation pressure beyond certain ranges creates extra pumping power losses. Additionally, it is important to consider the impact of increased capital costs.

Table 2.5. Comparison of ratios of real heat efficiency against Carnot Cycle efficiency between MEA and GPS bases separation process.

Process	Steam P (psia)	Saturation T (°C)	Carnot Cycle Efficiency	Real Efficiency	Ratio
MEA	138	177.8	0.306	0.304	0.99
GPS	45	134.4	0.232	0.226	0.98

2.2.3 Less CO_2 partial pressure recovery above certain operating pressure

The GPS column operating pressure primarily consists of partial pressures of three components: water vapor (steam), captured CO_2 and high-pressure stripping gas (N_2). At a given operating temperature, water vapor partial pressure quickly approaches its equilibrium pressure and thus can be regarded as a constant. CO_2 partial pressure, however, approaches its equilibrium pressure slower than water vapor or N_2, as shown in Figure 2.10. Although CO_2 partial pressure increases with increasing operation pressure owing to the increase of stripping gas (N_2), the rate of CO_2 partial pressure increase decreases with increasing operation pressure. As a result, the percentage of CO_2 partial pressure as a function of total pressure decreases with increasing operating pressure. For example, the percentage of CO_2 partial pressure in total pressure decreases rapidly from 76.4%, 53.2%, and to 39.7% when operating pressure increases from 10, 20, and to 30 bar. This implies that there is an optimum range for operating pressure since there is decreasing benefit in terms of CO_2 partial pressure as the operating pressure is increased. This is especially important when considering capital equipment costs.

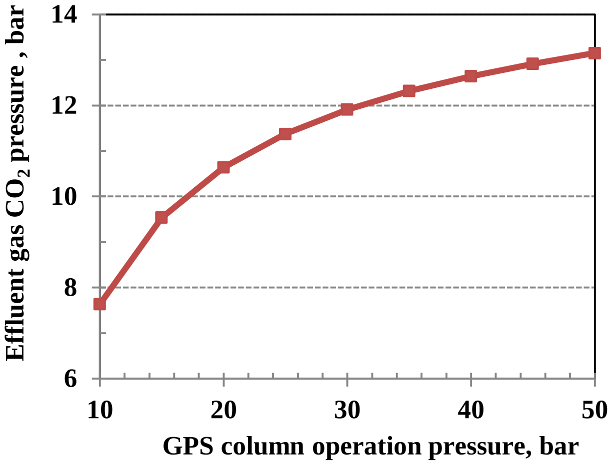

Figure 2.10. Effect of operation pressure on CO_2 partial pressure recovery for GPS process

2.2.4 Identification of Operating Pressure Range for GPS based Process

The impact of operating pressure on both compression work and pumping work is shown in Figure 2.11. Pumping work increases linearly with operating pressure, while compression work has a nonlinear relationship with operating pressure. Compression work refers to the power required to compress 1 kg CO_2 from a selected operating pressure to 100 bar. It can be seen that the reduction in the compression work as a function of operating pressure (i.e., slope of compression work plot) is quite significant when operating pressures are less than 20 bar. This reduction in compression work with increasing operating pressure decreases significantly when operating pressures are greater than 20 bar. In comparison, pumping work increases linearly with increasing operating pressure. This tradeoff illustrates a means to identify potential operating pressure ranges.

For example, consider the plot for 3% solvent working capacity. The maximum operating pressure should be less than 20 bar. This is indicated by the intersection between the compression work curve and the pumping work curves. Additionally, for solvent working capacities of 4%, 5%, and 10%, the corresponding maximum operating pressures are about 25, 30, and 40 bar, respectively. Since the GPS system typically performs at 3% solvent working capacity, the operating pressure should be maintained below 20 bar.

In sum, thermal compression does not increase the heat efficiency of LP steam applications comparing to that for direct power generation. Meanwhile, it appears that there is an optimal operating pressure range based on balancing reductions in CO_2 compression work, pumping work, and capital equipment costs. This optimum range is 20 bar or less, significantly lower than the originally planned operating range for GPS.

This has a positive impact of simplifying the GPS design and reducing other concerns related to operating the GPS process at higher pressures.

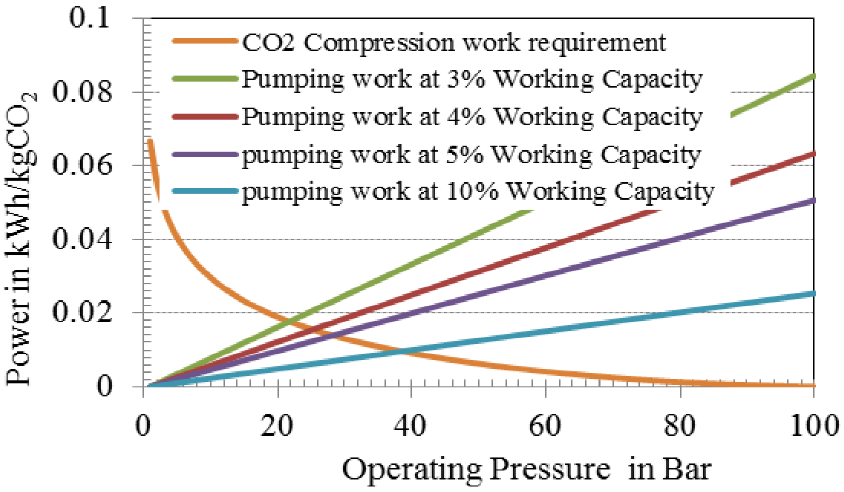

Figure 2.11. Effect of operation pressure on CO_2 compression work and pumping work

2.2.5 Overall Energy Performance of a Modified GPS based Process

According to discussions with engineers from Nexant, Inc, the steam-to-electricity conversion efficiency can be estimated through comparison of power generation and steam consumption between the well-known MEA process and the GPS process. According to Case 12 of the NETL (2007) report[3], the MEA process would generate 683.1 MWe after extracting 2.045 million lbs/hr steam at 45 psia, with a reboiler duty of 548.8 MWt. If the MEA process is replaced by the GPS process, however, the GPS process would generate 696.0 MWe after extracting 1.83 million lbs/hr steam at 45 psia, with a reboiler duty of 491.5 MWt. The conversion efficiency can be estimated by the differences of power generated and steam extraction:

Conversion efficiency = (696.0MWe-683.1MWe)/(548.8MWt-491.5MWt)

= 0.226 MWe/MWt

The overall energy performance can be estimated based on our modified GPS process design with a split gaseous stream from the GPS column, which includes **20%** of the overall recovered CO_2. Only the extracted gaseous stream goes through the second absorption cycle, the remaining 80% of the overall recovered CO_2 was compressed directly as part of CO_2 product. The flue gas data is given in Table 2.2. The GPS process shown in Figure 2.12 operates at a pressure of 8 bar. This operating pressure is determined on basis of the simulation results discussed previously. It was assumed that there was a fraction of N_2 in the CO_2 product (from top of the GPS column), thereby reducing the CO_2 product purity from 99.70% to 97.86% (dry base). Note that this purity is still better than the DOE requirement of 95%. The product specification for CO_2 produced from the modified GPS design is listed in Table 2.6. The energy performance in kWh/kg CO_2 is listed in Table 2.7. These results demonstrate that the overall energy performance is less than 0.22 kWh/kg CO_2, hence achieving the milestone set for BP2.

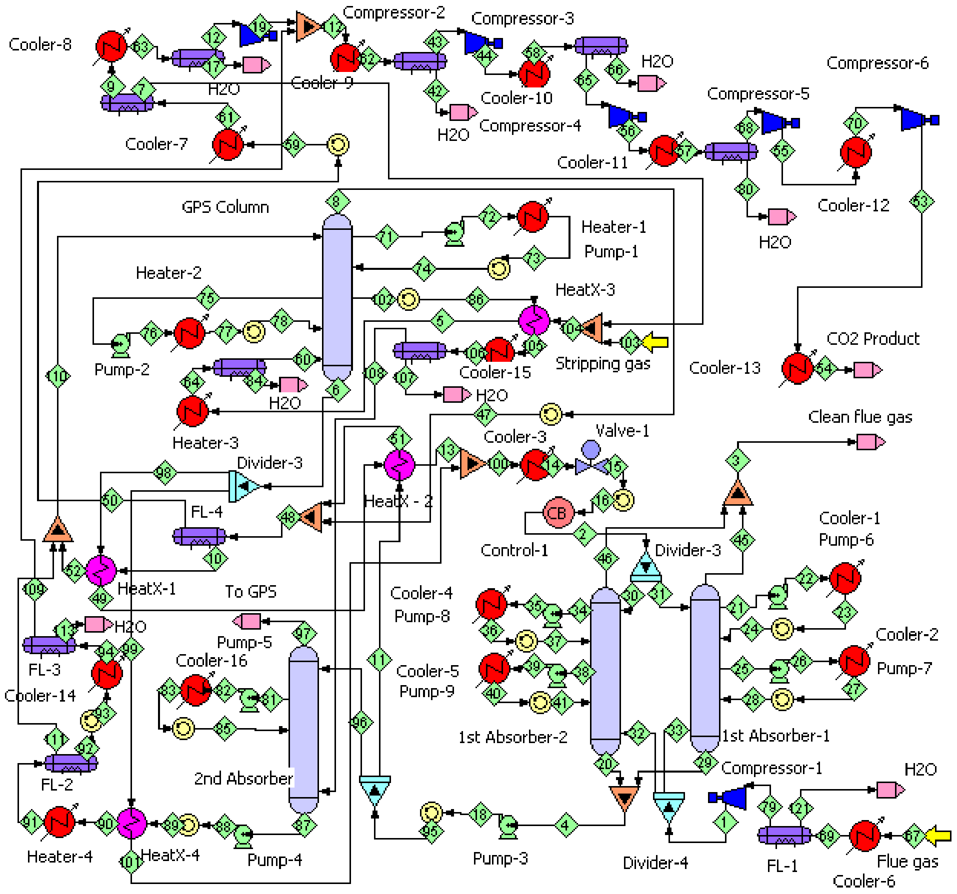

Figure 2.12. Flowchart for the modified GPS processes with split gaseous stream

Table 2.6. Product specification for the modified GPS process

Parameter	Unit	Value
Product rate	kmol/hr	13,112
Temperature	°C	40.0
Pressure	bar	153
Composition		
CO_2	%mol	97.63
H_2O	%mol	0.24
N_2	%mol	2.13

Table 2.7. Overall energy performance for the modified GPS process

Category of energy	Equivalent work MW	Energy performance kWh/kg CO_2
Heat demand for CO_2 capture	75.4	0.131
Work demand for CO_2 capture	21.0	0.036
Work demand for CO_2 compression and refrigeration	29.8	0.052
Overall energy performance	126.2	0.219

2.3 Simulation of Alternative Separation Method for GPS Product Stream

2.3.1 GPS Process with a Compound Compression/Refrigeration Separation Process

The product gas stream from the GPS column is a mixture of CO_2 and a stripping gas, such as N_2. In the initial design, the product gas stream goes through a subsequent absorption/stripping step to separate CO_2 from N_2 and recycle N_2 into the GPS column. An alternative to such design is simply to use a compression/refrigeration process to separate CO_2 from N_2 if the gas composition is unsuitable. Since the boiling points of CO_2 and N_2 are very different, such a mixture may be separated fairly easily depending on the N_2 concentration. The goal of this effort is to further reduce the overall energy performance of the GPS process to 0.20 kwh/kg CO_2, a milestone set to this project. For this purpose, simulation studies were conducted to identify an optimal N_2/CO_2 composition for the subsequent compression/refrigeration separation process. Higher N_2 concentration in the product gas stream will make the separation more difficult, whereas lower N_2 concentration may not be able to achieve the required lean loading of the amine solution unless the total operating pressure in the GPS column is reduced. The parameters to be investigated in this simulation are operating pressure, product gas N_2 concentration and refrigeration temperature.

Initially, a design that utilized the GPS column with a slipstream and 2nd absorption column was evaluated using the simulation model. It was discovered that this design was unable to achieve the energy performance milestone (equal to or less than 0.20 kWh/kg CO_2). These design iterations, though not successful, proved to be instructive since they enabled the team to uncover that it was critical to re-design the process in a fashion that would eliminate the 2nd absorption column. The re-design effort uncovered that replacing the 2nd absorption column with a downstream compression and refrigeration process significantly enhanced the overall energy efficiency of the GPS process.

The compound compression and refrigeration process improves energy efficiency, while still maintaining high-purity CO_2 product. The primary advantage of the compression/refrigeration process is elevating the pressure of gas effluent from the GPS column so as to reduce compression work and stripping heat. Figure 2.13 is a schematic for CO_2 capture from flue gas and CO_2 stripping using GPS technology. High-pressure CO_2 and N_2 mixtures are produced with GPS technology. If the GPS column does not employ a split flow, as per Figure 2.13, the CO_2 in the mixture is ~90% volume at an operating pressure of 8 bar for the same flue gas as that used in Case 12 of the DOE/NETL study[3].

The high-pressure CO_2 and N_2 mixture from the GPS column is further separated with a compound compression and refrigeration process, as shown in Figure 2.14. After dehydration, the mixture goes through three stages of compression: 8-18 bar, 18-40 bar, and 40-80 bar. The compressed gaseous mixture is cooled to 35°C after compression. After this first compression cycle, the gaseous mixture is further cooled to -5°C to liquefy the majority of CO_2 from the mixture. After the third compression cycle, the gas is cooled further to -20°C in order to further liquefy CO_2 and to ensure that the N_2 concentration meets stripping gas specifications. The remaining gases then enter three stages of expansion to recover power in the high pressure gases. The expansion cycles used were 80-40 bar, 40-18 bar, and 18-8 bar. Finally, the remaining gas stream (at 8 bar) is recycled to the GPS column for use as a stripping gas. After the second stage of compression, the pressure of the liquefied CO_2 stream is increased to 80 bar. This 80 bar CO_2 stream is mixed with streams from the third compression stage to produce CO_2 at 99.7% purity. The refrigeration heat in the cooled gases and CO_2 product are recovered through heat exchangers to 30°C.

The refrigeration heat is provided by the refrigeration process shown in Figure 2.15. Ammonia is used in the circulation. Refrigeration heat is generated by expanding high-pressure ammonia gas to low-pressure to obtain a low-temperature gas-liquid mixture. The temperature of the mixture is controlled by adjusting the expander outlet pressure.

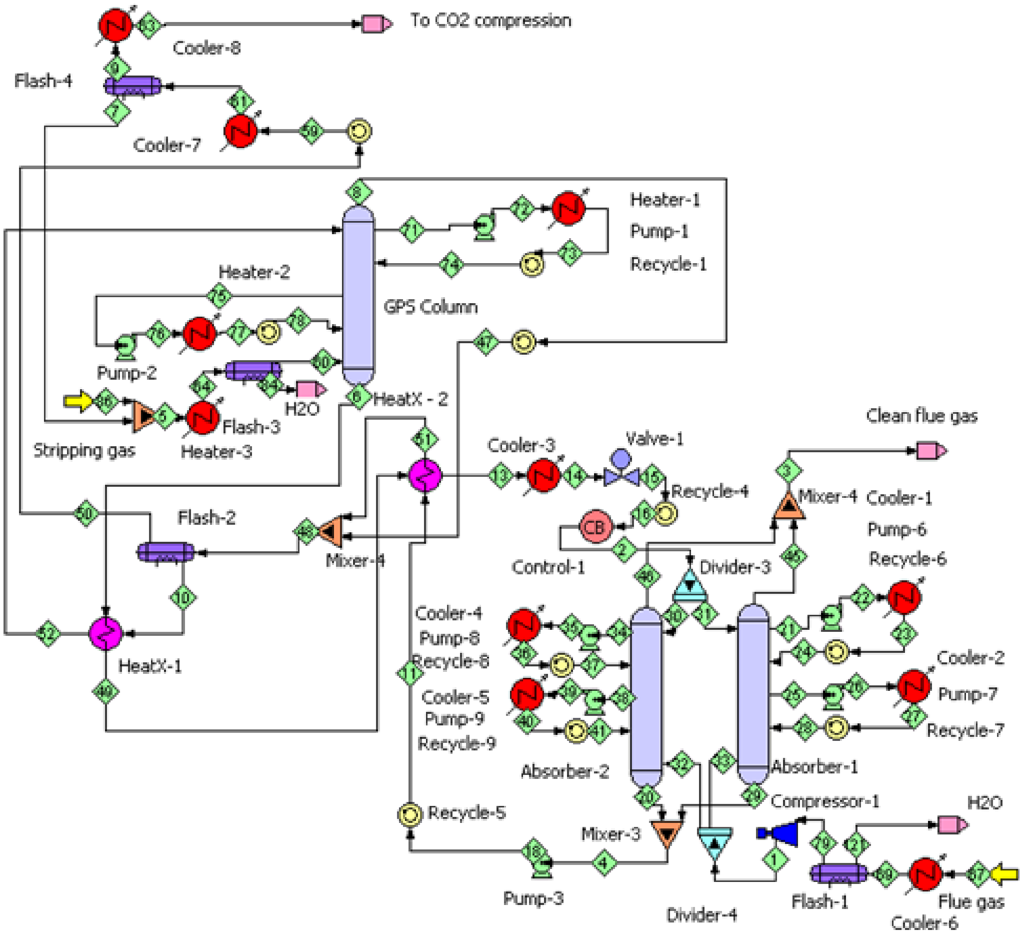

Figure 2.13. Schematic of CO_2 absorption combined with GPS process for enhanced energy efficiency

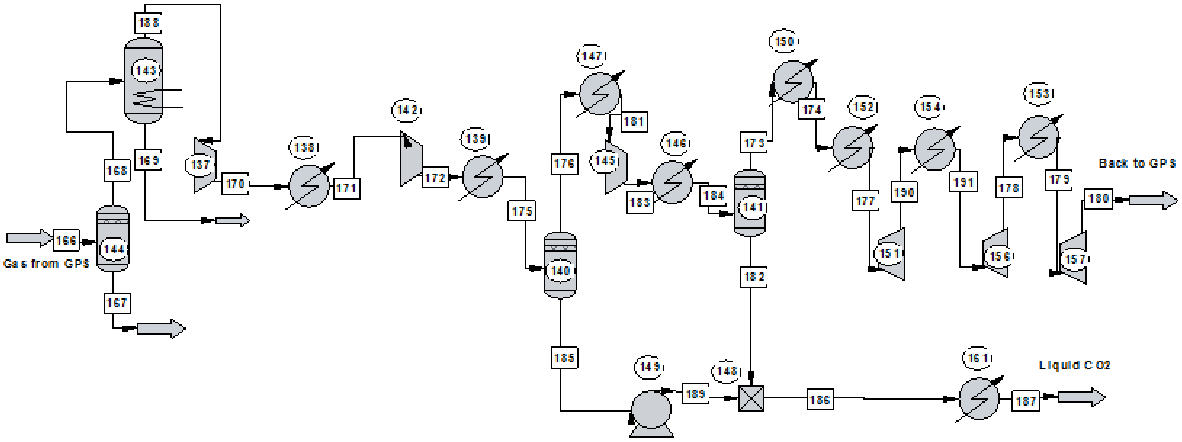

Figure 2.14. Flowchart for CO_2 cooling and compression

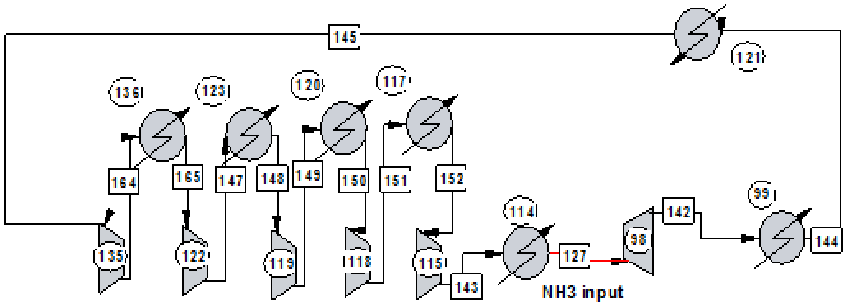

Figure 2.15. Schematic of refrigeration process

Table 2.8 summarizes the refrigeration heat demand and work demand for the compound compression and refrigeration process. Please note that the calculation for heat and work are based on 80% efficiency for all compressors, expanders, and pumps.

Table 2.8. Energy performance of compound compression / refrigeration process

Parameters	Value
Refrigeration duty category:	
Refrigeration temperature, °C	-5 to -20
Refrigeration duty, MW	-48.33
Recovered refrigeration heat, MW	-22.51
Sum of refrigeration heat demand, MW	-25.82
Work category:	
Total compression work for NH_3, MW	9.77
Total compression work for CO_2, MW	23.42
Total pumping work for liquefied CO_2, MW	0.50
Recovered work by N_2 expansion, MW	-2.78
Sum of work demand, MW	30.91

The overall energy performance is computed by combining the performance of the GPS process with the compound compression and refrigeration process. The conversion efficiency of the LP steam from heat-to-work is 22.6% (based on efficiencies for current power plants and further validated by discussions with NEXANT). When 90% CO_2 removal is achieved, the production rate for the liquefied CO_2 is 573 tonne/hr (based on Case 12 analysis). Table 2.9 summarizes the calculation of the overall energy performance. The overall energy performance of the absorption column, GPS column, and compression / refrigeration system is 0.198 kWh/kg CO_2, which is less than the milestone of 0.20 kWh/kg CO_2 originally set for BP3.

Table 2.9. Calculation of overall energy performance

Category of energy	Equivalent work MW	Energy performance kWh/kg CO_2
Heat demand for CO_2 capture	64.4	0.112
Work demand for CO_2 capture	18.0	0.031
Work demand for CO_2 compression and refrigeration	30.9	0.054
Overall energy performance	113.3	0.198

2.3.2 Simplified GPS Process without Requirement of GPS Product Gas Separation

During the computer simulation of GPS column behavior, it was revealed that lowering the operating pressure of the GPS column reduces the CO_2 partial pressure in the product gas exiting from top of the GPS column, as shown in Figure 2.10. It is interesting to note that even though the CO_2 partial pressure in the product gas decreases as the GPS column operating pressure is reduced, the concentration of CO_2 in the product gas actually increases. Clearly, if CO_2 concentration in product gas can be increased to above 95% without significantly sacrificing column thermodynamic performance, GPS column product gas will not require any further separation and the capital cost of the GPS process can be reduced. To examine this option, computer simulation related to GPS column behavior and optimization was revisited. Figure 2.16 is the reinterpretation of some computer simulation results. Clearly, as the column operating pressure is reduced from 20 to 6 bar, CO_2 concentration in effluent gas of GPS column increased from 52 to 95%. Since 95% purity (with <5% N_2) satisfies DOE requirement, no further purification would be required, thus the second absorption/stripping cycle or a downstream compression/refrigeration unit can be removed. To confirm the computer simulation results, the experimental results obtained with GPS column were also reviewed. The results are also displayed in Figure 2.16 (square marked points). The experimental data and computer simulation results follow the same trend. Due to this finding, a skid-mounted bench-scale GPS system was then designed based on this simplified GPS process, where the second absorption and flashers are eliminated entirely (see Figure 1.3). The performance of this simplified GPS process was investigated in detail at NCCC by using a skid-mounted, continuous GPS system with real post-combustion flue gas. The techno-economic performance of the same process was also studied by Nexant, Inc. The results of these studies are described in Sections 5 and 6, respectively.

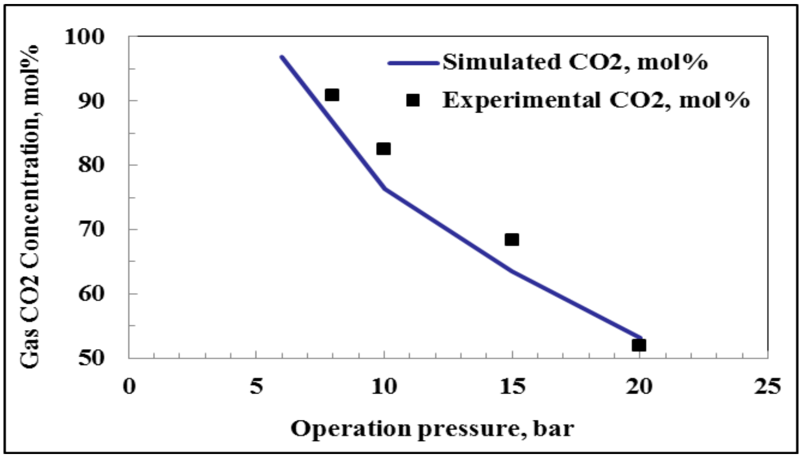

Figure 2.16. CO_2 purity and operating pressure of the GPS column

3. MEASUREMENT OF SOLVENT VLE, THERMAL AND OXIDATIVE STABILITY, AND CORROSION AT HIGH TEMPERATURE AND HIGH CO_2 LOADING

3.1 Vapor-Liquid Equilibrium Measurement of CO_2-H_2O-MDEA-PZ Systems

This section describes measurement of vapor-liquid equilibrium (VLE) behavior of the quaternary system consisting of CO_2, MDEA, PZ, and H_2O at the conditions encountered in the GPS process. VLE data for this system have become more commonplace in the literature as interest has grown in using aqueous PZ/MDEA solvents for CO_2 capture applications. However, the reported data generally cover the range of operating conditions typically used in conventional post-combustion absorption processes and, as such, are insufficient for describing the GPS process. Most studies are limited to temperatures ≤120°C, CO_2 partial pressures ≤150 kPa, and solvents containing ≤12% PZ by weight. The design of the GPS process requires an understanding of equilibrium behavior at conditions outside of those reported in the literature, including higher temperatures (up to 130°C), greater CO_2 partial pressures (up to 10,000 kPa), and more concentrated solvents (up to 25% PZ by weight). In the absence of published experimental measurements covering this range of conditions, simulations of the GPS process have relied upon equilibrium conditions estimated using ProTreat software (Optimized Gas Treating, Inc., Houston, TX). Therefore, experimental VLE measurements were performed to fill the gaps in the published data and confirm or improve upon these ProTreat estimates, leading to the development of more accurate design and process simulation results for the GPS process.

3.1.1 Experimental system setup

An experimental apparatus for measuring the VLE of CO_2-aqueous amine systems was designed, procured, assembled, and validated. The centerpiece of the apparatus is a 970-mL autoclave supplied by Parr Instrument Company (Moline, IL), which is constructed from T316 stainless steel and rated for a maximum allowable working pressure of 2,900 psi at 350°C. The autoclave, which is outfitted with a variable-speed stirrer, 1,000-W heating jacket assembly, internal cooling coil, thermowell with Type J thermocouple, pressure gauge, rupture disc, gas/liquid sampling vessel, and programmable controller, was ordered in December 2011 and shipped in February 2012. It then was integrated with a vacuum pump (for evacuating the autoclave prior to performing the VLE measurements), a CO_2 cylinder and set of CO_2 buffer tanks (for introducing a measured amount of CO_2 into the autoclave), a liquid introduction system (for introducing a measured amount of aqueous amine solvent into the autoclave), a personal computer (for data logging), and all required instrumentation, tubing, valves, and pressure relief devices. A photograph of the experimental apparatus is presented in Figure 3.1.

The experimental procedure for the VLE measurements was developed to be consistent with the procedure employed by a number of previous studies reporting similar measurements for CO_2-aqueous amine systems.[5-10] In general, it relies upon: 1) evacuating the autoclave using the vacuum pump, 2) introducing a measured quantity of aqueous amine solvent (prepared to the desired composition) into the autoclave using the inside vacuum, 3) measuring the vapor pressure of the aqueous amine solvent at each temperature for which a VLE measurement will be made, 4) introducing a measured quantity of CO_2 into the autoclave from the buffer tanks (to achieve the approximate desired CO_2 loading), 5) measuring the total pressure in the autoclave at equilibrium for each temperature of interest, 6) calculating the equilibrium partial pressure of CO_2 at each temperature of interest based on the measured vapor pressure and total pressure, and 7) calculating the actual CO_2 loading in the liquid phase (mol CO_2 / mol amine) at equilibrium based on the measured charges of CO_2 and aqueous amine solvent in the autoclave, the composition of the solvent, the equilibrium temperature and CO_2 partial pressure, and the estimated liquid level in the autoclave.

The vapor pressure measurements and equilibrium total pressure measurements are made in duplicate (once during heating and once during cooling of the autoclave) in order to establish repeatability and check for hysteresis (which could result if solvent degradation occurs during the course of the experiments). A detailed protocol was developed to document this experimental procedure and all related safety considerations. Both the protocol and the experimental apparatus underwent a comprehensive safety review, in accordance with the guidelines specified in the CONSOL R&D Safety Manual, before any experimental work was initiated.

Figure 3.1. Photograph of the experimental apparatus for solvent VLE measurements.

To validate the performance of our experimental apparatus and procedure, VLE measurements were made for the ternary system consisting of CO_2 and 48.9% (w/w) aqueous MDEA at temperatures ranging from 40-100°C and CO_2 loadings ranging from 0.1-1.1 mol/mol amine. Results were compared with experimental VLE data for the same system reported by Jou et al[11] and with simulated VLE data derived using ProTreat software. These comparisons are depicted graphically in Figure 3.2. In general, the VLE data measured using the apparatus agreed well with both the simulated data and the previous experimental results, confirming the accuracy of our approach.

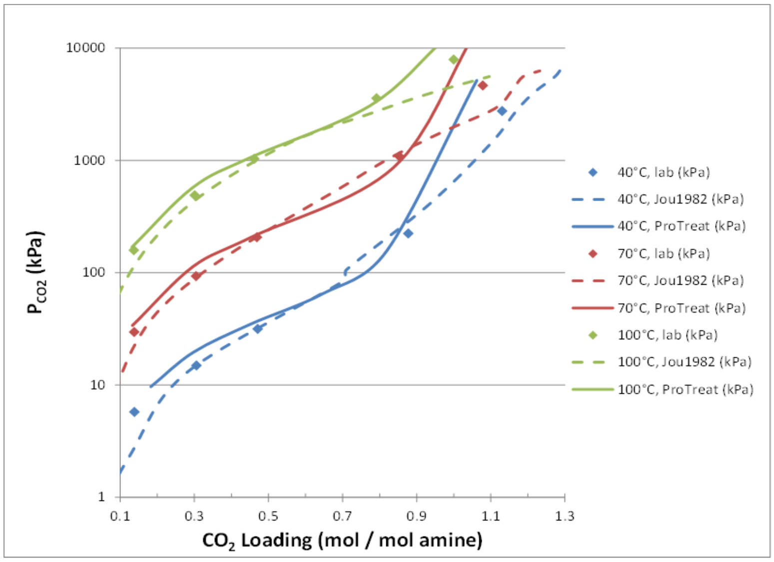

Figure 3.2. VLE measurements for CO_2 in 48.9% (w/w) aqueous MDEA solvent. Data are compared with the results of Jou et al.[11] and with ProTreat simulation results.

3.1.2 Solvent VLE Data Measurement

The purpose of VLE measurement, focused on the aqueous PZ-MDEA solvent proposed for use in the GPS process, is to generate VLE data at temperatures, CO_2 loadings, and solvent compositions that have not been studied in previous experiments, but that represent potential operating conditions for the GPS process. The original experimental matrix of VLE measurements was revised to better align with the expected GPS process operating conditions, as determined through CCS LLC's process simulation and experimental work during BP1. The revised matrix, shown in Table 3.1, includes VLE measurements at 297 sets of conditions.

Table 3.1. Experimental matrix for solvent VLE measurement.

Variable	**Original Design**		**Current Design**	
	Range	**Number of Data Points**	**Range**	**Number of Data Points**
PZ/MDEA wt%	30-50	3	10-20% PZ 30-40% MDEA	3
Temperature (°C)	30-140	12	30-130	11
CO_2 Loading (mol CO_2 /mol amine)	0.4-1.0	7	0.1-0.9	9
Total Data Points		252		297

* The actual number of experimental data points may be less than the number indicated in the table, because the system pressure may exceed safe operating limits at certain temperatures and CO_2 loadings. The autoclave will only be operated up to a total system pressure of 1,500 psi.

Figures 3.3 to 3.5 present the experimentally measured VLE data for the CO_2/PZ/MDEA/H_2O system and compare these data with ProTreat simulation results. As indicated in Table 3.1, VLE measurements were performed for three different solvent compositions. Figure 3.3 presents results for solvent containing 15% PZ, 35% MDEA, and 50% H_2O by weight. Figure 3.4 presents results for solvent containing 25% PZ, 25% MDEA, and 50% H_2O by weight, and Figure 3.5 presents results for solvent containing 20% PZ, 30% MDEA, and 50% H_2O by weight.

As shown in the figures, the experimental data exhibit reasonable agreement with the simulation results at low-to-moderate CO_2 loadings (e.g., 0.3-0.6 mol/mol), indicating that use of the simulation results provides a reasonable representation of equilibrium behavior in this range. However, the experimental data and simulation results diverge appreciably at both lower and higher CO_2 loadings. This is shown more clearly in Figure 3.6, which plots the extent (percentage basis) to which the CO_2 partial pressures predicted by ProTreat differ from the experimentally measured partial pressures for the 25% PZ/25% MDEA/50% H_2O solvent.

Measurement error is a plausible explanation for the deviations observed between the measured and simulated VLE data at low CO_2 loadings and low temperatures. At these conditions, the equilibrium CO_2 partial pressures being measured (<10 kPa) are similar in magnitude to the reported accuracy of the pressure gauge (0.5% of full scale, or approximately 4 kPa), calling the validity of the experimental data into question. In general, better agreement between the measured and predicted results is observed as the temperature is increased, resulting in greater equilibrium CO_2 partial pressures that can be more reliably measured.

At higher CO_2 loadings (i.e., greater than ~0.6 mol/mol amine), the measured equilibrium CO_2 partial pressures become markedly greater than those predicted by ProTreat. This trend is consistently observed for all three solvent compositions that were studied, lending credence to the experimental results. The project team has been working to rule out alternative explanations for this behavior, and thus far has been unable to identify any potential sources of measurement error that would cause a systematic bias of the magnitude that has been observed. Some error in the ProTreat simulation results might be expected at these conditions, which are well outside the range covered by previous experiments and therefore require significant extrapolation in the model.

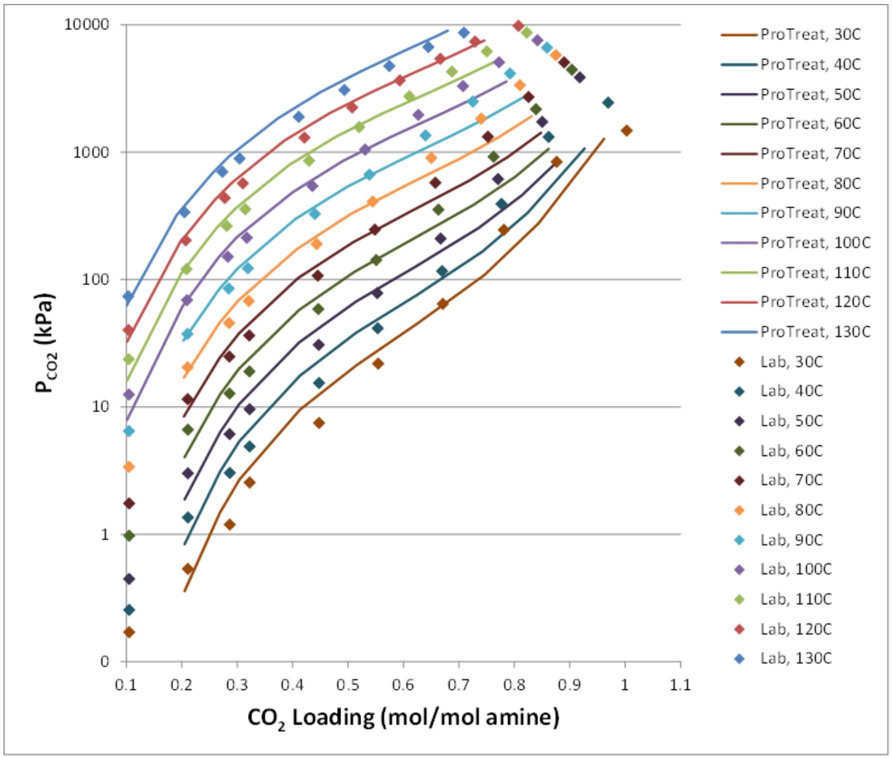

Figure 3.3. VLE measurements for CO_2 in 15% PZ / 35% MDEA / 50% H_2O (w/w) solvent. Data are compared with ProTreat simulation results.

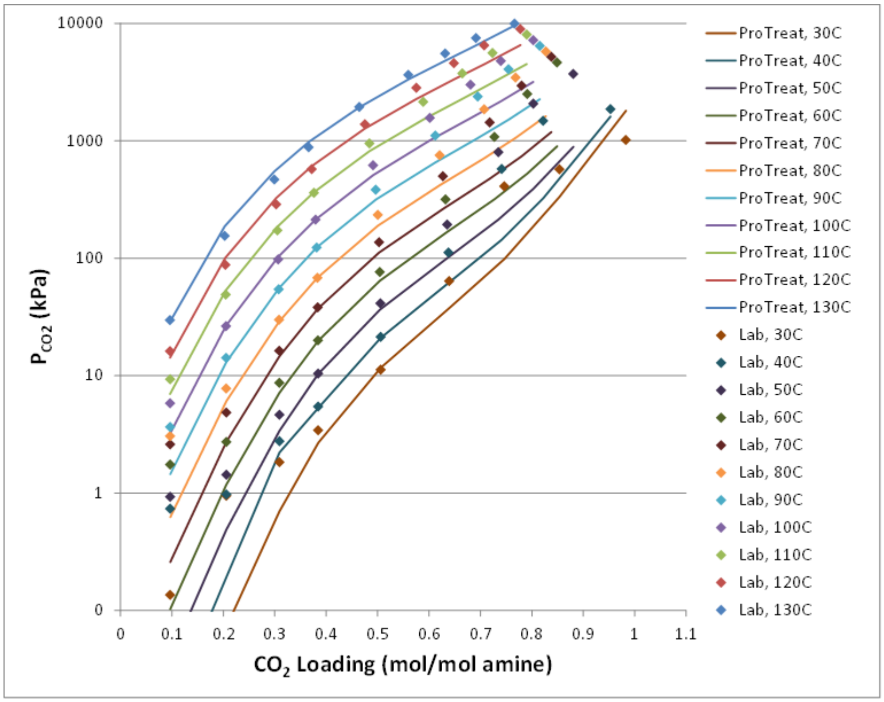

Figure 3.4. VLE measurements for CO_2 in 25% PZ / 25% MDEA / 50% H_2O (w/w) solvent. Data are compared with ProTreat simulation results.

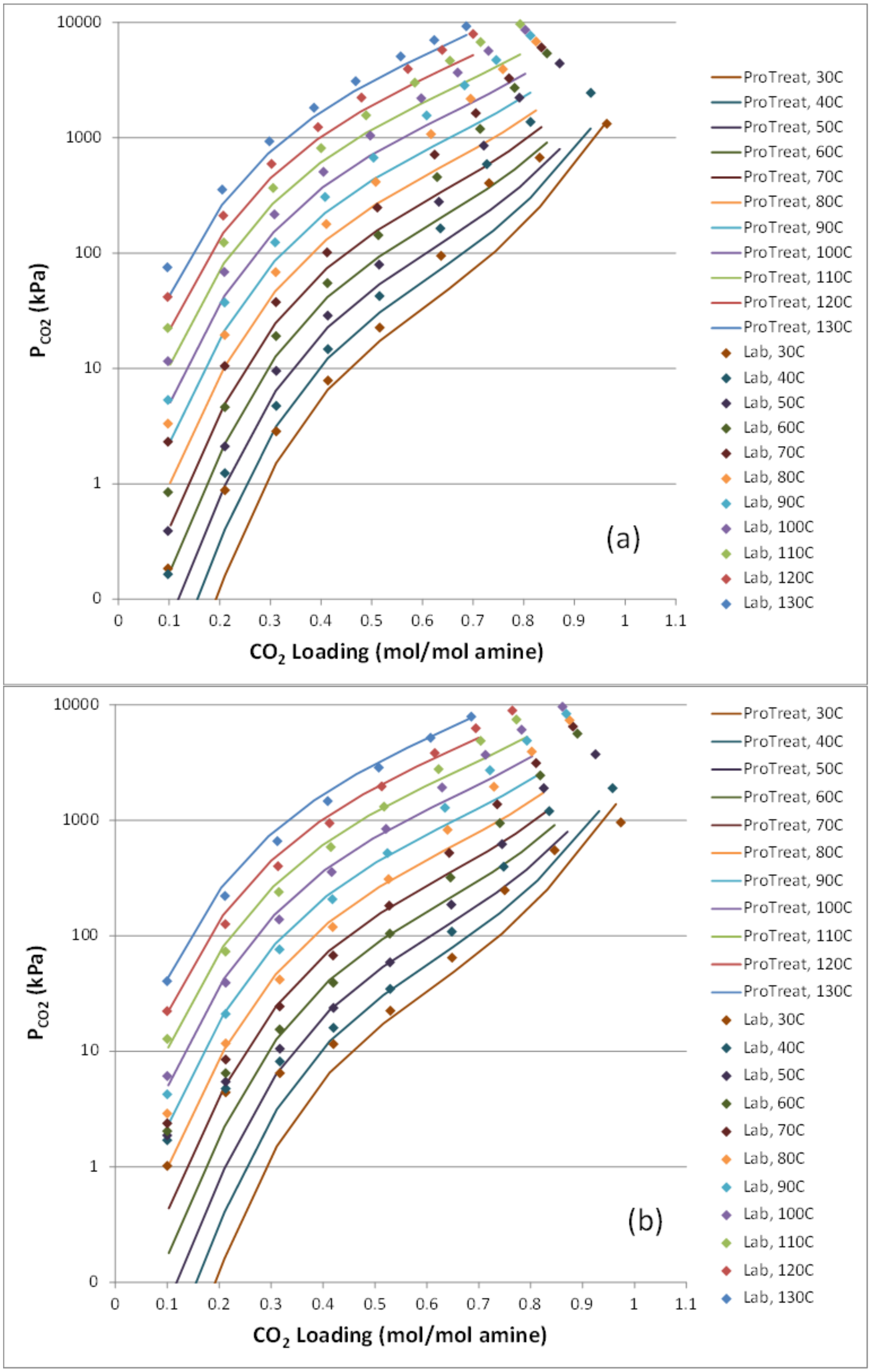

Figure 3.5. VLE measurements for CO_2 in 20% PZ / 30% MDEA / 50% H_2O (w/w) solvent. The measurements in (a) were completed in July 2012, and the measurements in (b) were completed in September 2012 using a different batch of solvent.

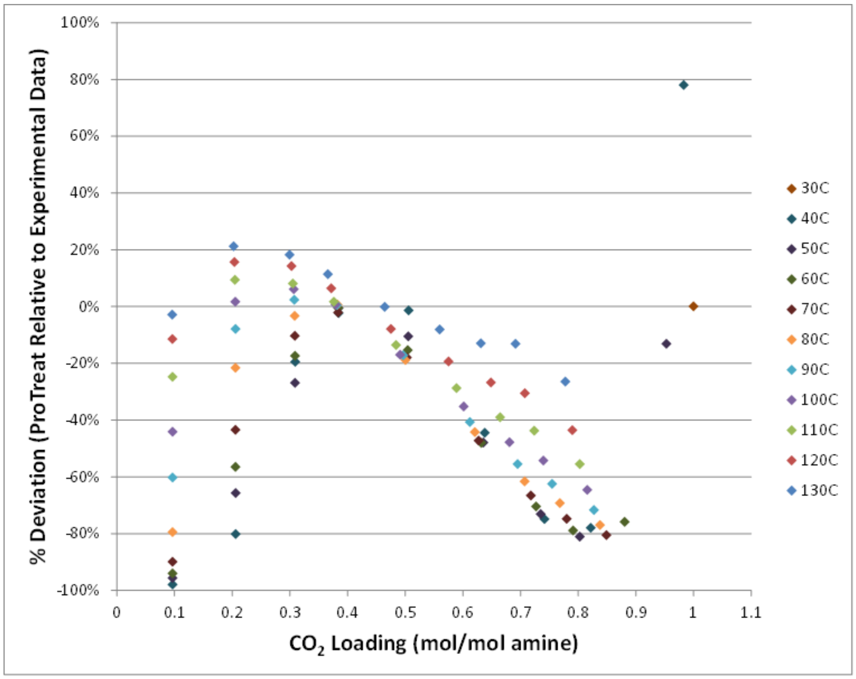

Figure 3.6. Percent deviation of the equilibrium CO_2 partial pressures predicted by ProTreat from those measured experimentally for the 25% PZ / 25% MDEA / 50% H_2O (w/w) solvent.

The experimental VLE data presented in Figures 3.3-3.5 are the averages of duplicate pressure measurements performed at each set of experimental conditions. As described above, measurements were made in duplicate (once during heating and once during cooling of the autoclave) to quantify the precision of the experimental method and to check for hysteresis, which could result if thermal degradation of the solvent occurred during the autoclave heating and cooling cycle**.** Figures 3.7-3.9 show the relative percent differences (RPDs) for the duplicate equilibrium pressure measurements made for three solvents that were studied. With a few noteworthy exceptions (which are indicated in the figures), the RPDs are consistently very low (i.e., <3%). This confirms the repeatability of the measurements and suggests that thermal degradation of the solvent likely did not occur to any appreciable extent.

Another indication of precision is provided by the two sets of independent measurements that were performed for the 20% PZ/30% MDEA/50% H_2O solvent in July and September 2012. These measurements, which are summarized in Figure 3.5**,** were performed by two different operators using different batches of solvent, enabling an assessment of the reproducibility of the method. As evidenced in Figure 3.5 and shown more clearly in Figure 3.10, the equilibrium CO_2 partial pressures measured in September were generally less than those measured in July. The cause of this relative bias is unknown. Both the July and September measurements exhibited similar trends of deviation from the ProTreat simulation results at very low and high CO_2 loadings and low-to-moderate temperatures, as exemplified in Figure 3.10*a*. The July and September measurements approximately bracketed the simulation results at high temperatures, as shown in Figure 3.10*b*.

The experimental VLE data presented in Figures 3.3-3.5 reveal an interesting behavior at low temperatures (i.e., 30-50°C) and high CO_2 loadings (i.e., >0.8-0.9 mol/mol amine), which was observed for all three solvent compositions that were studied. At these conditions, which fall within the potential operating range for the second absorption column in the GPS process, the experimentally observed CO_2 partial pressures are substantially lower than would be predicted from the trends exhibited by the rest of the data. The uniqueness of these data points is quite evident in Figure 3.6. Moreover, the repeatability data presented in Figures 3.7-3.9 show that several of these low-temperature, high-loading measurements had uncharacteristically large RPDs, indicating instability at these conditions. The cause of this behavior is unknown; however, the project team has hypothesized that solids precipitation is a likely explanation. This hypothesis is supported by the finding that crystals were present (at room temperature) in the CO_2-loaded solvent (20% PZ/30% MDEA/50% H_2O) removed from the autoclave at the conclusion of the September test series, as shown in Figure 3.11. The lower-than-expected equilibrium partial pressures that have been observed would be consistent with precipitation involving a product of the CO_2 absorption reaction (e.g., carbamate or dicarbamate species), as the removal of a reaction product from solution would tend to drive the equilibrium to the right via Le Chatelier's principle.

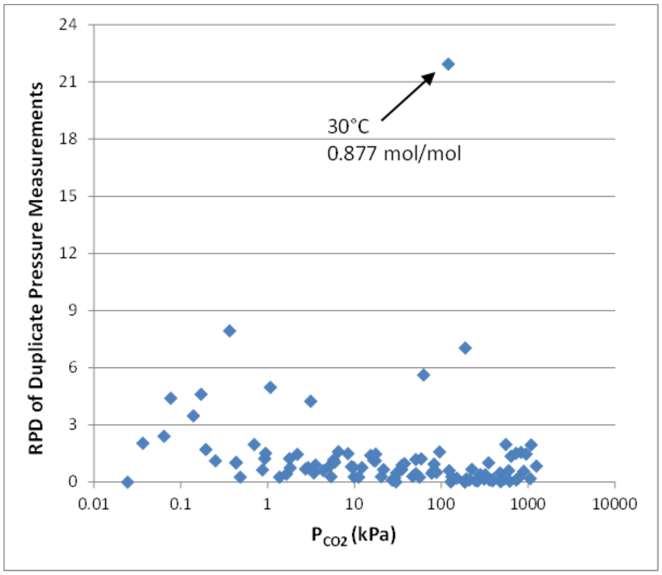

Figure 3.7. Relative percent difference of duplicate equilibrium pressure measurements for CO_2 in 15% PZ / 35% MDEA / 50% H_2O (w/w) solvent

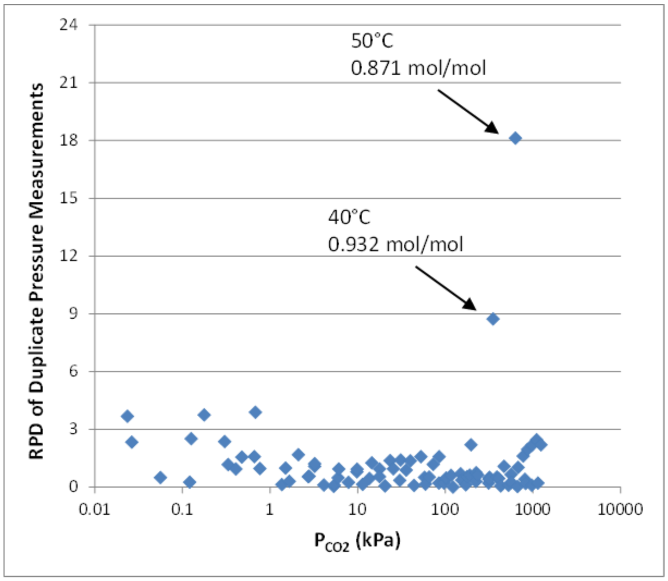

Figure 3.8. Relative percent difference of duplicate equilibrium pressure measurements for CO_2 in 20% PZ / 30% MDEA / 50% H_2O (w/w) solvent (July 2012).

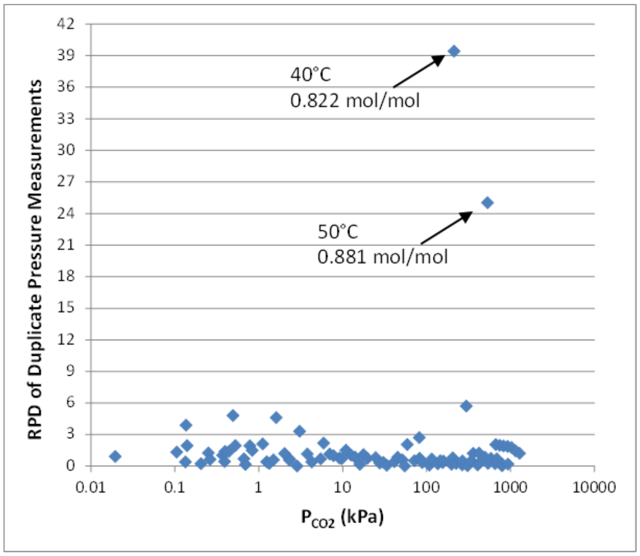

Figure 3.9. Relative percent difference of duplicate equilibrium pressure measurements for CO_2 in 25% PZ / 25% MDEA / 50% H_2O (w/w) solvent

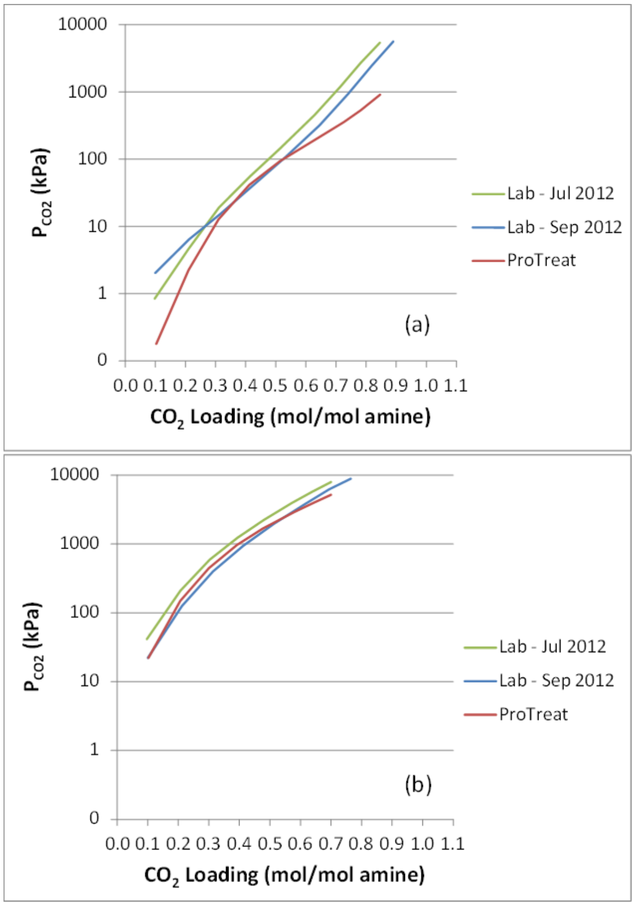

Figure 3.10. Comparison of measured and simulated VLE data for the 20% PZ / 30% MDEA / 50% H_2O (w/w) solvent at (a) 60°C and (b) 120°C. Independent VLE measurements were made in July 2012 and September 2012. Simulations were performed using ProTreat software.

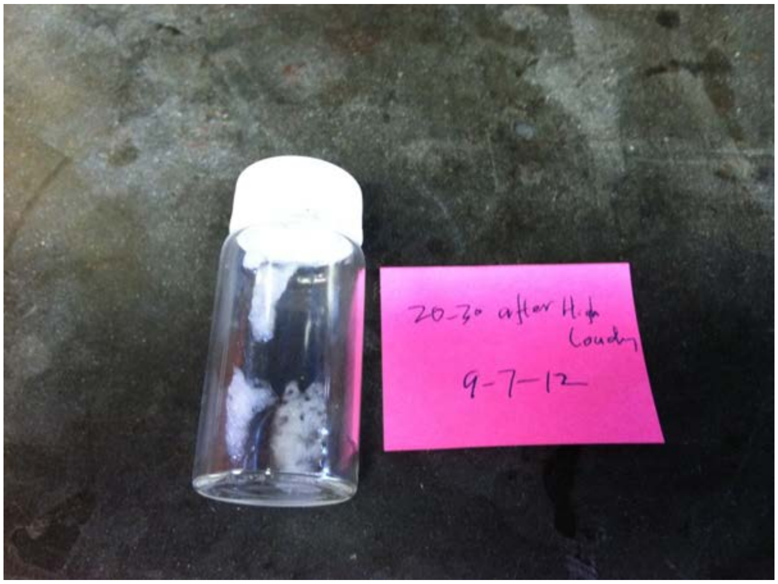

Figure 3.11. Photograph showing crystals recovered from the autoclave at the conclusion of the September 2012 VLE measurements for 20% PZ / 30% MDEA / 50% H_2O (w/w) solvent. The crystals were observed when the solvent was removed from the autoclave at room temperature following the high CO_2 loading measurements.

3.2 Solvents Stability test at High CO_2 Loading and High Temperature

The stability of the PZ/MDEA solvent has been studied extensively by many researchers. However, since these studies only cover the operating conditions seen in conventional processes, the stability data at high temperatures and high CO_2 loading levels are not available. Yet, these data are critical to commercialization of the GPS process to establish operating parameters.

The thermal stability of the solvents is a critical parameter for the GPS process. One of the critical milestones of the project is that solvent loss due to degradation is less than 3 kg/ton CO_2. Therefore, a thermal stability testing was conducted. In addition, the stability of the solvents in the presence of oxygen is also an important parameter and thus was also measured.

3.2.1 Experimental System Set-Up

The system for measuring the thermal stability of solvents is shown in Figure 3.12. Solvent and CO_2 are loaded in sample holders which are then placed in the oven. Samples are periodically removed from the oven and a small portion of the solvent is removed and then injected into the Gas Chromatograph (GC) for analysis. This analysis is used to determine the amount of thermal degradation of the solvent.

The virgin solvent is measured with a GC, which illustrates peaks occurred as signatures of the solvents. The presence of degradation products appears as additional peaks in the GC measurement. Comparison of GC measurements before and after exposure to various temperatures and times provides a reliable means to detect thermal degradation of the solvent. GC measurements have been shown in the literature to accurately detect thermal degradation of the solvents used in this project. This procedure enables the degradation process to be followed as well as determining the source for the degradation (i.e., degradation of PZ relative to MDEA).

Figure 3.12. Sample holder for thermal evaluation (left), oven used in stability evaluations (right)

3.2.2 Thermal Stability Study

The thermal stability of the solvents is a key factor in achieving the milestone set for solvent loss. The original testing scheme from the SOPO is shown in Table 3.2.

Table 3.2. Thermal stability testing parameters

Parameters	Range	Data Points
Solvent concentrations (wt.%)	PZ 10~30, MDEA 20~40	3
CO_2 molar loading	0.4~1	4
Temperature (°C)	80~150	5
Time (weeks)	2~10	5

* Actual experiment points may be less because at some temperature and loading the system pressure could be too high. Our plan is to measure up to 100 atm.

The range of solvent concentrations was adjusted due to the attributes of the solutions containing PZ. Precipitation occurred in solvents when the PZ concentration exceeded 20 wt%. A solution with precipitate cannot be assumed as a single-phase fluid, nor can it be assumed to be well-mixed (essential in quantitative analytical tests). Therefore, the upper range for PZ in the solvent was limited to 20 wt%. The solutions prepared for the stability analysis were 10%/40%/50%, 15%/35%/50%, and 20%/30%/50% (PZ/MDEA/H_2O (wt/wt)). In addition, because the flash points of CO_2 loaded solutions reduces significantly with increasing CO_2 loading, the high loading samples could not be tested at high temperature. Based on the simulation results in Section 2, the pressure throughout all the components in the GPS system would be less than 60 bar (6,000 kPa). The VLE data in Section 3.1.2 demonstrates that the maximum CO_2 molar loading and temperature would be 0.8 and 120°C, respectively, at pressure of 60 bar (6,000 kPa). As a result, the maximum CO_2 molar loading explored was 0.8, while the maximum test temperature was extended to 140°C.

The solvent stability milestone is that the solvent loss due to degradation is less than 3 kg/ton CO_2 under typical GPS process conditions. This loss calculation can be made based on Equation 3.1,

$$\boldsymbol{L} = \frac{\mathbf{907.2} * (\boldsymbol{f_{PZ}} * \boldsymbol{k_{PZ}} * \boldsymbol{t_{RS}} + \boldsymbol{f_{MDEA}} * \boldsymbol{k_{MDEA}} * \boldsymbol{t_{RS}})}{\boldsymbol{W_c}} \qquad 3.1$$

Where, L is solvent loss due to degradation in kg solvent/ton CO_2; W_c is weight of CO_2 absorbed per weight of solvent (working capacity); f_{PZ} is weight fraction of PZ in solvent; f_{MDEA} is weight fraction of MDEA in solvent; k_{PZ} is degradation rate of PZ (time^{-1}); k_{MDEA} is degradation rate of MDEA (time^{-1}); and t_{RS} is residence time of solvent within hot zone (time).

Both k_{PZ} and k_{MDEA} are calculated from data obtained during the thermal stability testing.

The residence time is 15 minutes based on the estimated residence time of the solvent in the GPS process. Thermal degradation of solvent in the GPS process only takes place in zones where temperatures exceed 100°C. It is important to include all these zones when estimating a residence time for thermal degradation purposes. The residence time considered in the GPS process includes the time in the cross flow heat exchangers, the rich solvent heater before the GPS column, the GPS column, the flashers, the hot solvent storage vessels, and the hot solvent volume in transport pipe. Preliminary estimates by Nexant suggest that a conservative value for the total residence time would be approximately 15 minutes.

The working capacity is based on the lean and rich loading, while the weight concentrations are known based on the formulation of the solvent. The rates of degradation (i.e., k_{PZ} and k_{MDEA}) were estimated from the GC analyses based on peak area comparison with respective virgin sample.

Tests were performed at 140°C and 120°C with CO_2 molar loadings of 0.4, 0.6, and 0.8. The solvent compositions (in weight percentage of PZ/MDEA/H_2O) tested are 10%/40%/50%, 15%/35%/50%, and 20%/30%/50%. Table 3.3 lists all experimental conditions and the estimated results. For all tested samples, the estimated solvent loss (L) is significantly less than the milestone target of 3 kg solvent/ton CO_2. This result even occurs when the residence times are greater than the conservative value of 15 minutes. These data indicate that the solvent system has much less solvent loss than the milestone of 3 kg solvent/ton CO_2 set for the thermal degradation when applied to the GPS system, as shown in Figures 3.13 and 3.14.

Table 3.3. Thermal degradation summary

		120℃			***140℃***		
Solvent Concentration Wt.% (PZ/MDEA/H_2O)	CO_2 Loading	PZ degradation rate (fraction/day)	MDEA degradation rate (fraction/day)	*Degradation (kg solvent lost/ton CO_2)	PZ degradation rate (fraction/day)	MDEA degradation rate (fraction/day)	*Degradation (kg solvent lost/ton CO_2)
10/40/50	0.4	0.00629	0.00109	0.0445	0.03604	0.00868	1.6538
	0.6	0.00164	0.00184	0.2107	0.03465	0.00612	1.3825
	0.8	0.00302	0.00098	0.1623	n/a	n/a	n/a
15/35/50	0.4	0.01293	0.00383	0.7671	0.02104	0.00268	0.9565
	0.6	0.00666	0.00148	0.3545	0.02452	0.00389	1.1782
	0.8	0.00038	0.00084	0.0822	n/a	n/a	n/a
20/30/50	0.4	0.00185	0.00100	0.1467	0.00785	0.00621	0.8027
	0.6	0.00133	0.00096	0.1296	0.01782	0.00720	1.3379
	0.8	0.00984	0.00147	0.5635	n/a	n/a	n/a

*Assumed 15 minute residence time within hot zone

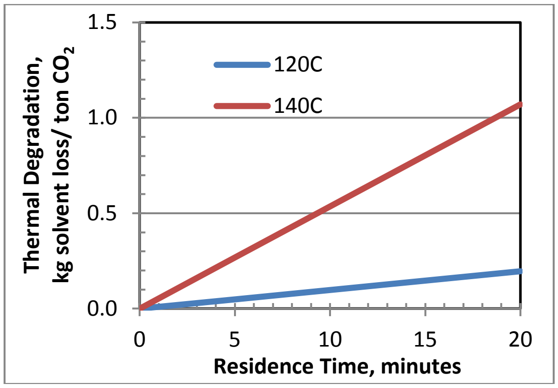

Figure 3.13. Solvent loss due to degradation, 0.4 molar Loading, 20%/30%/50%

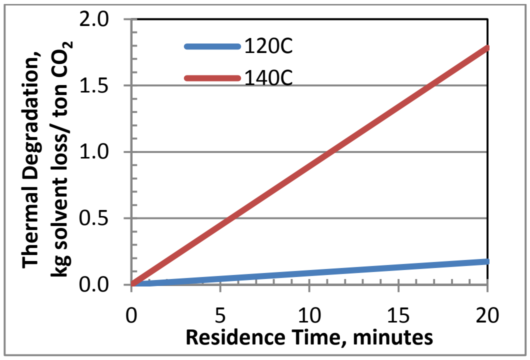

Figure 3.14. Solvent loss due to degradation, 0.6 molar Loading, 20%/30%/50%

3.2.3 Oxidative stability of selected solvent formulations

The solvent compositions used in the thermal stability tests were also used in the oxidative stability tests. Since oxygen is not involved after the solvent leaves the first absorption column, oxidative degradation of the solvent was carried out only under the conditions of the first absorption column. The original testing scheme from the SOP is listed in Table 3.4.

Table 3.4. Variables investigated in oxidative stability test

Parameters	Range	Data Points
Solvent concentrations (wt.%)	PZ 10~30, MDEA 20~40	5
Temperature °C	30~60	4
Time (weeks)	1~5	5

The system for the oxidative stability tests is shown in Figure 3.15. The glass flasks serve as stirred tank reactors. The three reactors shown in Figure 3.8 represent three different solvent compositions. All reactors were tested at 40°C. The gas stream has a composition of 3-5% CO_2 and 95-97% O_2. The CO_2 concentration is selected to simulate the operating condition typical at the middle of the first absorption column. The high O_2 concentration is selected to accelerate the oxidation process. The gas stream was bubbled through the liquid in the stirred reactor to maximize the dissolution of O_2. The solvent components and their oxidation products along with the CO_2 loading in the solvent were analyzed using the GC.

Oxidative degradation was evaluated for all three solvents, at three CO_2 loadings, and at three temperatures. The results are summarized in Table 3.5. For all samples tested, the estimated solvent loss (L) is significantly less than the milestone target of 3 kg solvent/ton CO_2.

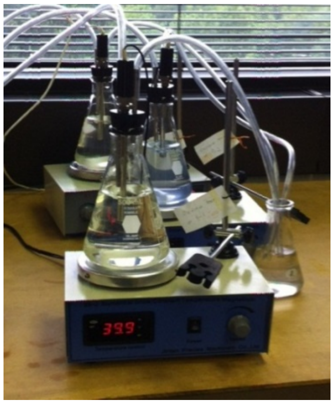

Figure 3.15. System for oxidative stability testing

Table 3.5. Summary of oxidative stability testing

Solvent composition*	Temperature	PZ Degradation (fraction/day)	MDEA Degradation (fraction/day)	PZ Degradation (kg/ton CO_2)	MDEA Degradation (kg/ton CO_2)	Total Degradation (kg/ton CO_2)
10/40/50	40°C	0	0	0	0	0
	50°C	0.00167	0.00071	0.00068	0.00117	0.00185
	60°C	0.00289	0.00099	0.00118	0.00163	0.00281
15/35/50	40°C	0	0.00033	0	0.00048	0.00047
	50°C	0.00280	0.00303	0.00172	0.00434	0.00606
	60°C	0.00052	0.00073	0.00032	0.00104	0.00136
20/30/50	40°C	0.00152	0.00162	0.00124	0.00199	0.00323
	50°C	0.00194	0.00261	0.00159	0.00321	0.00480
	60°C	0.00406	0.00230	0.00332	0.00283	0.00615

*PZ/MDEA/H_2O (wt%)

3.3 Corrosion Test at High Loading and High Temperature

The aqueous amine solution is corrosive to steel and stainless steel. The corrosion by amine solvent is one of the most severe operational problems in the typical CO_2 capture plants. MDEA is considered least corrosive among many amines. The corrosion rate was found to be higher with higher temperature, higher amine concentration and high CO_2 loading. All of the previous corrosion studies do not cover the operating condition of the GPS process, which involves high CO_2 loading and high temperature. To address this issue, the corrosion rate of the blended amine-based solvent under high CO_2 loading and high temperature was tested.

3.3.1 Experimental system set-ups

An electrochemical corrosion test method was used to measure the corrosion rate. Because the secondary absorption and GPS columns operate at high pressure, the experimental system for the corrosion test must be able to handle high pressure. A high-pressure autoclave was used for this purpose. To measure the corrosion rate, a three electrode linear polarization resistance probe was installed into the testing chamber.

The corrosion measuring system is shown in Figure 3.16. Metal coupons were first placed inside the chamber, the chamber was then filled with the solvent, and finally measurements were made at different residence times. The metal test chamber was also placed inside an oven to make measurements at different temperatures.

Figure 3.16. Corrosion test chamber along with measuring device

Testing coupons were mounted as shown in Figure 3.17. Three coupons can be mounted at one time, which can reduce the testing time. The inside of the test chamber is shown in Figure 3.18.

Figure 3.17. Metal coupons mounted for testing inside the chamber

Figure 3.18. View inside the test chamber

3.3.2 Corrosion at high loading and high temperature

The sample was prepared and the test was carried out in accordance with an ASTM standard. Corrosion rates of carbon steel and two stainless steels (304L and 316L) in the amine-based solvent were measured. In addition, oxidative corrosion occurs in the first absorption column when the solvent contacts with flue gas, which contains about 3% oxygen. There is no literature data of oxidative corrosion rate of the blended amine-based solvent. Therefore, oxidative corrosion rate was also measured under the first absorption column operating condition. To measure such a corrosion rate, O_2 and CO_2 mixed gas was purged into a corrosion cell. The conditions of the tests were selected based on the process operating conditions. The corrosion rate (k) is calculated in mils/yr, given by,

$$k = \frac{weight\ lost}{surface\ area \times density \times exposure\ time} \qquad 3.2$$

and

$$mil = \frac{inch}{1000} \qquad 3.3$$

A summary of the experimental measurements is shown in Table 3.6, where the rates are expressed in mils/year. The resolution of the testing system is ± 0.01 mils/year with a deviation of ± 0.03 mils/year and accuracy of ± 0.02 mils/year.

Table 3.6. Summary of corrosion data rates in mils/year

Sample	Rich Solvent			Lean Solvent					Lean solvent with O_2	
Temperature	20°C	50°C	80°C	20°C	50°C	80°C	100°C	110°C	20°C	50°C
Stainless 304L	0.03	0.04	0.08	0.03	0.10	0.06	0.31	0.96	0.01	0.05
Stainless 316L	0.11	0.03	0.25	0.01	0.05	0.07	0.28	0.84	0.05	0.06
Carbon Steel (1010 grade)	0.02	0.04	0.11	0.03	0.04	0.27	0.36	1.23	0.04	0.20

Experimental results listed in Table 3.6 show that the average corrosion rate is less than 0.1 mils/yr for all steel samples in all solvents when the temperature is less than 50°C. However, the corrosion rate is higher when the temperature is over 80°C and increases rapidly when the temperature is over 100°C for all steel samples. An activation energy plot of the carbon steel corrosion data is shown in Figure 3.19. The experimental values agree well with those reported in the literature for samples exposed to MDEA in the presence of CO_2. The results show the behavior of the solvent under typical process conditions within the absorption column and the GPS column. As anticipated, corrosion increased with CO_2 concentration, O_2 concentration, and temperature. Corrosion rates for carbon steel were higher than those of the stainless steels. The corrosion rates for stainless 304L were greater than that of stainless 316L. For all metals, corrosion was noticeably low at low temperatures.

These results indicate that while the corrosion rate depends on the material type, the overall rates are relatively low. All corrosion rates in Table 3.6 are less than 1.0 mils/year for temperatures less than 100°C, thereby suggesting that carbon steel could be used in equipment components that do not exceed 100°C. In comparison, equipment components that exceed processing temperatures of 80°C may benefit from being fabricated from stainless steel. This type of design could assist in decreasing the overall capital cost.

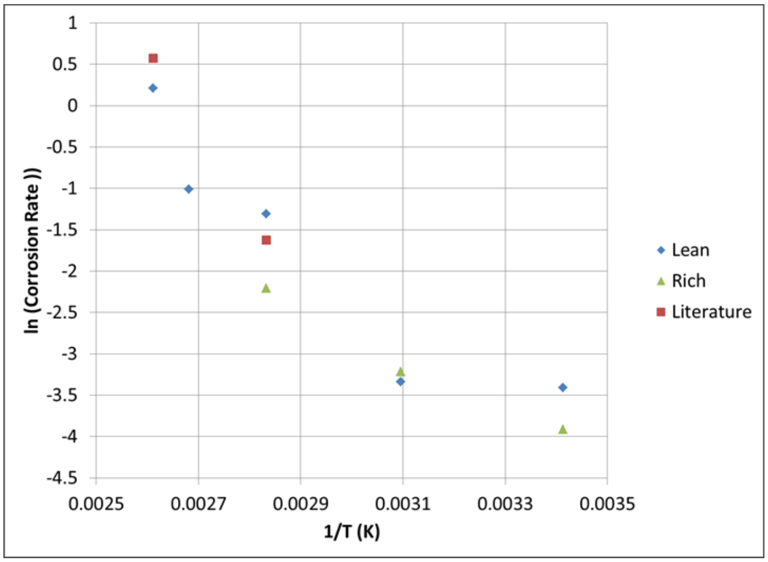

Figure 3.19. Activation energy plot for carbon steel experimental data. Data is compared to literature values.

4. LAB-SCALE EXPERIMENTAL TESTING OF GPS PROCESS PERFORMANCE

4.1 First Absorption Column Testing

Due to the requirements of the GPS process, the operating conditions of the first absorption column are slightly different from a conventional amine-based CO_2 absorption process. The first absorption column not only operates at a state closer to equilibrium than a conventional absorber, but also includes inter-stage cooling zones in the design and fabrication of the column.

4.1.1 Design and Set-up of the Column

The first absorption column and its ancillary equipment were constructed. The column, shown in Figure 4.1, is approximately 12 feet in height (9 feet of packed column) and 4 inches ID, and constructed using a PVC tube. It is purposely constructed to be modular in nature to facilitate the introduction of a variety of cooling regions along the length of the column. The system was designed with two cooling zones. The applied column packing is shown in Figure 4.1 (right). The metering pumps are placed in the left foreground of the picture as shown in Figure 4.1 (left). A steam generator is located on the other side of the columns (invisible in Figure 4.1) and is used to humidify the incoming stream to the column. An additional component to the system is a stripper tank which is used to remove the CO_2 from the solvent (to regenerate the solvent). The solvent can then be reused. Figure 4.2 illustrates the stripper tank (right) and the inside of the tank (left). This tank can be seen in the Figure 4.1 to the left of the operator.

Figure 4.1. Adsorption Column and ancillary equipment (left); packing used in column (right)

Figure 4.2. Stripper tank (left) and inside of tank with top removed (right)

In the absorption step, solvent is pumped from the lean solvent tank through the column and into the rich solvent tank. The column has two inter-stage cooling sections allowing three solvent control points (inlet to top of the column, and the inlet following each cooling stage). The temperature at each of these inlets was monitored and controlled. In addition, the solvent flow rate and the flow rates of each of the gaseous components were also controlled. Sample valves were used to collect samples from both the inlet and outlet of the solvent and the mixed gases to measure the concentration of the gas and the solvent.

For solvent regeneration, the rich solvent was pumped from the rich solvent tank to the regeneration tank where batch stripping was operated to convert the rich solvent into a lean solvent. Then, the lean solvent was pumped to the lean solvent tank for the absorption tests. A 4,000-W steam generator was used to provide heat for the solvent regeneration.

4.1.2 Testing of the selected solvents

It is important to evaluate the impact of various process variables on the performance of the absorption column, which provides insights to analyze sensitivities for parameters of the process conditions and robustness of the process. The original testing scheme from the SOPO is shown in Table 4.1.

Table 4.1. Parameters and ranges for evaluation of first adsorption column

Factors	Range	Data Points
PZ/MDEA wt%	30~50	3
Feed gas flow rate (L/min)	50~70	3
Liquid/gas ratio (mol/mol)	4~6	3

According to the process simulations described in Section 2, it was discovered that higher total amine concentration was more favorable in terms of energy performance of the GPS-based process. From industrial experience, total amine concentration of 50% was selected. During the experiments, however, precipitation occurred in the solvents that contained high PZ concentration. The results from the phase equilibrium data validated the results by the computer simulations. As a result, conditions from simulations were used to design and select operating conditions for the first absorption column, including flue gas composition, lean loading, operating temperature and L/G ratio. The 15%/35%/50% , 20%/30%/50% and 25%/25%/50% solvent compositions (PZ/MDEA/H_2O (w/w)) were evaluated in the absorption tests.

For the 15%/35%/50% solvent system, the feed gas flow rate and L/G ratio was varied to determine their impact on process performance, i.e. percent of CO_2 capture. Figure 4.3 illustrates the impacts of feed gas flow rate and L/G ratios on the column performance. Results illustrate that, for the existing laboratory column with the existing height, the column should be operated at a gas flow rate of less than 20 liters/min to achieve ~90% CO_2 capture. The percentage of CO_2 capture decreases with increasing feed gas flow rate. When the lean loading was fixed at 3.8 wt%, the L/G ratio was varied by ±10% around the target value of 2.42 mole/mole. The range of variation is much greater than that expected during normal operation of the column. Even so, the effect of the L/G ratio on percentage of CO_2 capture is negligible as shown in Figure 4.3, which demonstrates the robust design of the column.

To assess the impact of lean loading on CO_2 capture, the lean loading was varied along with the gas flow rate. Figure 4.4 demonstrates the effect of the gas flow rate and the lean loading on CO_2 capture performance. When the lean loading decreases from 3.8 to 3.3 wt%, the 90% capture target can be achieved at gas flow rates up to 30 L/min. Similarly, at flow rates less than 15 L/min, 90% capture can be achieved for the lean loadings up to 4.0 wt%.

Similar results were achieved for the 20%/30%/50% and 25%/25%/50% solutions, as shown in Figures 4.5-4.8. The maximum gas flow rate for 90% CO_2 capture increases with increasing PZ concentration.

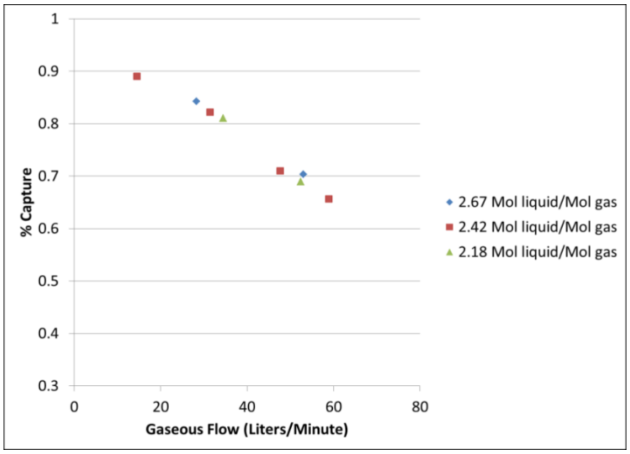

Figure 4.3. Impact of L/G Ratio and Gas Flow rate on performance of absorption column for 15%/35%/50% solvent

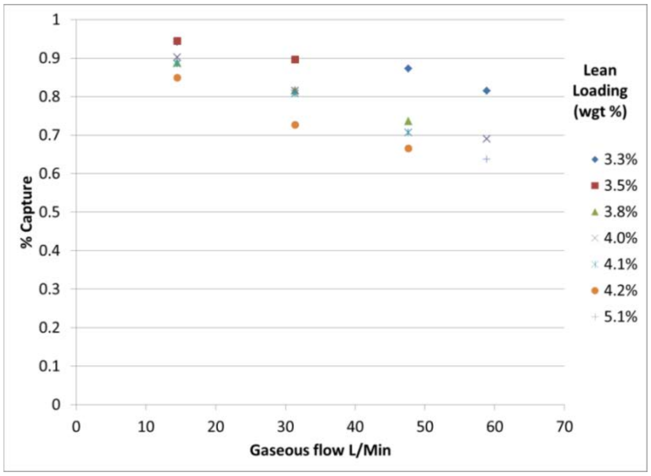

Figure 4.4. Impact of gas flow rate and lean loading on performance of absorption column for 15%/35%/50% solvent

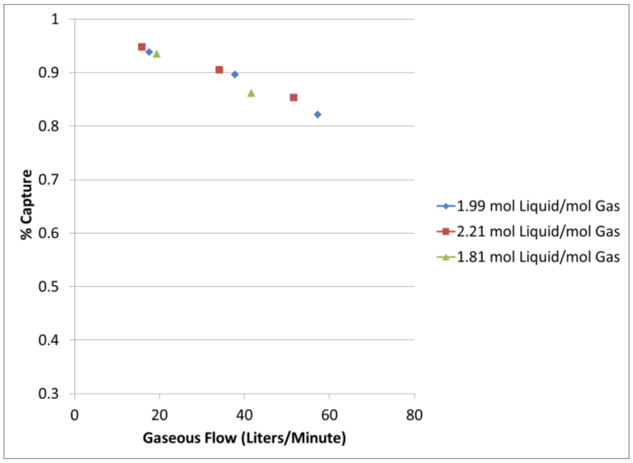

Figure 4.5. Impact of L/G Ratio and Gas Flow rate on performance of absorption column for 20%/30%/50% solvent

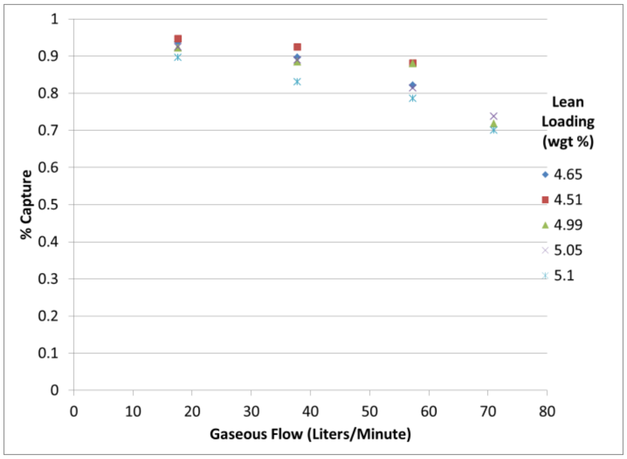

Figure 4.6. Impact of gas flow rate and lean loading on performance of absorption column for 20%/30%/50% solvent

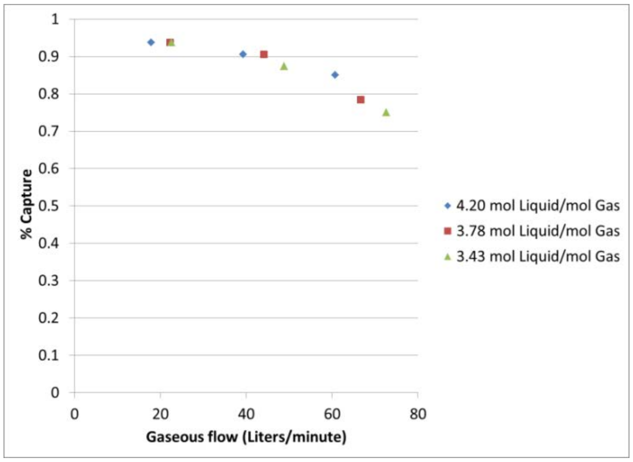

Figure 4.7. Impact of L/G Ratio and Gas Flow rate on performance of absorption column for 25%/25%/50% solvent

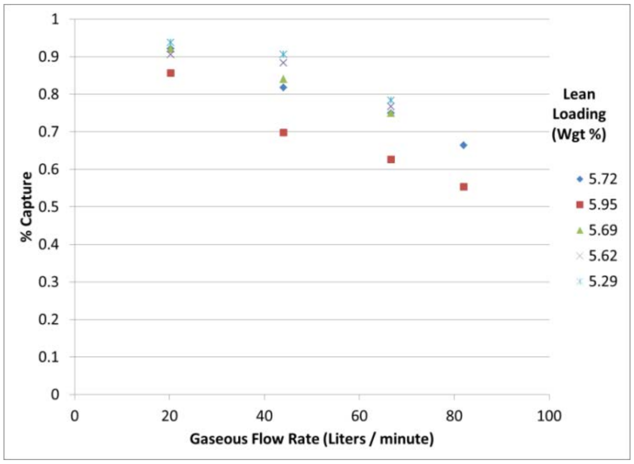

Figure 4.8. Impact of gas flow rate and lean loading on performance of absorption column for 25%/25%/50% solvent

4.2 GPS Column Design / Fabrication & Testing

A GPS column is the key component in the GPS-based process. Similar to a conventional stripping column, the GPS column is used to regenerate the solvent so that the solvent can be recycled to the absorption column of the GPS process. The difference is that the GPS column produces a CO_2 stream at higher pressure than that by conventional stripping. It is necessary to obtain experimental data including hydrodynamics, mass and heat transfer, and reaction kinetics to reliably scale-up the GPS process.

4.2.1 Design and fabrication of GPS column

The GPS column has multiple heating locations along the column depth. The heating sources (electricity) applied external heating tapes. Random packing was used in the GPS column. The backbone of the GPS column was fabricated by an outside equipment vendor, JR Piping and Construction Co., LLC. Accessories were made by the CCS LLC engineers.

Based on the simulation results introduced in Section 2, a GPS column was fabricated, assembled, and connected to existing infrastructure within the facility in the CCS LLC laboratory. As shown in Figure 4.9, the column is constructed of stainless steel 304 with an outside diameter (OD) of 1.315 inch and wall thickness of 0.133 inch. The height of the entire unit (including support base) is 7 feet with a packing height of 6 feet. The liquid collection component is approximately 8” in length. The system is designed to withstand a maximum pressure of 36 bar, with a standard operating pressure in the range of 6-10 bars. Heating along sections of the column is achieved by wrapping heating tape on the outside of the column. Pressurized nitrogen (N_2) gas is used as the stripping gas in the GPS column. The packing utilized in the column is a major design feature. Extensive analysis was performed to select an appropriate packing for the column. The random packing used in the column is depicted in Figure 4.10.

Figure 4.9. GPS column on mounting stand assembled in CCS LLC's laboratory

Figure 4.10. Packing used in the GPS column

The first absorption column introduced in Section 4.1 was modified and applied in coupling with the GPS column to facilitate semi-continuous operation of the system.

4.2.2 Installation and shakedown

The GPS system was installed in CCS LLC's lab and shakedown tests were performed using water/air to ensure that the system worked properly. Analysis of the streams exiting the GPS column was facilitated by the installed RGA mass spectroscopy system shown in Figure 4.11. Shakedown testing with air and water was successful and no leaking of the column was observed. The system was then used for planned experiments.

Figure 4.11. Mass spectroscopy system used in the analysis of outgoing streams from the GPS column

4.2.3 Testing of the Selected Solvents

The performance of the GPS column was evaluated using amine-based solvents to investigate the influence of different operating parameters. The operating parameters examined include the total operating pressure (determined by stripping gas), total feed gas flow rate, and L/G ratio. A split vapor flow GPS column design concept, which decreases the amount of effluent vapor stream going through the second absorption column and flasher, was also evaluated. The data obtained can be used to further optimize the formulation of the amine-based solvent for the GPS process.

The objective of the GPS column tests was to demonstrate the effectiveness of a GPS column in replacing traditional stripping columns in amine-based CO_2 capture processes. Similar to a traditional stripping column, the function of the GPS column is to release CO_2 from the CO_2 rich solvent to produce a CO_2 rich gas outlet, and to regenerate the solvent to be used cyclically in the CO_2 capture process. The GPS column differs from traditional stripping in that it uses a stripping gas that drives gas flow and elevates the operating pressure of the column beyond the pressures typically used in the conventional systems. In addition, GPS uses side boilers along the height of the column instead of a reboiler at the bottom of the column. A slipstream was also extracted from the GPS column (called split flow) at a point along the height of the column to investigate the recirculation of a partially-stripped solvent stream to the second absorption column.

The testing results validate the simulation results described in Section 2. While Section 2 demonstrates the GPS operations based on principles of unit operations and thermodynamics, the experimental data validate the operation of the GPS column. In addition, the VLE data introduced in Section 3 represents the thermodynamic limitations of the column that result from heat and mass transfer limitations. The conditions of the top, bottom, and slipstreams directly represent practically steady conditions as the column's heat and mass transfer approach thermodynamic equilibrium.

The GPS column was evaluated using an amine-based solvent system to investigate the influences of different operating parameters. The operating parameters were selected based on the results and analysis from Sections 2 and 3. For example, a split flow (slipstream) was systematically examined to determine its impact on the performance of the process. Table 4.2 outlines the testing parameters and their ranges.

Table 4.2. Process parameters evaluated for GPS column

Parameters	Range
Total Operating Pressure	6~10 bar
Gas/Liquid Ratio (std cc stripping gas/ g solvent)	1-25
Fraction of Gas via Slipstream	0-0.4

The most important performance parameter for the GPS column is the lean loading at the bottom of the column. This parameter represents the process' ability to regenerate the solvent. While varying the lean loading, the rich loading is maintained at 7.85% CO_2 by weight. The other important performance parameter is product (CO_2) purity, i.e., the ability to produce CO_2 at 95% purity.

Measurements for CO_2 purity were made by gas sampling through an RGA. Solvent samples were analyzed for CO_2 concentration by the following methods: 1) instantaneous lean loading measurements were made by cooling the solvent and then running the exit gaseous and solvent streams through an over-designed absorption column and using the gaseous concentration and temperature at the top of this absorption column in conjunction with thermodynamic equilibrium data (from Section 3 or through simulation); 2) solvent could also be directly sampled using phosphoric acid method (CO_2 in the presence of acid is instantly released as a gas into a closed system where the gaseous concentration was measured); and 3) lean solvent loading was determined by performing a mass balance on CO_2 gained by the gaseous flow through the column (i.e., direct measurement). Rich solvent on the other hand could only be measured by direct sampling into the phosphoric acid method. Lean loading was found to be most accurate by re-absorption equilibrium calculations.

The GPS column operation can be validated by validation of the physical attributes of the column. This step entails examining the temperature profile along the column, validating that the working capacity of the column is acceptable, and that an acceptable working capacity and CO_2 purity can be obtained at typical processing conditions. To perform this validation, the rich loading was maintained at ~8% (7.85%), thus resulting in a target lean loading percentage of ~4%. This target would result in an acceptable working capacity for the GPS column. At the same time, it is also important to examine the CO_2 product purity, which should be at least 95%. A traditional column uses a reboiler at the bottom of the column and has a large temperature gradient along the height of the column, which impacts performance. The GPS column is equipped with heaters along the height of the column to provide more uniform heating and reduce temperature gradients. Figure 4.12 depicts the temperature measured at various points along the GPS column.

The physical attributes of the GPS column were validated by varying the solvent flow rate over a range of typical process conditions. The operating pressure was maintained at 6 bars throughout these tests. The impact of solvent flow rate on lean loading and CO_2 purity is shown in Figures 4.13 and 4.14, respectively. Figure 4.13 demonstrates that the target lean loading (~4%) was achievable over a range of solvent flow rates. At the same time, Figure 4.14 illustrates that the CO_2 purity was influenced by the solvent flow rate. Figure 4.14 suggests that the solvent flow rate should be maintained at less than 150 g/min in order to achieve the targeted working capacity and CO_2 purity. Based on the results shown in Figure 4.14, the solvent flow rate was maintained in the 80-100 g/min range for all subsequent tests.

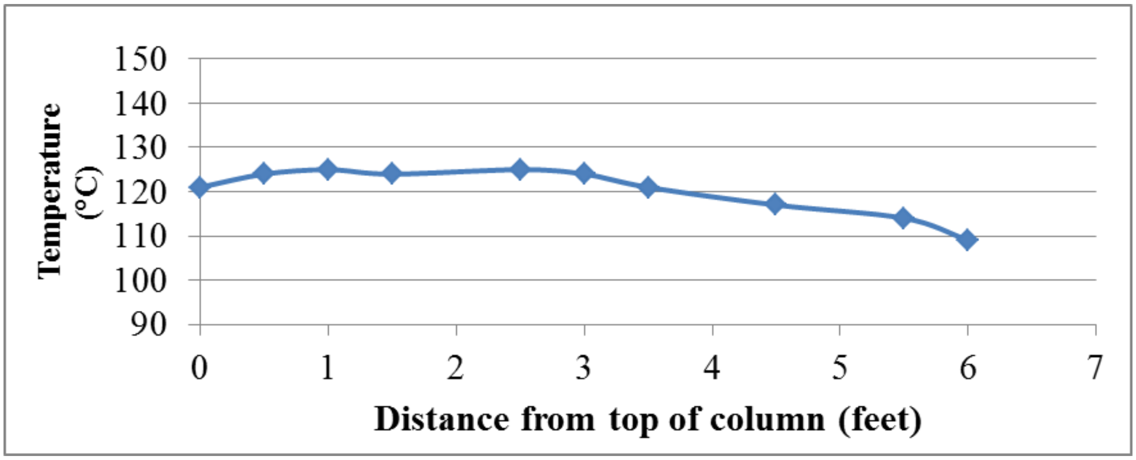

Figure 4.12. Temperature measurements performed along length of GPS column

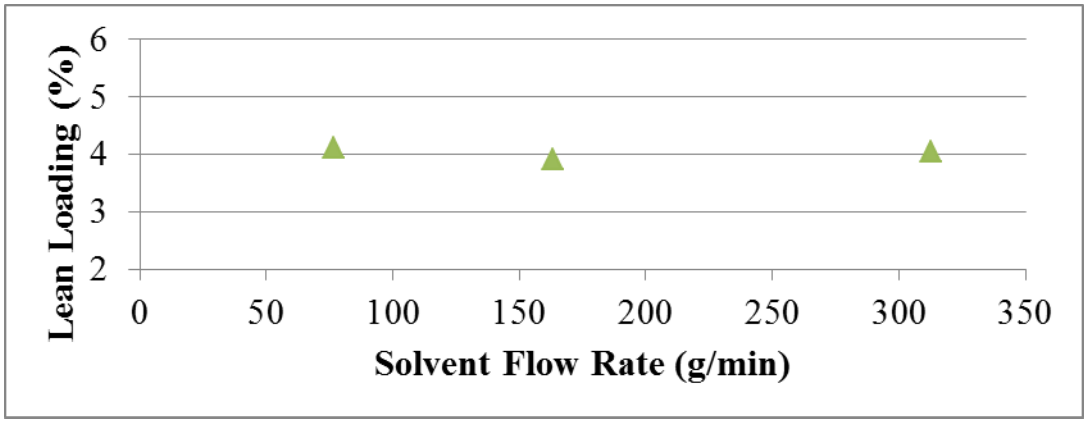

Figure 4.13. Effect of solvent flow rate on lean loading for GPS column at operating pressure of 6 bar

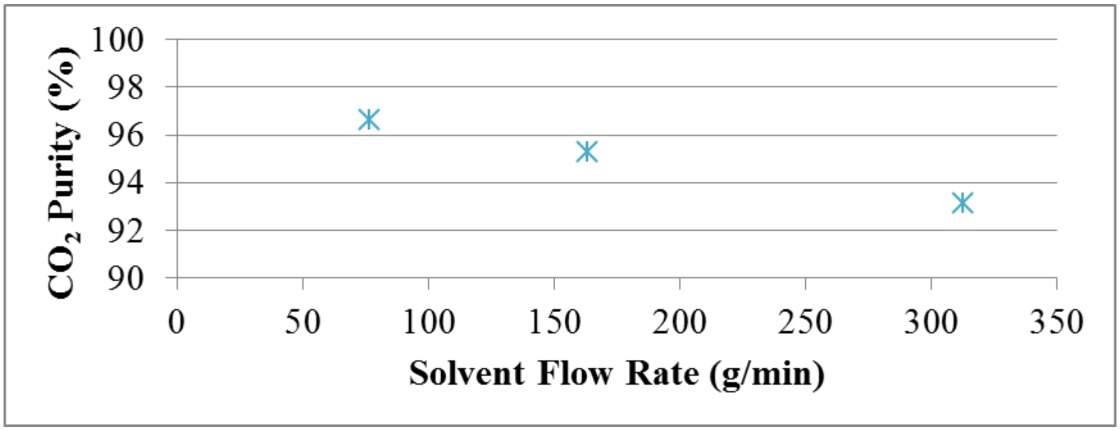

Figure 4.14. Impact of solvent flow rate on CO_2 purity at operating pressure of 6 bar

The further evaluation of GPS column was to investigate the impact of operating pressure on the G/L ratio. These ratios were obtained at conditions where the lean loading was maintained at ~4%. The results are shown in Figure 4.15. The G/L ratio increases with increasing operating pressure as expected according to thermodynamics and simulation data.

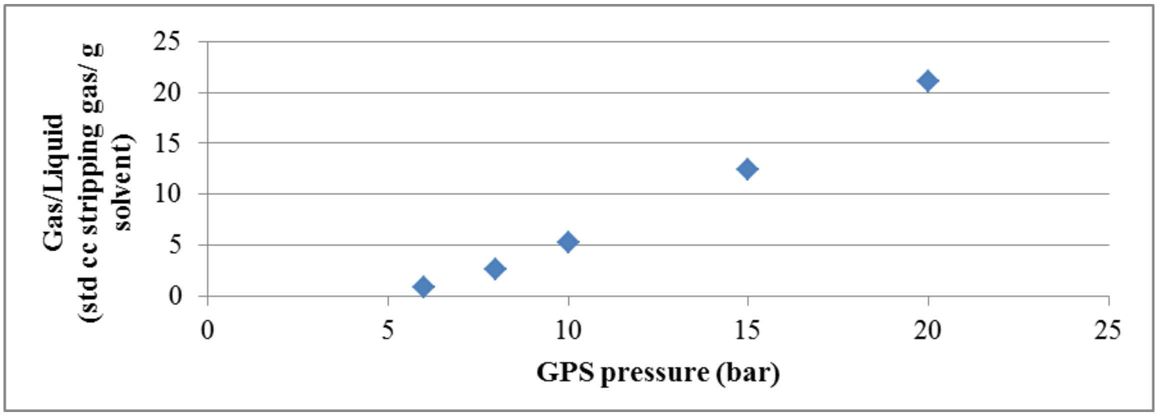

Figure 4.15. Impact of operating pressure on G/L ratio with lean loading of ~4%

The impact of introducing a slipstream on the performance of the GPS column was also investigated. The column was initially operated at 8 bars. Figures 4.16-4.18 illustrate the impact of G/L ratio and gas fraction in slipstream on lean loading and CO_2 purity. The target lean loading was ~4%. It can be seen that introducing the slipstream still enables the GPS column to deliver the required working capacity and CO_2 purity.

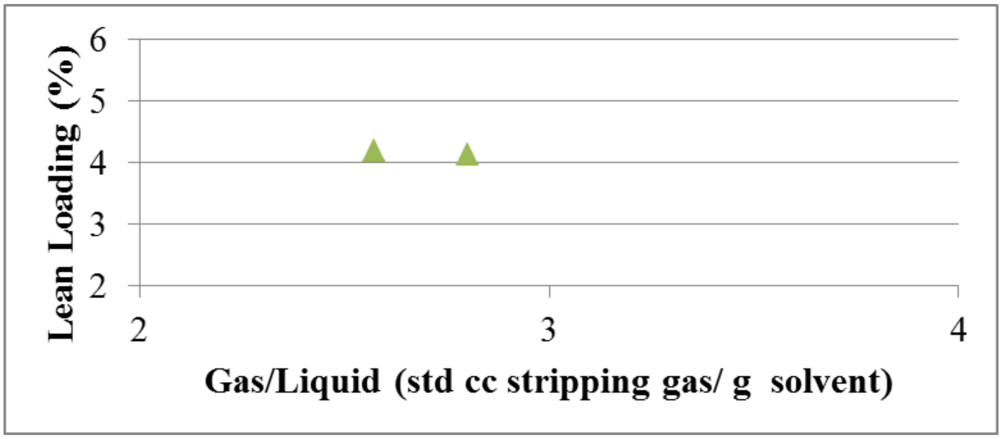

Figure 4.16. Impact of Gas/Liquid ratio on lean loading at 8 bar

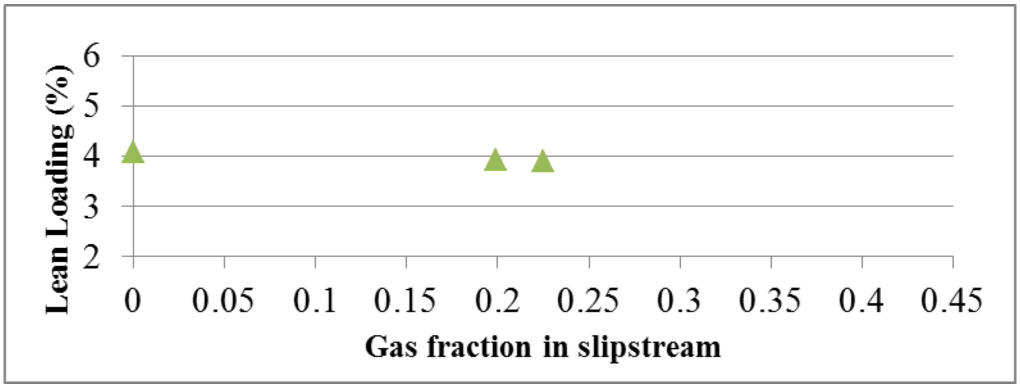

Figure 4.17. Impact of gas fraction in slipstream on lean loading at 8 bar

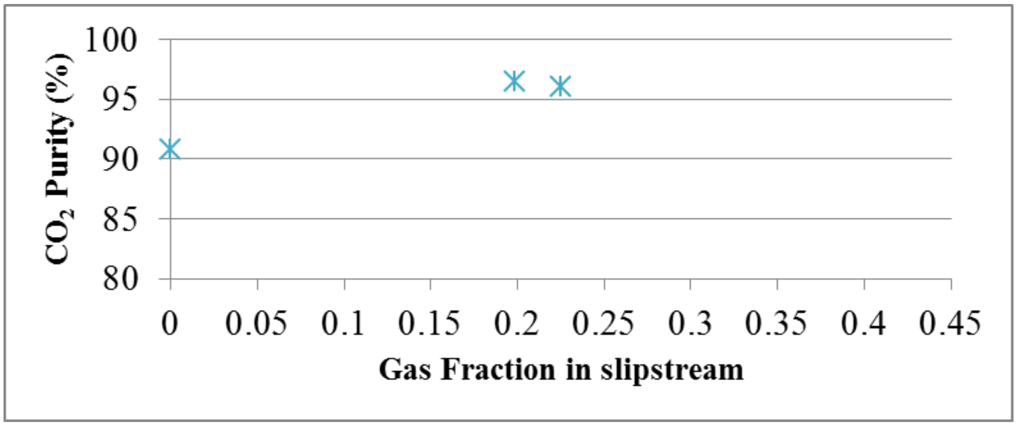

Figure 4.18. Impact of gas fraction in slipstream on CO_2 purity at top of GPS column at 8 bar

The operating pressure was then increased to 10 bar and the performance of the GPS column was also evaluated. Figures 4.19-4.21 illustrate the impact of G/L ratio and fraction of gas in slipstream on lean loading and CO_2 purity. The target lean loading was still ~4%. It can be seen that introducing the slipstream still enables the column to maintain the required working capacity and CO_2 purity.

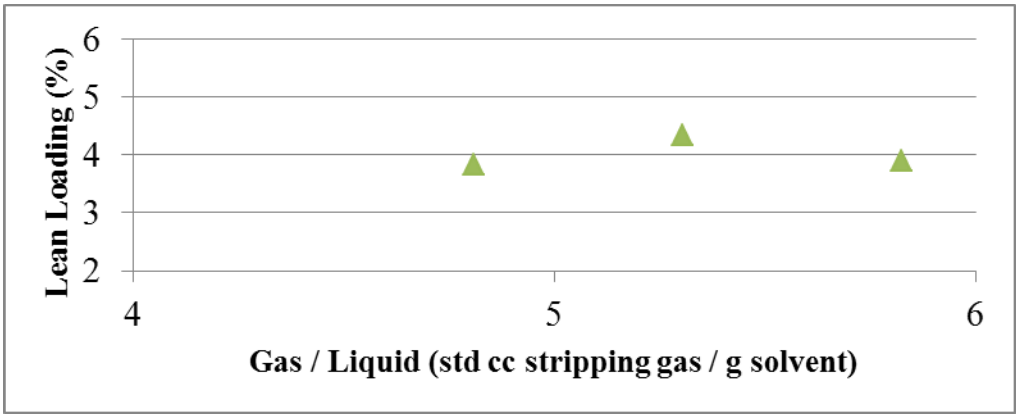

Figure 4.19. Impact of Gas/Liquid ratio on lean loading at operating pressure of 10 bar

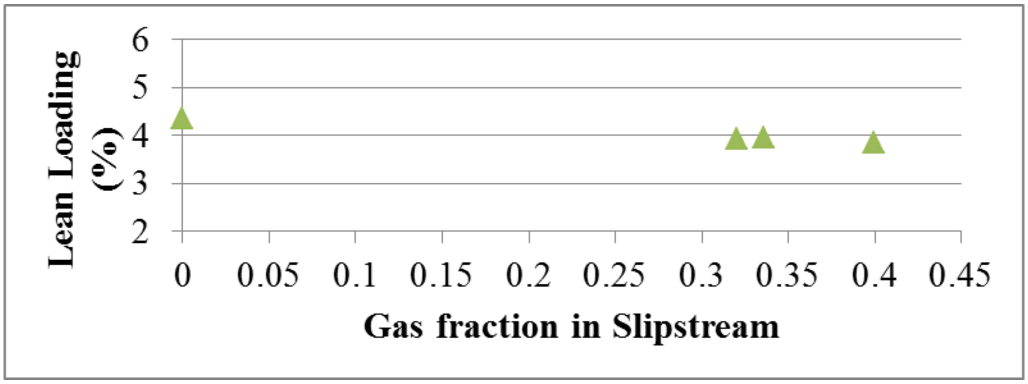

Figure 4.20. Impact of Gas fraction in slipstream on lean loading at operating pressure of 10 bar

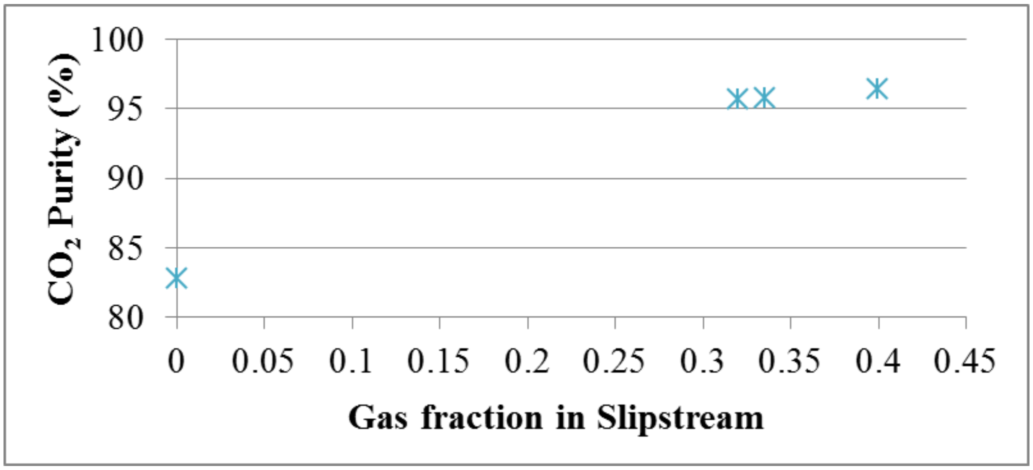

Figure 4.21. Impact of gas fraction in slipstream on CO_2 purity at operating pressure of 10 bar

The primary function of the GPS column is to regenerate the solvent as required for the absorption stage of the process (similar to traditional stripping). The results of lean loading measurements demonstrate the GPS column functions as planned. In addition, the gaseous outlet at the top of the GPS column produces high purity product – a critical parameter to monitor. The results also demonstrate that the use of a slipstream can assist in achieving process performance goals.

The efficiency of the GPS column was analyzed through the use of a thermal study. During the performance tests, the power supplied to the GPS column was measured through the use of a power meter to estimate the heat duty provided to the column. This heat duty represents power supplied in relation to heat loss, sensible heat, stripping heat, and reaction heat. The power meter measures the electric current through the heating tapes, which provides the heat provided by the heating tapes when combined with the measured voltage. The heat loss from both the tape and column can be determined by running the column with water under isothermal conditions. This methodology enables the sensible, stripping, and reaction heats to be estimated. The results from this analysis are presented in Table 4.3, which were performed at 6 bar without the use of a slipstream. The range of liquid flow rates was based on the range in Figures 4.13-4.14.

Table 4.3. Thermal study for GPS column

Total of Column Heating (W)	526	494	706	817	654	680
Liquid Flow Rate (g/min)	74.4	65.5	115	115	110	110
Heat Loss (W)	432	411	515	588	481	498
Heat GPS (W)	93.9	83.0	155	193	137	146
Heat GPS (W/(g/min))	1.26	1.27	1.35	1.68	1.25	1.33
Heat GPS Sensible (W/(g/min))	0.39	0.39	0.56	0.84	0.45	0.67
Heat GPS Stripping and Reaction (W/(g/min))	0.87	0.88	0.79	0.84	0.80	0.66
Reaction (kJ/Kg CO2)	1377	1386	1248	1327	1267	1042

The theoretical minimum heat duty for the column is determined by,

$$\Delta H_{min} = R\frac{T_2T_1}{T_2-T_1}\ln({}^{P_2}/_{P_1}) \qquad 4.1$$

Where:

ΔH_{min} = theoretical minimum heat duty
R = Gas Constant
P_1 / P_2 = CO_2 Partial Pressure in flue gas / CO_2 Partial Pressure of outlet gas from GPS
T_1 / T_2 = CO_2 Temperature in flue gas / CO_2 Temperature of outlet gas from GPS

Based on these values, the theoretical minimum was determined to be 818 kJ/kg CO_2. The measured heat duty was based on an average of the values shown in Table 4.3 and was determined to be 1,274 kJ/kg CO_2. The thermal efficiency is a ratio of the theoretical minimum to actual duty, which is approximately 64%. This result is an important milestone since traditional columns have much lower efficiencies (typical 20% or less). These estimations demonstrate that the design of the GPS column has enabled it to meet the 50% thermal efficiency milestone.

4.3 Second Absorption Column Test

The initial GPS process design included a second absorption column. Similar to the first absorption column, the operation of the second column is under certain restriction imposed by the GPS column. It is necessary to investigate the performance of the second absorption column experimentally and to obtain process design data for scaling-up of GPS process.

4.3.1 Experiments setup for the second absorption column

The 2nd absorption column is downstream from the GPS column. The function of the 2nd absorption column is similar to that of the GPS column. Whilst the primary objective of the GPS column is to regenerate the solvent to its CO_2 lean state, the function of the 2nd absorption column is to restore the stripping gas to its CO_2 lean state. In the modified GPS process configuration, the 2nd absorption column's inlet stream is the slipstream from the GPS. As a result, the composition of the gaseous inlet stream for the 2nd absorption column is identical to that of the GPS slipstream during the same operating pressure. Since 8-10 bar were determined to be optimum for the GPS column with slipstream, the same pressures were used in evaluating the 2nd absorption column.

The design, materials, and construction of the 2nd absorption column were similar to those of the GPS column, because the operating conditions and parameters for the 2nd absorption column are almost identical to those of the GPS column. Both columns have the solvent and gaseous inlets and outlets at the top and bottom of the column and have similar flow rates and identical operating pressures. The primary differences between the 2nd absorption column and the GPS column are that the temperature is much lower in the 2nd absorption column and the inlet gas flow rate is greater than the outlet gas flow rate (opposite of the GPS column). The second absorption column was fabricated with an inter-cooling system. After the column was installed, shakedown testing using water/air system was conducted to ensure that the system works properly before solvent tests.

During the second absorption column test, the solvent was preloaded with CO_2 to a desired level. The loading level was set constant at which the CO_2 equilibrium pressure of the solution at 40°C is around 0.10 atm. The preloaded amine solvent then was used to absorb CO_2 from the rich stripping gas in the second absorption column. The gas stream feeding to the second absorption column was prepared using mixture of CO_2 and N_2. The compositions of the prepared gas mixture are determined according to the cooled (to 40°C) rich stripping gas from the GPS column (obtained in the previous task). The parameters to be investigated include solvent concentration, G/L ratio, and feed gas flow rate.

4.3.2 Second absorption column testing

The performance of the 2nd absorption column was evaluated at 8 bar using an inlet stream that was 67% CO_2 (the GPS slipstream composition at 8 bar) and then at 10 bar with an inlet stream of 60% CO_2 (the GPS slipstream composition at 10 bar). The lean loading was maintained at 7.85% (the same value used in evaluating the GPS column's performance). The G/L ratio (cc stripping gas / g solvent) was 46 at 8 bar and 32 at 10 bar. Measuring the concentration of CO_2 in the gaseous outlet provides a means to validate the ability of the 2nd absorption column to recover the stripping gas to its lean state. The target CO_2 composition of the lean stripping gas is less than 5%.

The effects of temperature at the top of the column and the G/L ratio on the CO_2 concentration in the outlet gas stream of the 2nd absorption column are shown in Figures 4.22-4.23 for 8 bar operating pressure. The similar results are presented for an operating pressure of 10 bar in Figures 4.24-4.25. The simulation results showed that the CO_2 concentration in the outlet gas stream would increase with increasing temperature at the top of the column, as well as with increasing G/L ratio. The first trend was observed in the experimental data. The 2nd absorption column performance exceeds its target that CO_2 concentration is less than 5%. This anticipated performance trend is noticed through the increase of CO_2 in the gaseous outlet.

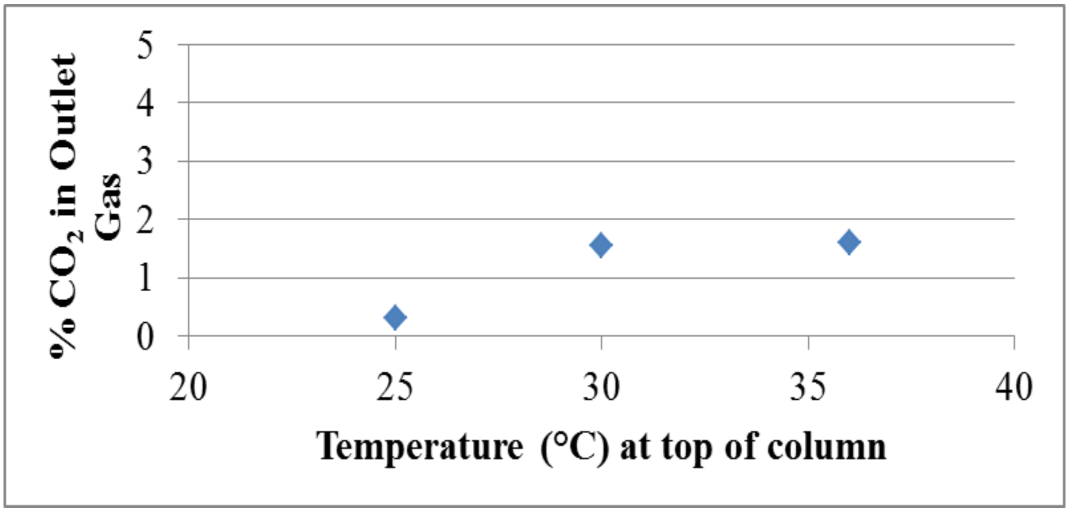

Figure 4.22. Effect of column top temperature on CO_2 level in outlet gas at operating pressure of 8 bar

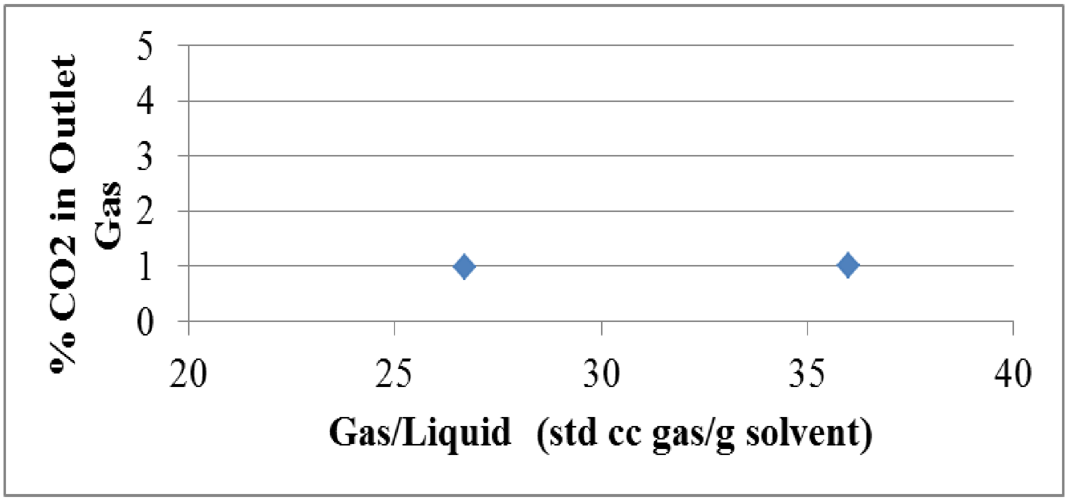

Figure 4.23. Effect of gas/liquid ratio on CO_2 level in outlet gas at operating pressure is 8 bar

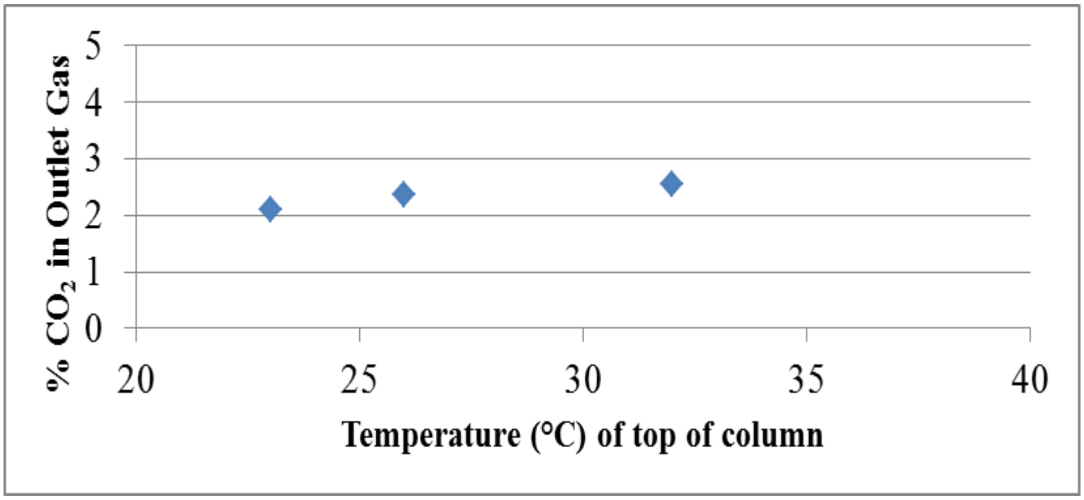

Figure 4.24. Effect of temperature on CO_2 level in outlet gas at operating pressure of 10 bar

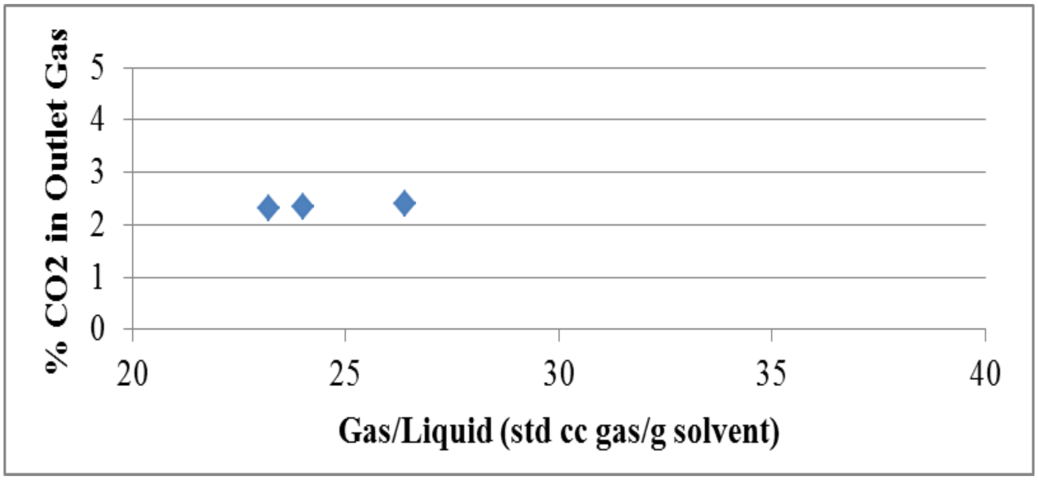

Figure 4.25. Effect of gas/liquid on CO_2 level in outlet gas at operating pressure is 10 bar

This good performance is a combination of a large driving force at the bottom of the column and the ability to achieve thermodynamic equilibrium at the top of the column. These results can be understood by examining the gap between the gaeous CO_2 concentration and the corresponding equilibrium CO_2 concentration along the column depth. In traditional systems, this gap is relatively small and tends to remain constant along the depth of the column, hence the driving force to equilibirum is minimal. In comparison, for this 2nd absorption column design, the gap is relatively large and changes along the length of the column. This means that the driving force is large at the bottom of the column and enables equilibrium to be achieved at the top of the column. This large driving force is due to the ability to operate at a low temperature with high CO_2 partial pressure at the bottom of the 2nd absorption column.

4.4 Flasher Tests

In original GPS-based process design, a series of flashers would be used for regeneration of the rich solvent from the second absorption column. The flasher tests were used to determine the appropriate operating conditions (i.e., pressure and residence time).

4.4.1 Experiments setup for the flasher

The autoclave used for VLE tests introduced in Section 3 was modified and operated herein as a continuously stirred tank reactor to determine the appropriate operating conditions (i.e., pressure and residence time) for the flasher tests. The experimental apparatus for VLE measurements was modified for the flasher tests, as shown in Figure 4.26. The major modifications included:

- Adding a solvent feed tank used to prepare and introduce CO_2 loaded feed streams to the flasher;
- Adopting a high-pressure metering pump to introduce the CO_2 loaded solvent into the autoclave;
- Applying P&ID controlled heating elements along this pumping line to achieve the desired feed temperature of 120°C;
- Setting up a sampling system inside the autoclave that cools the sample to prevent desorption of CO_2 upon exposure to atmospheric pressure; and
- Adding a backpressure regulator and cooling elements to the outlet of the autoclave.

The original test matrix from the SOPO is shown in Table 4.4. These testing conditions were carried out on all three proprietary solvent mixtures, which are the same solvents as used in the solvent VLE tests. Solvents were tested at four backpressure regulator set points (10, 20, 40, and 60 bar). Measurements were taken at three residence times (1, 2, and 4 minutes) for each backpressure regulator set point.

Table 4.4. Experimental ranges for Flasher Test

Factors	Range	Data Points
Pressure (bar)	10~100	10
Residence time (minutes)	1~20 minutes	10

Figure 4.26. The autoclave system modified for the flasher tests

4.4.2 Flasher testing

The objectives of the flasher tests are: 1) to demonstrate that the outcome of the process was independent of residence time, which indicates that the process is controlled by heat transfer rather than mass transfer thus there is no need to oversize flasher; and 2) to validate that the attributes of the outlet stream from the flasher would match the phase equilibrium data obtained from the VLE tests described in Section 3. These results further verify the flasher simulation predictions.

The results from the flasher tests are illustrated in Figures 4.27-4.29 ("5.2 exp" in the legend refers to the results of corresponding VLE measurements from the Project Task 5.2). For all three solvents, the results measured experimentally agree well with the data collected at 10 and 20 bar. At operating pressure of 40 and 60 bars, however, the measured CO_2 pressure was greater than those by corresponding simulation. One potential source for this deviation was the sampling technique. Samples were cooled to prevent CO_2 desorption from the solvent. The prevention of CO_2 desorption from the solvent sample was much more difficult when pressures were greater than 40 bar. While at higher operating pressures the solvent has a much higher loading than when at lower pressure. Another challenge was the precipitation of PZ as observed in VLE tests at high loadings and high PZ concentrations in the solutions. This precipitation effect could limit the PZ concentration that could be used in the GPS process.

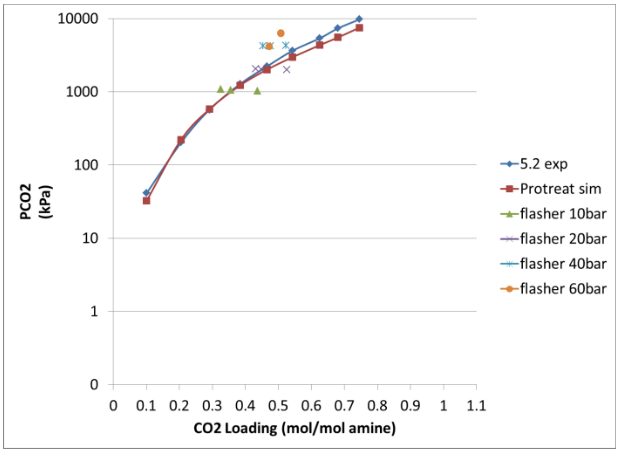

Figure 4.27. Flasher measurements for CO_2 in 15% PZ / 35% MDEA / 50% H_2O (w/w) solvent. Data are compared with ProTreat simulation and VLE testing (5.2 exp)

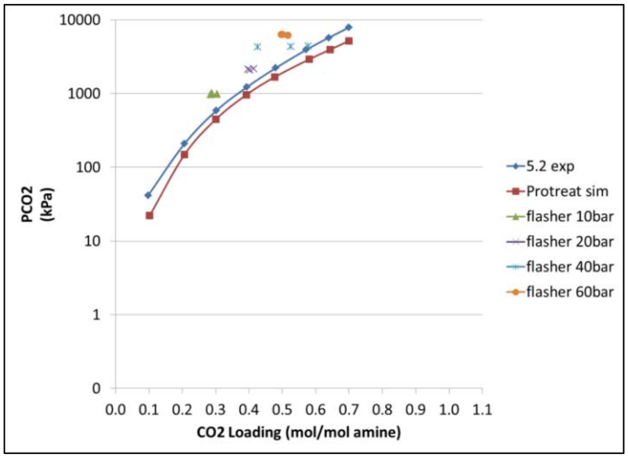

Figure 4.28. Flasher measurements for CO_2 in 20% PZ / 30% MDEA / 50% H_2O (w/w) solvent. Data are compared with ProTreat simulation and VLE testing (5.2 exp)

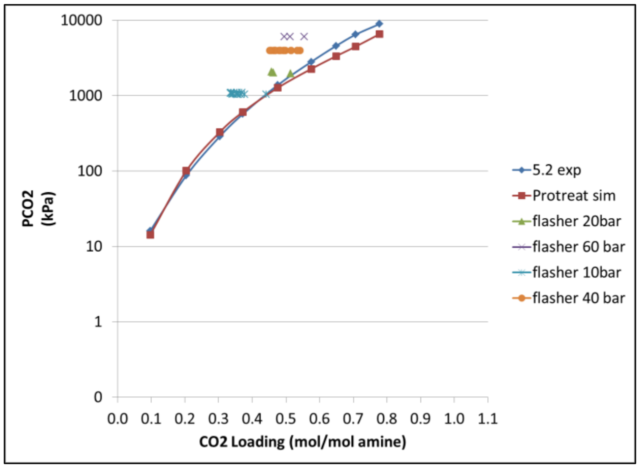

Figure 4.29. Flasher measurements for CO_2 in 25% PZ / 25% MDEA / 50% H_2O (w/w) solvent. Data are compared with ProTreat simulation and VLE testing (5.2 exp)

4.5 RPB Unit Evaluation at CCS LLC Laboratories

A lab-scale standard rotating packed bed (RPB) was evaluated at anticipated absorption and stripping operating conditions to determine the necessary design modifications for GPS system operation and to convey these design modifications to the project partner, HiGee Environment & Energy Technology (HiGee USA). The investigation of RPB may mitigate the project risk, because the RPB-based GPS system can provide a low capital cost alternative.

4.5.1. Setting-up of bench scale RPB unit

The project partner, HiGee USA, supplied a standard lab-scale RPB unit for this task. After review and discussion between a HiGee USA scientist and CCS LLC engineers, potential design enhancements were achieved to enable the unit to be optimized for the GPS process. A schematic of the RPB is shown in Figure 4.30. RPB has been used at commercial facilities in China for a variety of applications, including the control of primary pollutants. The technology has been shown to be scalable to a 50 MWe utility power plant and has been safely operated at industrial facilities in China for years. The RPB unit used in the tests is shown in Figures 4.31-4.32. Figure 4.31 illustrates the RPB unit and Figure 4.32 shows the RPB testing system.

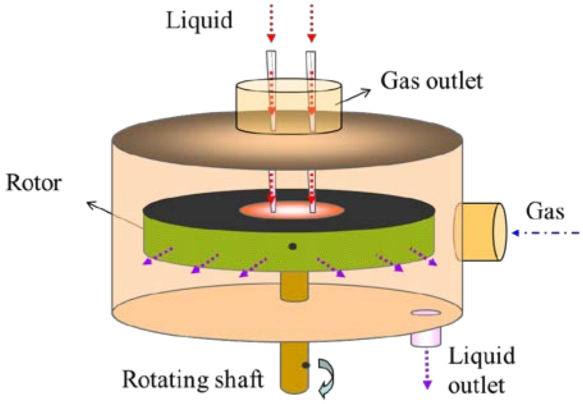

Figure 4.30. Schematic of RPB unit

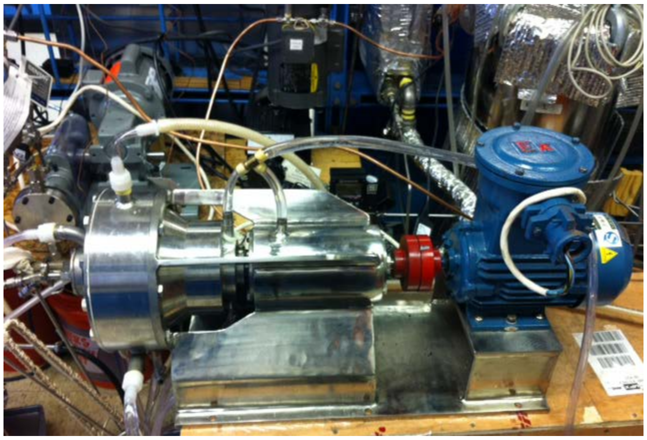

Figure 4.31. Lab-scale RPB unit

Figure 4.32. RPB testing system at CCS LLC facility

4.5.2. Testing of bench scale RPB unit

The standard lab-scale RPB unit was tested at anticipated absorption and stripping operating conditions. The operating parameters evaluated during the lab-scale tests are rotational speed, gas/liquid ratio, CO_2 loading and inflow gas flow rate under absorption and stripping operating modes, respectively. The results obtained from these experimental tests can be used to assess the potential of the enhanced RPB unit to replace conventional packed columns.

Evaluation of the RPB unit was performed at CCS LLC's laboratory. Preliminary tests on this lab-scale RPB unit have focused on exploring whether the size reduction exhibited for other applications can be achieved when the RPB is adapted for GPS applications. Figure 4.33 shows the relationship between equivalent mass transfer height ratio and lean loading at two different flow rates for a lab-scale RPB unit. The larger the equivalent height ratio is, the smaller the expected footprint for an RPB-based system. The results in Figure 4.33 indicate that the use of RPB could effectively reduce the equipment footprint by 20 times or more, hence greatly reduce capital cost of the columns.

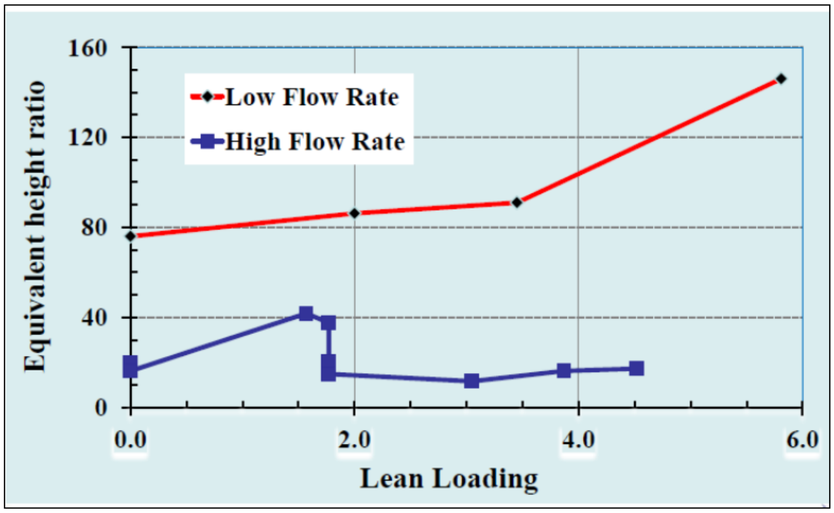

Figure 4.33. Relationship between equivalent height ratio to lean loading for RPB

Based on the experimental results obtained from the standard RPB unit and corresponding computer simulation results, the size of the RPB absorber was determined. It became clear that the radius of an RPB unit cannot be reduced owing to the requirement of necessary contacting time between gas phase and liquid phase. The radius of an RPB unit corresponds to the packing height of a conventional column, whereas the radius (related to the cross-section area) of a conventional column corresponds to the disk thickness of the RPB unit. When the scale is reduced, only the disk thickness of the RPB unit is reduced. That is why a bench-scale RPB unit still has a large radius, but a very thin disk thickness. On the other hand, it is good for scaling-up an RPB unit since scaling-up the disk thickness of an RPB unit is much easier than scaling-up the radius of the RPB unit.

5. CONTINUOUS SKID TESTING OF A BENCH-SCALE GPS BASED PROCESS

The purpose of continuous testing of a bench-scale GPS based process is to design and fabricate a bench-scale GPS unit capable of achieving at least 90% CO_2 capture from a nominal 500 slpm coal-derived flue gas slipstream at the NCCC operated by Southern Company Services in Wilsonville, Alabama. This testing system is skid-mounted with appropriate control systems to enable evaluation at the NCCC. The skid-mounted GPS system has only one absorption/stripping cycle and the slipstream tests was conducted with this one cycle system, as shown in Figure 1.3. The specific objectives of this skid testing are: 1) validate the GPS process simulation results with experiments under real flue gas; 2) investigate the influence of key operating parameters on GPS process performance; 3) experimentally measure the GPS process energy consumption; and 4) evaluate solvent stability and GPS skid performance during long-term, continuous operation.

5.1 Introduction to the Bench-Scale GPS based skid

A simplified process flow diagram for the GPS bench unit is shown in Figure 5.1. More information on the technology can be found in reference [13]. Both absorber and stripper can have two inter-stage heat exchangers for cooling or heating. Following flue gas cooling and desulfurization, CO_2 is absorbed from the flue gas in the absorber. The solvent temperatures at the inter-stage cooling in the absorber are controlled at around 31°C. The high-pressure GPS column (4-10 bar absolute) operates at 125°C to strip CO_2 from the amine-based solvent at the desired purity.

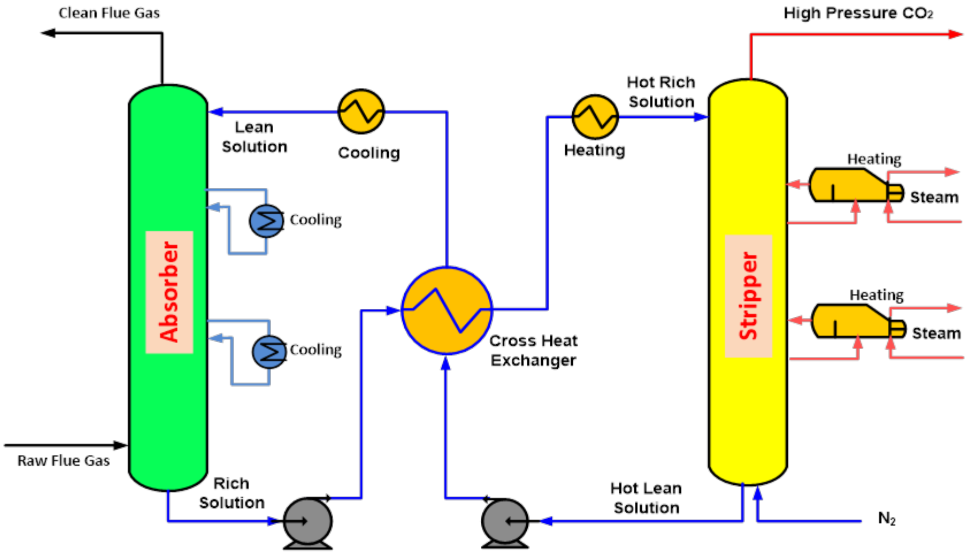

Figure 5.1. The flow diagram of the bench-scale GPS test unit

The skid has dimensions of 10’6” length and 8’ width. The absorber has 8’’ ID and 32’ height and the GPS column has 6” ID and 30’ height. The skid was equipped with PLC control system and able to run without manual intervention. To protect the heat exchangers and pumps in the outdoor condition, a guard made of large stainless metal panels was installed.

As shown in Figure 5.2, the absorption column (blue) and stripping column (silver) are two key components in the GPS skid-mounted system. Both columns are ASME certified vessels and 3/8 inch stainless steel Pall ring packing is used for both columns. The specifications of the columns are listed in Table 5.1. There are three sections of packing in series in the absorber. The absorber has two inter-stage cooling sections connecting the three packing sections. These sections are connected by flanges. The inter-stage cooling sections have liquid collectors, heat exchangers and redistributors. The liquid from upper packing sections is collected by the liquid collectors, flows through the heat exchanger to be cooled down, and then is sprayed into the lower packing section by the redistributors. For the stripper, there are also three sections of packing in series. The stripper has two inter-stage heating sections connecting the three packing sections. The design of the inter-stage sections is the same as the absorber. The operating pressure in the GPS column can go up to 10.3 bar (absolute) at 125°C. The flow rate of N_2 stripping gas can be as high as 30 slpm.

-+

Figure 5.2. Photos of the GPS-based skid

The GPS skid electrical system is comprised of two panels – a PLC panel with touch screen and data logger, and an electrical panel for motor drivers and the transformer. Many operating parameters are controlled via the PLC panel, including the incoming flue gas flow rate, the solvent flow rate, the solvent levels at the inter-stage liquid collectors and the solvent temperatures in the cooling/heating loops. The stripper pressure is controlled by a back-pressure valve. The nitrogen flow rate into the stripper is controlled by a manual valve.

Table 5.1. Specifications of the bench-scale absorber and stripper

	Absorber	Stripper
ID (inch)	8	6
Total height of packing (foot)	23	21
Total height of column (foot)	32	30

Fabrication of the skid was completed in early May 2014, followed by the preliminary factory acceptance test with air, water and steam conducted at Ascension Industries. The skid was shipped from Ascension Industries to NCCC in June 2014. The relevant documents for the skid, including P&ID, bill of materials, the testing reports, owner’s manual and equipment data sheet, were completed accordingly by the CCS team. Installation of the skid was completed in early August 2014, followed by commissioning and shakedown tests. CCS team provided engineering support to NCCC for the installation of the skid. After the shakedown test, CCS team engaged in the parametric test and long-term test.

5.2 Experimental results

The experiments included parametric tests, energy consumption measurements (through calibration of heat loss) and the long-term tests.

5.2.1 Parametric tests

Parametric testing spanned March 2-22, 2015. Due to a broken upper cooler (broken during the cold weather) in the absorber, parametric test data were obtained with one cooler (the lower cooler) in the absorber and two heaters in the stripper operating. Parametric tests investigated the influence of total flue gas flow rate, G/L volume ratio, stripper operating pressure and N_2 flow rate on the GPS system performance. The performance was characterized by the CO_2 removal rate in the absorber and CO_2 product pressure and purity in the stripper. The CO_2 removal rate was calculated based on the average CO_2 concentration at the absorber inlet and outlet, and the CO_2 purity was based on the averaged CO_2 concentration at the stripper outlet.

Representative data of the CO_2 concentration after the skid reached a steady-state is shown in Figure 5.2. For each parametric test, the data was recorded after the skid reached steady-state for new conditions. It normally took 30-60 minutes for the skid to transition from one steady-state to another when GPS bench unit parameters were adjusted.

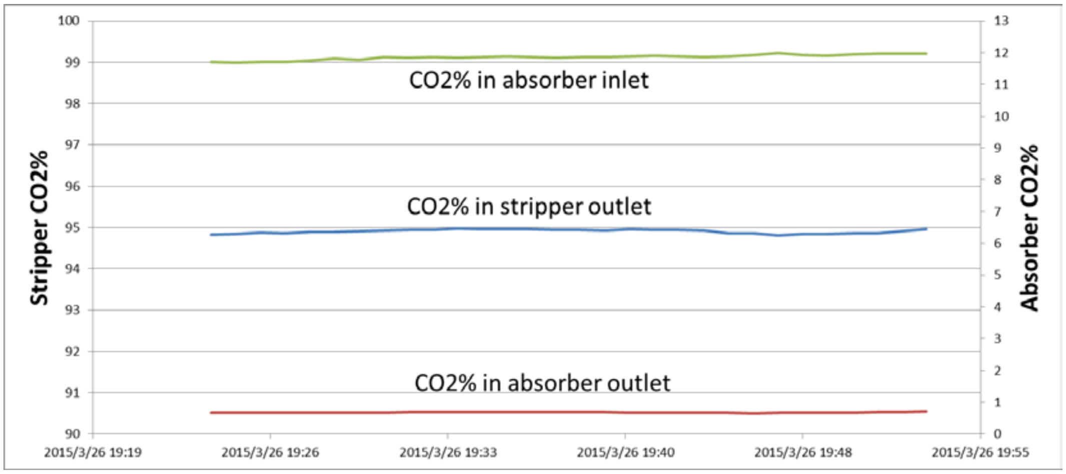

Figure 5.2. CO_2 concentrations under a steady state on March 26, 2015

The influence of total flue gas flow rate on GPS bench unit performance is illustrated in Figure 5.3. In these tests, the G/L volume ratio was kept at 145 and the stripper operating pressure was at 6.1 bar (absolute). The N_2 flow rate into the stripper was adjusted proportionally with the flue gas flow rate. With the increase of total flue gas flow rate, the CO_2 removal rate decreased, while the CO_2 product purity also decreased slightly. As the flue gas and solvent flow rate increased, the residence time for CO_2 absorption decreased and less reaction time led to lower reaction conversion, so that the CO_2 removal rate decreased. Although the residence time in the stripper also decreased, the height of stripper packing was more over-designed than that of absorber and the stripping reaction was faster due to its higher temperature. Thus, reduced reaction time had less influence on CO_2 stripping than absorption, which explains why the reduction of CO_2 purity is less significant.

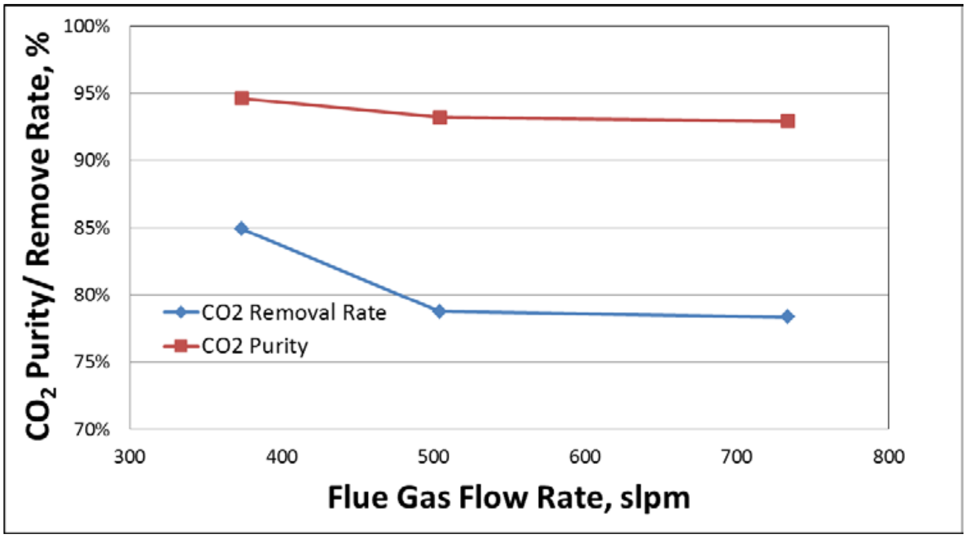

Figure 5.3. Influence of total flue gas flow rate on the performance of GPS technology

The effect of G/L volume ratio on GPS process performance is shown in Figure 5.4. The stripper operating pressure, solvent flow rate and nitrogen flow rate into the stripper were held constant at about 6 bar, 0.89 GPM and 2.35 slpm, respectively. The G/L volume ratio was changed by altering the flue gas flow rate and holding the solvent flow rate constant. With increase of G/L volume ratio, the CO_2 removal rate reduced significantly, but CO_2 purity was not affected. As the G/L volume ratio increased, the amount of flue gas processed per mass of solvent increased. In this case, to achieve the same CO_2 removal rate as the low G/L volume ratio, the height of absorber packing needed to be increased, because the required number of transfer units increased when the G/L volume ratio increased. However, since the same absorber was used in these experiments, CO_2 removal rate is reduced. On the other hand, due to the fact that the operating conditions in the stripper were kept the same as the G/L volume ratio increased, there was small variation in CO_2 purity from the stripper.

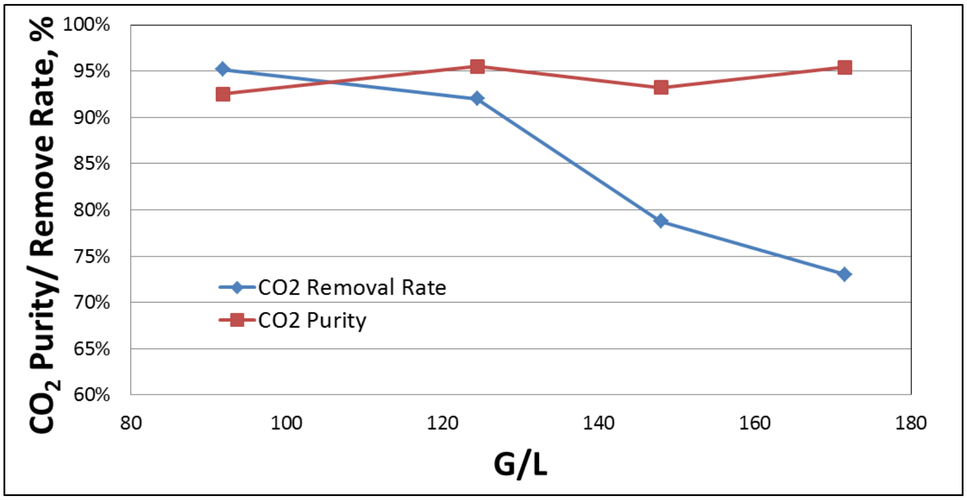

Figure 5.4. Influence of G/L ratio on the performance of GPS technology

The influence of stripper operating pressure on GPS process performance is shown in Figure 5.5. The flue gas flow rate and solvent flow rate were maintained at about 455 slpm (16 SCFM) and 0.95 GPM, respectively. During the experiments, the N_2 flow rate to the stripper was increased accordingly to ensure the lean loading was sufficient to achieve over 90% CO_2 removal in the absorber. With the increase of stripper operating pressure, both the CO_2 purity from the stripper and CO_2 removal rate in the absorber decreased. Because the CO_2 equilibrium partial pressure was a strong function of temperature and the stripper temperature was held constant for the four tests, CO_2 purity at the top of the stripper decreased as the total pressure increased. As the stripper operating pressure increased, the solvent lean loading at the stripper outlet increased in order to maintain a higher equilibrium partial pressure of CO_2. Higher solvent lean loading compromised the performance in the absorber, and as a result, the CO_2 removal rate decreased.

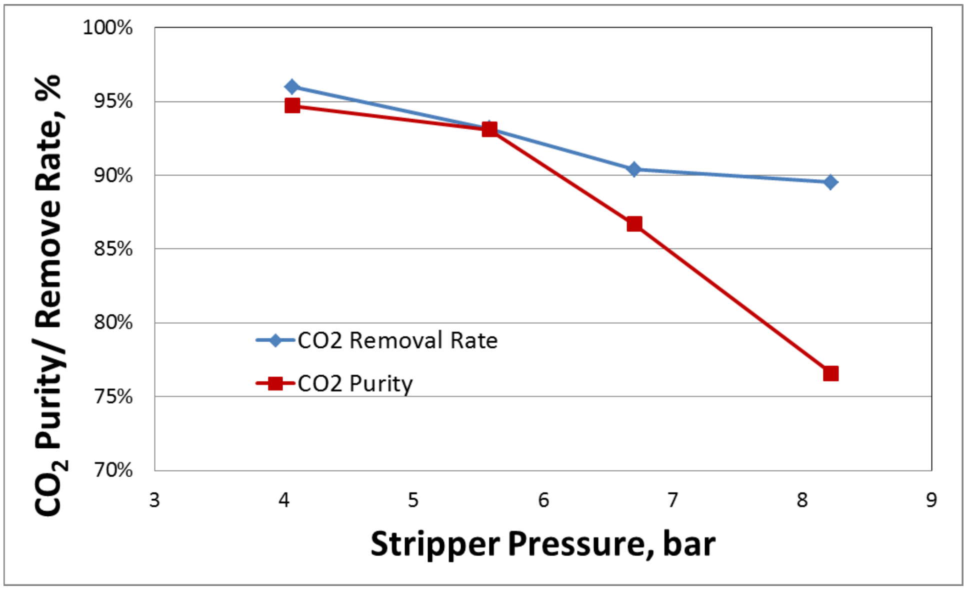

Figure 5.5. Influence of stripper operating pressure on the performance of GPS process

The effect of N_2 flow rate on GPS process performance is shown in Figure 5.6. In the experiments, the flue gas flow rate, stripper operating pressure and solvent flow rate were held constant at 500 slpm (18 SCFM), 5.9 bar and 1.09 GPM, respectively. With the increase of N_2 flow rate, the CO_2 purity reduced, but CO_2 removal increased. As the N_2 flow rate increased, the lean solvent loading at the stripper outlet decreased due to the lower CO_2 concentration at the bottom of the stripper. The solvent with lower lean loading enhanced CO_2 capture in the absorber. However, owing to the dilution of N_2, CO_2 purity from the stripper reduced.

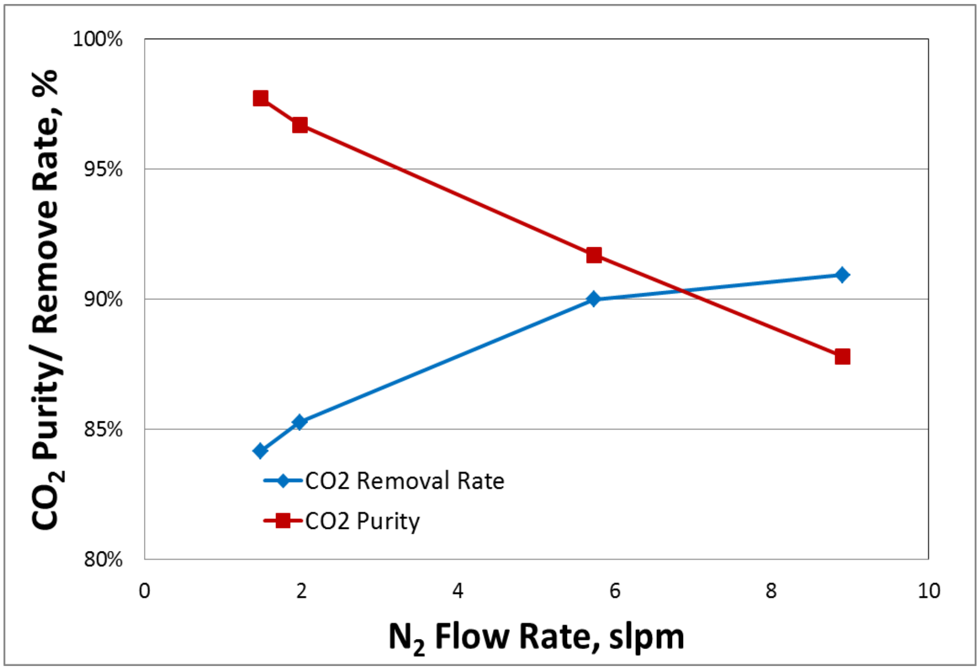

Figure 5.6. Influence of N_2 flow rate on the performance of GPS technology

Previous results showed the GPS bench unit could reach 90% CO_2 removal rate in the absorber (one cooler operating) and deliver 95% purity CO_2 product from the stripper. However, those experiments were conducted with the G/L volume ratio in the range of 121 to 127, which did not fully use the capacity of the solvent. After the broken cooler was replaced by a new one, the skid could run with two coolers and two heaters operating. When the incoming flue gas was 504 slpm and G/L volume ratio was 160, CO_2 removal rate in the absorber and CO_2 purity from the stripper were 74% and 93%, respectively. When the incoming flue gas was 325 slpm and G/L volume ratio was 160, CO_2 removal rate in the absorber and CO_2 purity from the stripper were 90.3% and 94.8%, respectively. And this was chosen as the condition to run during long-term testing.

5.2.2 Energy consumption test

To validate computer simulation results that showed the GPS technology consumed much less energy than the DOE MEA baseline case, bench-scale energy consumption tests were conducted. Since the sensible heat strongly depends on the selection of a heat exchanger, the tests were designed to only measure the reaction and stripping heat. The sensible heat of the solvent can be estimated based on the CO_2 working capacity, specific heat of the rich and lean solvent streams and temperature driving force (ΔT) for the cross heat exchanger. When the ΔT in the cross heat exchanger is assumed between 5 to 10^{o}C, the estimated sensible heat was in the range of 250 to 500 kJ/kg CO_2 captured.

To measure the actual reaction heat and stripping heat, the steam usage data was obtained after the GPS system reached the steady-state. The net steam demand for the reaction heat and stripping heat was calculated as the difference between the steam usages when the system was operated with and without flue gas flow. The steam usage for the skid operation without flue gas flow is actually a sum of the sensible heat and heat loss. These results are listed in Table 5.2. The results showed that the reaction and stripping heat ranged between 1,562-1,600 kJ/kg CO_2 captured and they are very close (less than 3%) to each other indicating the stability of the system. These experimental results were also very close to the results obtained from computer simulations, which was at 1,570 kJ/kg CO_2 captured.

Table 5.2. Energy consumption test results.

Solvent flow rate (GPM)	Flue gas flow rate (SCFM)	Stripper pressure (bar)	N_2 flow rate (slpm)	The sum of reaction heat and stripping heat (kJ/kg CO_2 captured)	CO_2 removal rate in absorber	CO_2 purity from stripper
0.89	14.5	6	2.59	1,600	90%	94.1%
1.10	17.8	5.8	2.63	1,562	84%	95.8%
0.57	11.6	6	1.67	1,597	93%	95%

5.2.3. Long-term test

For the long-term tests, the skid was set to run at a condition that could achieve 90% CO_2 removal and 95% CO_2 product purity based on the results obtained from the parametric test campaign. The incoming flue gas and the solvent flow rates were kept at 330 slpm and 2.1 lpm, respectively, which equates to a G/L volume ratio of 156. The operating pressure of the stripper was kept at 6 bar (absolute) with a N_2 flow rate of 1.7 slpm. The skid was operated in 24-hour mode unless it was shut down for the following situations: (1) the components on the skid did not function properly, and CCS team needed to do maintenance or trouble-shooting; or (2) the flue gas or utilities were not available at NCCC. The long-term tests spanned from May 23, 2015 to August 10, 2015. The operation was fairly stable and representative CO_2 concentration data over a 24-hour period is shown in Figure 5.7. The historical data can be found in reference [14]. In general, the CO_2 removal rate was 70-90% and CO_2 product purity was 90-96%.

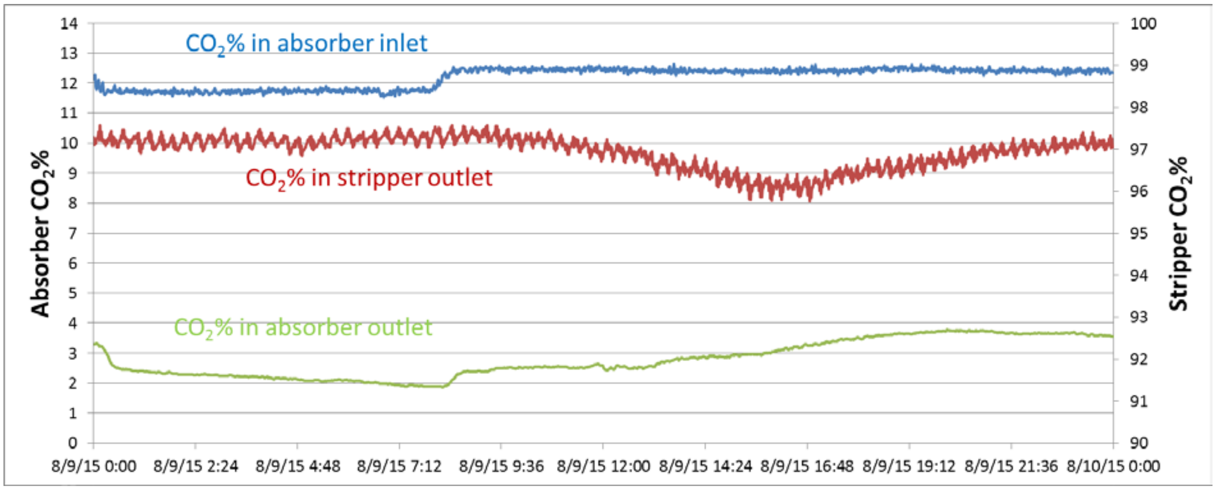

Figure 5.7. Summary of CO_2 concentrations in the long term tests

Long-term testing was conducted during the summer of 2015 at the NCCC host site in Wilsonville, AL and GPS bench unit performance was impacted by the local ambient conditions. In the summer time, the cooling water temperature was relatively high compared to other seasons and the heat exchangers installed on the CO_2 absorber had difficulty cooling the solvent to the target low temperature of 31°C. In addition, the cooling water temperature was always low in early morning and high in the afternoon. That caused the CO_2 removal rate in early morning to be higher than that in the afternoon. For example, on August 9, the average removal rate was 82.6% for the period from 0:00 to 7:00, and 78.2% for the period from 12:00 to 19:00.

CCS LLC monitored solvent loss during the long-term test. The measurements accounted for the loss of both water and amine due to their vapor in the gas phase and formed aerosols carried by the gas leaving the GPS bench unit. The loss rate was calculated by monitoring the liquid level in the lean solvent storage tank.

Based on the lean tank solvent level readings at 19:00 on July 27 and July 30, 2015, when the GPS bench unit continuously ran, the average solvent net loss was 2.9 kg/day. Based on the lean solvent tank level readings at 7:00 on August 7 and August 10, 2015, the average solvent net loss was 3.2 kg/day. Since the bench-scale skid system was not equipped with a solvent recovery system, the solvent loss rate was high. Normally, the industrial-scale absorber and stripper have a water wash section to recover the solvent. The goal of bench unit test was to study GPS technology, rather than an optimized process. Without the water wash section, the GPS technology can be evaluated via simpler operation at an affordable cost of solvent loss.

To investigate the influence of solvent loss on its amine concentration, CCS LLC took lean solvent samples regularly for NCCC analysis of PZ and water concentration. On July 23, fresh solvent with 15% PZ, 35% MDEA and 50% H_2O was loaded. Table 5.3 showed the test results in a period that no make-up solvent was added. The data showed that the PZ concentration increased gradually and water concentration decreased gradually as water loss out-paced solvent loss.

Table 5.3. Test results of piperazine and water concentration during long-term test

Date	Piperazine concentration wt%	Water concentration wt %
7/28/2015	18.2%	39.6%
7/30/2015	19.0%	38.2%
8/6/2015	19.7%	
8/7/2015	20.4%	34.8%

5.3. Summary of the skid testing

The tests of the bench-scale GPS skid unit at the NCCC were completed successfully. However, during the process many issues occurred and were resolved, and lessons were learned. The tests achieved the original goals in terms of validating and demonstrating the advantages of GPS technology over the traditional absorption/stripping process. The long-term tests demonstrate that the skid could operate continuously for a long period of time with required CO_2 removal from the flue gas and CO_2 product purity. The results have demonstrated that GPS process is able to achieve 90% CO_2 removal from typical coal-derived flue gas. GPS process is also able to produce high-pressure CO_2 product with required purity. Additionally, the energy consumption of the GPS process is much lower than that of the DOE MEA baseline case.

6. TECHNO-ECONOMIC STUDY OF GPS-BASED PCC PROCESS

6.1 Introduction

Under the DOE's Carbon Capture Program, CC LLC, working with the team members of the project, is developing a novel GPS process [1] to enable efficient post-combustion carbon capture (PCC) from coal-fired power plants. The techno-economic feasibility study is a required task for the project. The study analyzes a fully-integrated PC power plant equipped with GPS technology for PCC, and is carried out, to the maximum extent possible, in accordance to the methodology and data provided in Basis for Technology Feasibility Study of DOE Funding Opportunity Number: DE-FOA-0000403 [2].

The DOE/NETL report on "*Cost and Performance Baseline for Fossil Energy Plants, Volume 1: Bituminous Coal and Natural Gas to Electricity* (Original Issue Date, May 2007), NETL Report No. DOE/NETL-2007/1281, Revision 1, August 2007" [3] was used as the main source of reference to be followed, per the guidelines of DE-FOA-0000403. The DOE/NETL-2007/1281 study compared the feasibility of various combinations of power plant/CO_2 capture process arrangements. The report contained a comprehensive set of design basis and economic evaluation assumptions and criteria, which are used as the main reference points for the purpose of this study. Specifically, Nexant adopted the design and economic evaluation basis from Case 12 of the above-mentioned DOE/NETL report. This case corresponds to a nominal 550 MWe (net), supercritical greenfield PC plant that utilizes a benchmark MEA-based absorption system for CO_2 capture and compression.

For this TEA, GPS process replaces the MEA-based CO_2 absorption system used in the original baseline case. The objective of this study is to assess the performance of a full-scale GPS-based PCC design that is integrated with a supercritical PC plant similar to Case 12 of the DOE/NETL report, such that it corresponds to a nominal 550 MWe supercritical PC plant with 90% CO_2 capture. This plant has the same boiler firing rate and superheated high pressure steam generation as the DOE/NETL report's Case 12 PC plant. However, due to the difference in performance between the GPS-based PCC and the MEA-based CO_2 absorption technology, the net power output of this plant is not exactly 550 MWe.

This final TEA report updates the preliminary study report that was issued in October 2012, incorporating the latest bench-scale experimental and simulation optimization data generated on the GPS process.

6.2 Design Basis

6.2.1 Power plant design criteria

6.2.1.1 General

The design PC power plant used in this study is a supercritical steam-electric generating power plant with carbon capture to generate a nominal 550 MWe on a net basis, consistent with the DOE/NETL-2007/1281 report's Case 12 supercritical PC plant with CO_2 capture. The gross output of the plant is about 663 MWe. The steam generator for the supercritical PC plant is a drum wall-fired, totally enclosed dry bottom boiler, with superheater, reheater, economizer and air-heater. The steam turbine generator (STG) is operating at throttle conditions of 3,500 psig/1,100°F/1,100°F, and with surface condenser operating at ~2 inch Hg using 60°F cooling water that is available to the power plant.

The plant is designed for NOx reduction using a combination of low-NOx burner and overfire air as well as with the installation of a selective catalytic reduction (SCR) system. It is also designed for particulate control with baghouse and a wet limestone-based flue gas desulfurization (FGD) system for sulfur removal. This combination of pollution control technologies result in a significant co-benefit capture of mercury. The mercury co-benefit capture is assumed to be 90% for this combination, sufficient to meet current mercury emissions limits, hence no activated carbon injection is included in this case.

The power plant is considered to operate as a base-loaded unit, but with consideration for daily or weekly cycling. Annual capacity factor is 85 percent or 7,450 hrs/year at full capacity

6.2.1.2 Site-related conditions

The supercritical PC plant in this study is assumed to be located at a generic plant site in Midwestern USA, with site-related condition as shown below:

Location	Midwestern USA
Elevation, ft above sea level	0
Topography	Level
Size, acres	300
Transportation	Rail
Ash/slag disposal	Off Site
Water	Municipal (50%)/Groundwater (50%)
Access	Landlocked, having access by train and highway
CO_2 disposition	Compressed to 2,200 psig at battery limit before being transported 50 miles for sequestered in a saline formation at a depth of 4,055 ft (Study scope limited to delivery at battery limit only)

6.2.1.3 Meteorological data

Maximum design ambient conditions for material balances, thermal efficiencies, system design and equipment sizing are:

Atmospheric pressure, psia	14.7
Dry bulb temperature (DBT)	59°F
Wet bulb temperature (WBT)	51.5°F
Ambient relative humidity, %	60

6.2.1.4 Technical assumptions and data

Other technical data and assumptions include:

- Design coal feed to the power plant is Illinois No. 6 with characteristics presented in Table 2-1. The coal properties are from NETL's Coal Quality Guidelines.
- Selected flows and operating conditions for the turbine are listed below:

Turbine gross power output, MW	663
SH HP steam inlet flow, 1000 lbs/hr	5,241
HP turbine inlet pressure, psig	3,500
HP turbine inlet temperature, °F	1,100
HP turbine outlet pressure, psig	696
IP turbine inlet pressure, psig	639
IP turbine inlet temperature, °F	1,100
IP turbine outlet pressure, psig	123
LP turbine inlet pressure, psig	123
Surface condenser pressure, inches Hg	2.0
Deaerator pressure, psig	119

For this study, a GateCycle™ model of the steam cycle is developed and calibrated against the 2007 DOE/NETL report to define the reference supercritical PC power plant steam cycle characteristics.

See Figure 6.1 for a summary of the calibrated output. To estimate the power plant performance for the different potential PCC cases for the project, the low pressure turbine and condenser section of the calibrated GateCycle™ model is modified to meet the specific steam extraction required by each PCC scheme.

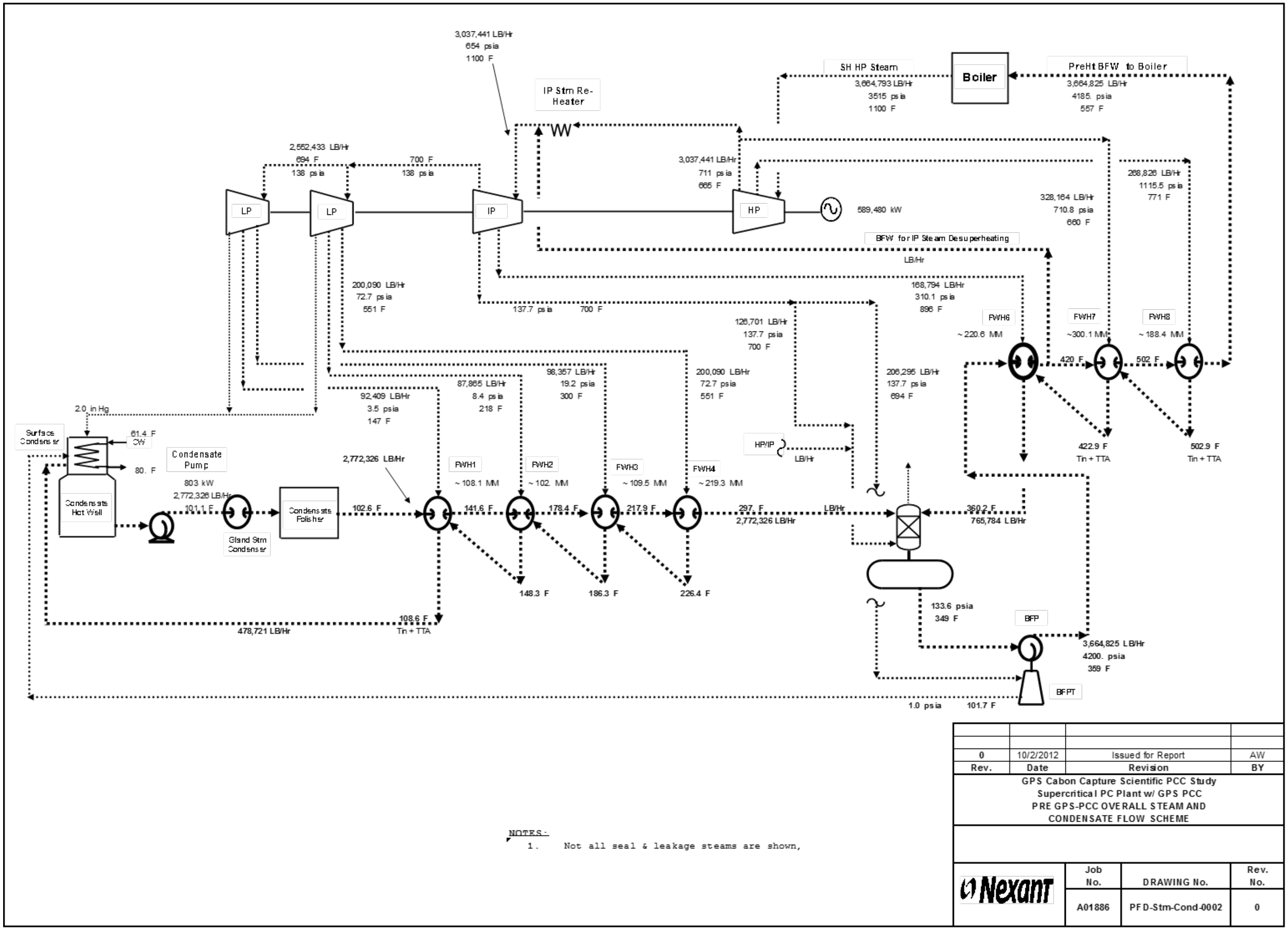

Figure 6.1. Pre-PCC Steam and Condensate Flow Scheme

- To generate the 5,241,000 lb/hr of SH HP steam to the STG, the boiler will burn 586,627 lb/hr, or 6,845 MMBtu (HHV)/hr of as-received Illinois No. 6 coal as listed in Table 6.1. The boiler firing rate and the SH HP steam generation are held constant for all PCC cases.

Table 6.1. Illinois No. 6 Coal Specification

Rank Seam Source	Bituminous Illinois #6 (Herrin) Old Ben Mine
Ultimate Analysis (as received), weight%	
Carbon	63.75
Hydrogen	4.50
Nitrogen	1.25
Chlorine	0.29
Sulfur	2.51
Oxygen	6.88
Ash	9.70
Moisture	11.12
Total	100.0
Proximate Analysis (as received), weight%	
Volatile Matter	34.99
Fixed Carbon	44.19
Ash	9.70
Moisture	11.12
Total	100.0
HHV (Btu/lb)	11,666

- Auxiliary loads for the overall plant can be separated into three categories: PCC-independent PC aux loads, PCC-dependent PC aux loads, and PCC loads. PCC-independent PC aux loads total 28,330 kWe, according to the following breakdowns:

Auxiliary load breakdown	kWe
Coal Handling & Conveying	490
Limestone Handling & Reagent Preparation	1,270
Pulverizer	3,990
Ash Handling	760
Primary Air Fans	1,870
Forced Draft Fans	2,380
Induced Draft Fans	10,120
SCR	70
Baghouse	100
FGD Pumps and Agitators	4,250
Condensate Pumps	630
Steam Turbine Auxiliaries	400
Miscellaneous BOP	2,000
Total PCC-independent PC aux loads	28,330

PCC-dependent PC aux loads include cooling water (CW) circulation pump loads, cooling tower (CT) fan loads, and transformer loss. PC CW and CT loads are proportional to the STG surface condenser duty which varies depending on the PCC steam extraction requirement. Transformer loss is proportional to STG gross power output which also varies with PCC steam extraction requirement.

PCC loads will vary depending on the PCC design and include power consumed in the CO_2 capture and compression processes, plus any new CW and CT consumptions due solely to the PCC cooling loads.

- It is assumed that the supercritical PC utilizes a mechanical draft, evaporative cooling tower, and all process blowdown streams are assumed to be treated and recycled to the cooling tower. The design ambient wet bulb temperature of 51.5°F is used to achieve a cooling water temperature of 60°F using an approach of 8.5°F. The PC cooling water range is assumed to be 20°F. The cooling tower makeup rate was determined using the following:

  Evaporative losses of 0.8% of the circulating water flow rate per 10°F of range;
  Drift losses of 0.001% of the circulating water flow rate;
  Blowdown losses are calculated as follows:
  Blowdown Losses = Evaporative Losses/(Cycles of Concentration - 1)
  where cycles of concentration is a measure of water quality, and a mid-range value of 4 is chosen for this study.

- Raw water makeup was assumed to be provided 50% by a publicly owned treatment works and 50% from groundwater.

6.2.1.5 Environmental or emissions requirements

Design emissions requirements and limits for the supercritical power plant with PCC in this study are as follow:

• SO_2	0.085 lb/MMBtu
• NOx	0.070 lb /MMBtu as NO_2
• Particulate Matter (Filterable)	0.013 lb/MMBtu
• Hg	1.14×10^{-6} lb/MMBtu
• VOC	0.0025 lb/MMBtu

6.2.2 PCC design criteria

6.2.2.1 General

The PCC plant is designed as an integral part of the supercritical PC plant to recover up to 90% of the CO_2 in the flue gas. For the supercritical PC plant with CO_2 capture, it is assumed that all of the fuel carbon is converted to CO_2 in the flue gas. CO_2 is also generated from limestone in the FGD system, and 90% of the total CO_2 exiting the FGD absorber is subsequently captured in the PCC.

The projected largest-single train size equipment is used to maximize economy-of-scale. Vessels exceeding transportation size limits (as specified in the Project Transportation Size Limitation section of this document) will be field fabricated. The equipment is designed for a 30-year plant life.

Rotating equipment critical to the continuous plant operation is spared. Where sparing is not feasible, alternate operation will be identified to maintain continuous power plant operation.

6.2.2.2 Flue gas feed specification

The PC plant boiler will be burning 586,627 lb/hr, or 6,845 MMBtu(HHV)/hr of as-received Illinois No. 6 coal to generate 5,241,000 lb/hr of SH HP steam to the STG, as per the Case 12 supercritical PC plant in the 2007 DOE/NETL report. Flue gas exiting the wet FGD before the vent stack is the design feed for the PCC plant. The corresponding flue gas feed composition and flow rate to the PCC plant are as following:

Composition, Vol. %:

N_2 (include Argon)	67.70
CO_2	13.26
O_2	2.35
H_2O	16.68 (by difference)
Emission components (see below)	0.01
Total Vol. %	100.00

Total gas volumetric flow rate, SCF/Hr	90,493,000 (calculated)
Total gas molar flow rate, lbmoles/hr	238,453
Total gas mass flow rate, lbs/hr	6,833,360
Temperature, °F	135
Pressure, psia	15.2

The estimated emission component flows included in the flue gas feed are assumed to be at the emission specifications and are as follows:

NO (assume 95 vol% of NOx)	297 lb/hr (max)
NO_2 (assume 5 vol% of NOx)	24 lb/hr (max)
SO_2	582 lb/hr (max)
PM $_{\text{Filterable}}$	89 lb/hr (max)

Emission component NO_2, and SO_2 can potentially be further removed from the flue gas through non-reversible reactions with the amine solvent used. NO and Hg are assumed to pass through the PCC recovery unit and released to the atmosphere with the treated flue gas. PM is assumed to be removed from the flue gas through water and amine solvent scrubbing.

6.2.2.3 Design CO_2 product specifications

Recovered CO_2 is sent to the battery limit (B/L) for delivery to a saline reservoir for sequestration via carbon steel pipeline with the following specifications, per the NETL's Quality Guidelines for Energy System Studies CO_2 Impurity Design Parameters report:

Inlet pressure, psig	2,200
Inlet temperature, °F	79
CO_2 concentration, vol%	> 95
N_2 concentration, vol%	< 4
O_2 concentration, vol%	< 4
H_2O, ppm$_{wt}$	< 300

6.2.2.4 Utility commodity specifications

- Low Pressure Steam

  Low pressure (LP) steam for PCC stripper reboiling can be extracted from the power plant to meet the following PCC B/L conditions:

Min pressure, psia	As Required
Temperature, °F	Sat + 10

  LP steam, if needed, is assumed to be desuperheated to 10°F above saturation temperature to allow positive control of desuperheater condensate injection. Degree of LP steam superheat can be varied to meet minimum desuperheater design requirement.

- Intermediate Low Pressure Steam

  Intermediate low pressure (ILP) steam for amine reclaiming, if needed, can be extracted intermittently from the power plant at the following B/L conditions:

Min pressure, psia	As Required
Temperature, °F	Sat + 10
Equivalent frequency, % of time	~ 15%

  The ILP steam is assumed to be desuperheated to 10°F above saturation temperature to allow positive control of desuperheater condensate injection. Degree of ILP steam superheat can be varied to meet minimum desuperheater design requirement.

- Return Condensate

  Reboiler steam condensate will be pumped back to the power plant hot at the following conditions:

Min pressure, psia	175
Temperature, °F	TBD by PCC Design

- Cooling Tower Water

  Cooling water from the new PCC cooling towers is available at the following conditions:

Maximum supply temperature, °F	60
Maximum return temperature, °F	100
Maximum supply pressure, psia	70
Maximum PCC pressure drop, psi	30

- Power Plant Condensate for Waste Heat Recovery

  Condensate from the power plant surface condenser hotwell is available, downstream of the condensate polisher, for waste heat recovery (WHR) in the PCC plant. Relevant condenser and condensate system parameters are indicated below:

Condenser inlet cooling water temperature, °F	60
Condensate maximum supply temperature, °F	80
Cond flow at 6,845 MMBtu/hr firing, 10^6 lbs/hr	3.95
Maximum cond available for WHR, 10^6 lbs/hr	3.2
Minimum condensate pressure before Deaerator, psia	130
Maximum PCC pressure drop, psi	30

  PCC plant heat source pressure, when containing amine compounds or CO_2, should be at least 30 psi lower than the minimum condensate pressure to avoid contaminating the condensate to the deaerator from heat exchanger leakage.

6.2.2.5 Process water streams

The PCC plant is designed to minimize/eliminate discharging hydrocarbon solvent-containing waste waters.

Process purge water from scrubbing the WFGD flue gas feed has no hydrocarbon solvent and will be recycled as makeup water to the new cooling tower system. If necessary, this feed scrubber purge water can be filtered and recycled as feed to the new demineralizer unit to minimize well water consumption.

6.2.3 Cost Estimation Methodology

The Total Plant Cost (TPC) and Operation and Maintenance (O&M) costs for the supercritical PC power plant and the associated CO_2 capture plant are estimated as described in this section. The estimates will be based on 2007 costs, per ATTACHMENT 3 of the FOA.

6.2.3.1 Capital Cost

The DOE/NETL report provided a cost estimate for 14 major subsystems of the Case 12 supercritical PC plant with CO_2 capture. Using this as the reference cost estimate, modifications to each subsystem were made either by capacity factoring or by direct replacement to obtain the overall cost estimate for the nominal 550 MWe supercritical PC plant with GPS-based PCC. For the subsystems in which capacity factoring was used to perform the cost estimates, a power factor of 0.7 was applied. The list of the Case 12 supercritical PC plant subsystems and bases for modifications are shown in Table 6.2.

- Supercritical PC Plant

  The capital cost estimates for the supercritical PC section of the overall plant are developed based on the Case 12 costs provided in the DOE/NETL report.

  The PCC section in this study differs from the CO_2 capture section provided in the DOE/NETL report, resulting in a variation of the PC plant performance due to the differences in PCC design as well as solvent selection. The revised PC plant with GPS-based PCC performance was estimated on GateCycle™, using the GPS PCC LP steam extraction rate, hence resulting in a different power generation rate from the DOE/NETL Case 12 supercritical PC plant. For this reason, the PC plant equipment costs (primarily for the LP steam turbine, condenser and CW/CT sections) are re-estimated on a capacity-factor basis using the DOE/NETL reported costs as a baseline reference.

  Material, direct labor, engineering and construction management fees and home office cost, and contingencies consistent with those used in the DOE/NETL report Case 12 are added to come up with the total supercritical PC plant cost estimate.

- PCC Plant

  Capital cost for GPS-based PCC is a major equipment (ME) factored estimate for the DOE/NETL Case 12 supercritical plant with a target accuracy of ±30%. Separate estimates are prepared for the CO_2 recovery facility and the CO_2 compression facility. For an ME-factored estimate, ME material and labor costs were developed from equipment sizes, quantities, and design parameters defined by the PCC design from CCS. Bulk material and labor costs were factored from the ME costs. The sum of the ME and bulk material costs, including shipping costs, forms the total direct cost (TDC).

  Construction indirect cost, factored from total direct labor cost, is added to the TDC to come up with the total field cost (TFC). Using factors consistent with the DOE/NETL report for the Case 12 TPC, the Engineering and Construction Management Fees and Home office cost, and contingencies are added to the TFC to come up with the TPC.

  The heat and material balances of the overall GPS process were modeled using ProTreat™ simulation software. The size for each piece of major equipment used in the GPS process was estimated based on the individual heat and material stream flows of the simulation. The size of the absorber columns and regenerator column (diameters and packed bed heights) were estimated based on ProTreat™ simulation.

  Upon generating the size estimates for the individual equipment, the costs for the equipment were generated using commercial estimation software (ASPEN ICARUS) with adjustments based on past quotes for similar equipment where necessary. No new quotations specific to this PCC design were solicited. Installation labor for each ME was factored from historical data by equipment type.

Costs for bulk materials such as instrumentations, piping, structure steel, insulation, electrical, painting, concrete and site preparation associated with the major equipment were factored from ME costs (which exclude subcontracted [S/C] item costs) based on historical data for similar services. Installation labor for each bulk commodity was factored from historical data by type.

Table 6.2. Cost Estimate Basis for Supercritical PC Plant with CO_2 Capture

Acct No.	Item/Description	Cost Estimate Basis	Capacity Factor Reference Basis (DOE/NETL Report Case 12)
1	COAL & SORBENT HANDLING	Capacity Factor	AR Coal
2	COAL & SORBENT PREP & FEED	Capacity Factor	AR Coal
3	FEEDWATER & MISC. BOP SYSTEMS		
3.1	Feedwater System	Capacity Factor	AR Coal
3.2	Water Makeup & Pretreating	Capacity Factor	CW Makeup
3.3	Other Feedwater Subsystems	Capacity Factor	AR Coal
3.4	Service Water Systems	Capacity Factor	AR Coal
3.5	Other Boiler Plant Systems	Capacity Factor	AR Coal
3.6	FO Supply Sys & Nat Gas	Capacity Factor	AR Coal
3.7	Waste Treatment Equipment	Capacity Factor	AR Coal
3.8	Misc Equipment (Cranes, Air Comp, etc)	Capacity Factor	AR Coal
4	PC BOILER	Capacity Factor	AR Coal
5	FLUE GAS CLEANUP	Capacity Factor	AR Coal
5B	CO_2 REMOVAL & COMPRESSION		
5B.1	CO_2 Removal System	Nexant Estimate	N/A
5B.2	CO_2 Compression & Drying	Nexant Estimate	N/A
6	COMBUSTION TURBINE/ACCESSORIES	N/A	N/A
7	HRSG, DUCTING & STACK	Capacity Factor	AR Coal
8	STEAM TURBINE GENERATOR		
8.1	Steam TG & Accessories	Capacity Factor	STG Output
8.2	Turbine Plant Auxiliaries	Capacity Factor	STG Output
8.3	Condenser & Auxiliaries	Capacity Factor	Cond Duty
8.4	Steam Piping	Capacity Factor	Gross Power Output
8.9	TG Foundations	Capacity Factor	Gross Power Output
8.10	Back Pressure TG & Accessories	Capacity Factor	BPTG Output
9	COOLING WATER SYSTEM		
9.1	Cooling Tower	Capacity Factor	CT Load
9.2	Circulating CW Pump	Capacity Factor	CT Load
9.3	Circulating CW Syst Aux	Capacity Factor	CT Load
9.4	Circulating CW Piping	Capacity Factor	CT Load
9.5	Makeup Water System	Capacity Factor	CW Makeup
9.6	Closed CW System	Capacity Factor	CCW Load
9.9	Circ CW Syst Foundations & Structures	Capacity Factor	CT Load
10	ASH/SPENT SORBENT HANDLING SYS	Capacity Factor	AR Coal
11	ACCESSORY ELECTRIC PLANT	Capacity Factor	Gross Power Output
12	INSTRUMENTATION & CONTROL	Capacity Factor	AR Coal

13	IMPROVEMENT TO SITE	Capacity Factor	AR Coal
14	BUILDING & STRUCTURES	Capacity Factor	AR Coal

Construction indirect cost was factored from total direct labor costs based on historical data. Construction indirect cost covers the cost for setup, maintenance and removal of temporary facilities, warehousing, surveying and security services, maintenance of construction tools and equipment, consumables and utilities purchases, and field office payrolls.

Installation labor productivity and cost (wages, fringe benefit costs & payroll based taxes and insurance premiums) used to calculate the installation costs at 2007 price levels are based on the past experience and database for this location, and are identical to those used in the previous EPRI studies for this site.

- Engineering and Construction Management, Home Office Fees & Contingencies

  Engineering and Construction Management are estimated as a percent of TFC. These costs consist of all home office engineering and procurement services as well as field construction management costs.

  Both the project contingency and process contingency costs represent costs that are expected to be spent in the development and execution of the project that are not yet fully reflected in the design. Project contingency is added to the TFC to cover project uncertainty and the cost of any additional equipment that would result during detailed design. Likewise, process contingency is added to the TFC to cover the cost of any additional equipment that would be required as a result of continued technology development. For this study, the factors used for the above fees and contingencies are consistent with those used in Case 12 of the DOE/NETL study.

6.2.3.2 O&M Costs

The O&M costs pertain to those charges associated with operating and maintaining the power plants over their expected life. These costs include:

- Operating labor
- Maintenance – material and labor
- Administrative and support labor
- Consumables
- Fuel
- Waste disposal

There are two components of O&M costs; fixed O&M, which is independent of power generation, and variable O&M, which is proportional to power generation. The variable O&M costs are estimated based on 85% capacity factor.

- Labor

  Operating labor cost is determined based on the number of operators required to work in the plant. Other assumptions used in calculating the total labor cost include:

2007 Base hourly labor rate, $/hr	$33
Length of work-week, hrs	50
Labor burden, %	30
Administrative/Support labor, % O&M Labor	25
Maintenance material + labor, % TPC	1.64
Maintenance labor only, % maintenance material + labor	40

- Consumables and Waste Disposal

  The cost of consumables, including fuel, is determined based on the individual rates of consumption, the unit cost of each specific consumable commodity, and the plant annual operating hours. Waste quantities and disposal costs are evaluated similarly to the consumables.

  The unit costs for major consumables and waste disposal are based on the values reported in the DOE/NETL report. These costs are escalated to 2010, the year when construction is completed and production starts.

6.2.4 Financial Modeling Basis

The NETL Power Systems Financial Model (PSFM) is used for economic analysis for the current study following the same methodology as used in the NETL/DOE 2007/1281 report. This method's figure-of-merit is the levelized cost of electricity (LCOE) over a 20-year period. The NETL PSFM was developed by Nexant for DOE to calculate the LCOE for power plants.

To calculate the LCOE, the PSFM requires a variety of inputs, among those, the capital cost and O&M costs of the plant, as described in Section 6.2.3. Other parameter assumptions required by the model include the following:

• Income tax rate, %	38
• Percentage debt, %	45
• Interest rate, %	11
• Equity desired rate of return, %	12
• Repayment term of debt, years	15
• Depreciation	20 years, 150% declining balance
• Working capital	None
• Plant economic life, years	30
• Tax holiday, years	0
• Start-up costs (% of TPC less contingencies)	2
• EPC escalation, % per year	0
• Coal price nominal escalation, %	2.35
• O&M cost nominal escalation, %	1.87
• Duration of construction, years	3
• First year of construction	2007
• Construction cost distribution, %	
o Year 1	5%
o Year 2	65%
o Year 3	30%

All costs are expressed in the "first-year-of-construction" year dollars, and the resulting LCOE is also expressed in "first-year-of-construction" year dollars.

The DOE/NETL report's net 550 MWe supercritical PC plant without CO_2 capture (Case 11) LCOE is to be used as the benchmark for the supercritical PC plant with CO_2 capture. The Case 11 20-year LCOE stated in the DOE/NETL report is 63.3 mills/kWh. Entering the relevant inputs from the report for this case into the PSFM model, the model returns an LCOE of 63.9 mills/kWh. The small difference (< 1%) between the DOE/NETL report and the PSFM model shows that the PSFM result is consistent with the DOE/NETL standards in reporting the LCOE for power plants.

The LCOE is evaluated using the PSFM model and is compared against the same model's result of 63.9 mills/kWh for the supercritical PC plant without CO_2 capture.

6.3 GPS-Based PCC Design, Performance and Cost Estimate

6.3.1 GPS Process Overview and Description

As described in Section 1.2, the GPS-based PCC process used for the TEA is one absorption/stripping cycle, as shown in Figure 6.2. This process utilizes a mixture of MDEA and PZ as the solvent to absorb CO_2. The solvent is cycled through a lower temperature absorption column and a higher temperature stripping column, same as that in general solvent-based separation. The primary difference between the GPS process and general solvent-based separation arises from the operation of the stripping column. The novelty of the GPS process is in the elevated pressure in which the stripper operates. To obtain the elevated operating pressure in the stripping column, an inert gas, such as nitrogen, at a desired pressure is introduced to the bottom of the column as a stripping gas. Additionally, GPS process obtains stripping energy by utilizing side boilers, where along the height of the column the solvent is pumped through a heat exchanger (steam) and redistributed back into the column just below the point where it was withdrawn. This is different from a conventional stripper with the reboiler at the bottom of the column. In a similar configuration, pumps and cooling heat exchangers are used along the height of the absorption column.

The PCC plant is designed as an integral part of the supercritical PC plant to recover up to 90% of the CO_2 in the flue gas. To reduce solvent loss caused by non-reversible reactions between emission components NO_2 and SO_2 and the amine solvent so as to prevent the accumulation of heat stable salts (HSS), the flue gas goes through a sulfur scrubber first before the absorber to further reduce NO_2 and SO_2 in the flue gas. After CO_2 absorption, the clean flue gas goes through an overhead water wash section at top of the absorption column to avoid solvent loss due to mechanical entrainment and evaporation and reduce amine emissions from the clean flue gas. The CO_2 product stream from the GPS column goes through a four-stage CO_2 compression, inter-stage cooling and condensate separation system and a supercritical CO_2 pump to produce CO_2 product at 153 bar.

6.3.2 GPS-Based PCC Performance Summary

The heat and material balances of the overall GPS process are modeled on ProTreat$^{\text{TM}}$ simulation software. Based on these balances, an overall utilities sheet was generated to summarize the GPS PCC process' total reboiling steam requirement and electrical consumption. The GPS process' steam consumption is used as an input to the GateCycle$^{\text{TM}}$ model of the supercritical PC plant to determine the gross power generated by the power plant's steam turbines.

The auxiliary loads for the overall plant are separated into three categories: PCC-independent PC auxiliary loads, PCC-dependent PC auxiliary loads, and PCC loads. The PCC-independent PC auxiliary loads are consistent with the values from the DOE/NETL report. The electrical load from the PCC utilities summary sheet is added directly to the total auxiliary loads as the PCC load. PCC-dependent PC aux loads, including CW circulation pump loads, CT fan loads and transformer losses, vary with the PCC steam extraction requirement. These are calculated based on the PCC utilities consumption from the summary sheet and added to the total auxiliary load as the PCC-dependent PC auxiliary loads.

The stream table for the PCC plant is provided in Table 6.3. The mass and heat balances for the PCC plant are also shown in Figure 6.2. The utilities consumption of the GPS PCC plant's CO_2 capture section and CO_2 compression section are listed in Tables 6.4 and 6.5, respectively. In total, 575 tonne/hr of CO_2 product is produced from the PCC plant; 298.6 MW of external low-pressure steam is required to meet the heat requirement; 22.42MW of electric power is need to operate the PCC plant.

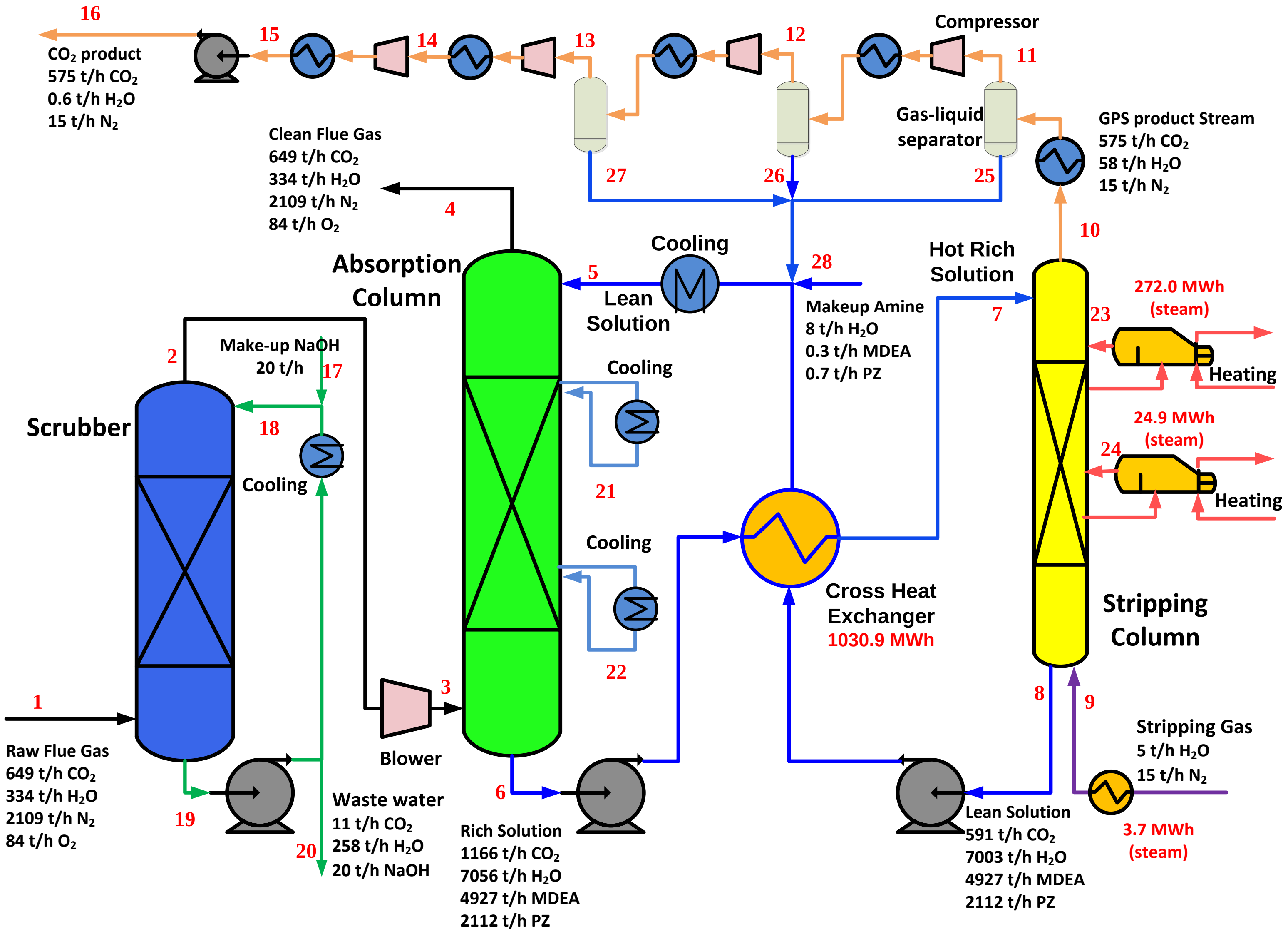

Figure 6.2. Flow diagram of GPS technology based solvent separation process with mass and heat balance

Table 6.3. GPS PCC CO_2 Capture Stream Table

Stream		1	2	3	4	5	6	7	8	9	10	11	12	13	14
Mole Fraction															
H_2O		0.1668	0.0317	0.0317	0.0452	0.8319	0.8092	0.8092	0.8306	0.3268	0.1913	0.0130	0.0068	0.0038	0.0025
CO_2		0.1326	0.1477	0.1477	0.0166	0.0285	0.0547	0.0547	0.0287	0.0069	0.7771	0.9491	0.9550	0.9579	0.9592
SO_2		0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
MDEA		0.0000	0.0000	0.0000	0.0000	0.0877	0.0854	0.0854	0.0883	0.0000	0.0002	0.0000	0.0000	0.0000	0.0000
Piperazine		0.0000	0.0000	0.0000	0.0000	0.0520	0.0506	0.0506	0.0524	0.0001	0.0003	0.0000	0.0000	0.0000	0.0000
NaOH		0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
N_2		0.6771	0.7931	0.7931	0.9067	0.0000	0.0000	0.0000	0.0000	0.6662	0.0311	0.0379	0.0382	0.0383	0.0383
O_2		0.0235	0.0275	0.0275	0.0315	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Flow Rate	kgmol/hr	111,221	98,149	98,149	85,854	471,709	484,052	484,031	468,030	795	16,803	13,770	13,685	13,643	13,624
Mass Flow	kg/hr	3,176,502	2,961,155	2,961,155	2,399,610	14,699,111	15,260,810	15,259,942	14,631,953	19,778	647,973	593,022	591,476	590,714	590,370
Molec Wt		28.56	30.17	30.17	27.95	31.16	31.53	31.53	31.26	24.86	38.56	43.07	43.22	43.30	43.33
Temperature	Celsius	57	27	28	35	35	36	112	119	120	109	40	40	40	40
Pressure	MPa	0.105	0.102	0.106	0.102	0.103	0.106	0.800	0.600	0.600	0.600	0.600	1.200	2.400	4.800
Enthalpy	kJ/kg	34.41	1.83	2.57	10.41	-1510.46	-1486.19	-1242.93	-1226.50	113.09	77.74	7.74	2.38	-8.96	-35.49
Density	kg/cum	1.09	1.23	1.28	1.12	1074.51	1111.49	512.94	1011.61	4.61	7.40	10.20	21.09	45.00	105.17

Table 6.3 (Continued). GPS PCC CO_2 Capture Stream Table

Stream		15	16	17	18	19	20	21	22	23	24	25	26	27	28
Mole Fraction															
H_2O		0.0025	0.0025	0.0000	0.8849	0.8837	0.9492	0.8224	0.8149	0.8189	0.8273	0.9977	0.9955	0.9917	0.9722
CO_2		0.9592	0.9592	0.0000	0.0156	0.0169	0.0168	0.0396	0.0485	0.0434	0.0328	0.0023	0.0045	0.0083	0.0000
SO_2		0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
MDEA		0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0866	0.0858	0.0865	0.0878	0.0000	0.0000	0.0000	0.0066
Piperazine		0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0513	0.0508	0.0513	0.0521	0.0000	0.0000	0.0000	0.0211
NaOH		0.0000	0.0000	1.0000	0.0995	0.0994	0.0340	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
N_2		0.0383	0.0383	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
O_2		0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Flow Rate	kgmol/hr	13,624	13,624	513	387,191	404,004	15,076	477,550	482,115	478,120	470,771	3,063	85	42	444
Mass Flow	kg/hr	590,370	590,370	20,503	8,000,226	8,322,568	289,232	14,947,246	15,145,645	15,004,379	14,733,618	56,068	1,547	761	8,783
Molec Wt		43.33	43.33	40.00	20.66	20.60	19.18	31.30	31.41	31.38	31.30	18.08	18.13	18.23	19.78
Temperature	Celsius	40	67	27	27	57	56	35	35	122	122	40	40	40	35
Pressure	MPa	9.600	15.272	0.105	0.105	0.105	0.105	0.204	0.205	0.630	0.650	0.600	1.200	2.400	0.103
Enthalpy	kJ/kg	-135.51	-118.92		-1764.32	-1682.96	-1683.84	-1503.81	-1496.14	-1199.69	-1217.39	-2371.05	-2360.58	-2341.99	
Density	kg/cum	399.63	461.66		1190.61	1170.98	1171.01	1090.37	1103.27	341.16	1014.59	993.36	986.51	974.66	

Table 6.4 GPS PCC CO_2 Capture Section Utilities

Plant No	Item No	Item Name	Load BHP		Elect. Power	Steam		Water Requirement					Cooling Water		Air Cooling		CO2 Regeneration Reboiling Duty	
						1000 lbs/hr		1000 lbs/hr										
			Norm.	Max	KW		45 PSIG/ 293F Sat	45 PSIG/ 293 Cond					CW, MMBtu/hr	C.W. circ. GPM	Cooling Load, MMBtu/hr	Circulating Air	MMBtu/hr	MW
Plant 100 -- CO2 Capture																		
		EXCHANGERS:																
100	E-100	Flue Gas Scrubber Cooler											725.6	72,483				
100	E-101	1st Absorber Draw Strm 1 Cooler											263.0	26,270				
100	E-102	1st Absorber Draw Strm 2 Cooler											173.9	17,377				
100	E-105	GPS Draw Strm 1 Heater					1,005.8	(1,005.8)									921.3	270.0
100	E-106	GPS Draw Strm 2 Heater					92.8	(92.8)									85.0	24.9
100	E-108	Absorber Lean Solution Cooler											365.3	36,490				
100	E-117	GPS Ovhd Cooler 1											35.0	3,494				
100	E-118	GPS Ovhd CO2 Cooler											130.0	12,983				
100	E-123	GPS Stripping Gas Heater					13.7	(13.7)									12.6	3.7
		COMPRESSORS:																
100	K-100	Flue Gas Blower	6,995		5,491													
		PUMPS:																
100	G-100	Flue Gas Scrubber Pump	3,019		2,370													
100	G-101	1st Absorber Draw Strm 1 Pump	662		519													
100	G-102	1st Absorber Draw Strm 2 Pump	658		516													
100	G-103	Rich Solvent Bottoms Pump	9,165		7,194													
100	G-104	GPS Column Draw Strm 1 Pump	799		627													
100	G-105	GPS Column Draw Strm 2 Pump	807		634													
100	G-112	Absorber Ovhd Wash Water Pump	246		193													
100	G-113	DFGD Pump	861		676													
		Package:																
		Nitrogen Plant			4,200													
		SUB-TOTAL			22,420	0.0	1,112.3	(1,112.3)	0.0				1,693	169,097	0.0	0.0	1,018.8	298.6
		TOTAL			22,420	0.0	1,112.3	(1,112.3)	0.0				1,693	169,097	0.0	0.0	1,018.8	298.6

NOTES:

REV	DATE	REVISIONS	PROC. ENG	UNIT ENG
2	6/9/2015	ssued for Review	HL	
1	1/28/2013	ssued for Review	AW	
0	9/28/2012	Issued for Report	HL	

DOE/NETL CO2 CAPTURE STUDY - CCS GPS
550 MW NET SUPERCRITICAL POWER PLANT
POST COMBUSTION CO2 CAPTURE BY GPS
CO2 CAPTURE
UTILITIES SUMMARY

JOB NUMBER	**01886-001**
DRAWING No.	**REV.**
DS-UTILITY-Design	**1**

Table 6.5 GPS PCC CO_2 Compression Section Utilities

Plant No	Item No	Item Name	Load BHP		Elect. Power	Steam		Water Requirement					Cooling Water		Air Cooling		CO2 Regeneration Reboiling Duty	
						1000 lbs/hr		1000 lbs/hr										
			Norm.	Max	KW		45 PSIG/ 293F Sat	45 PSIG/ 293 Cond					CW, MMBtu/hr	C.W. circ. GPM	Cooling Load, MMBtu/hr	Circulating Air	MMBtu/hr	MW
CO2 Compression Section																		
		EXCHANGERS:																
100	E-120	Stage 1 KO Drum Cooler											37.6	3,760				
100	E-121	Stage 2 KO Drum Cooler											38.4	3,831				
100	E-122	Stage 3 KO Drum Cooler											44.4	4,440				
100	E-124	Stage 4 KO Drum Cooler											96.2	9,608				
100	E-126	Supercritical CO2 Cooler											22.3	2,232				
		COMPRESSORS:																
100	K-102	Stage 1 CO2 Compressor	13,092		10,276													
100	K-103	Stage 2 CO2 Compressor	12,488		9,802													
100	K-104	Stage 3 CO2 Compressor	11,843		9,297													
100	K-105	Stage 4 CO2 Compressor	10,855		8,520													
		PUMPS:																
100	G-111	CO2 Product Pump	3,893		3,055													
		PACKAGED EQUIPMENT:																
100	C-110	TEG Dehydration Package			1,273		0.6	(0.6)					2.6	260			0.6	0.2
		SUB-TOTAL			42,223	0.0	0.6	(0.6)	0.0				241.6	24,131.3	0.0	0.0	0.6	0.2
		TOTAL			42,223	0.0	0.6	(0.6)	0.0				241.6	24,131.3	0.0	0.0	0.6	0.2

NOTES:

REV	DATE	REVISIONS	PROC. ENG	UNIT ENG			
2	6/9/2015	ssued for Review	HL		**DOE/NETL CO2 CAPTURE STUDY - CCS GPS**	**JOB NUMBER**	**01886-001**
1	1/28/2013	ssued for Review	AW		**550 MW NET SUPERCRITICAL POWER PLANT**	**DRAWING No.**	**REV.**
0	9/28/2012	ssued for Report	HL		**POST COMBUSTION CO2 CAPTURE BY GPS**	**DS-UTILITY-Design**	**1**
					CO2 COMPRESSION		
					UTILITIES SUMMARY		

6.3.3 *GPS-Based PCC Capital Cost Estimate*

The GPS process' CO_2 capture and CO_2 compression section major equipment (ME) lists are shown in Tables 6.6 and 6.7, respectively.

The estimated TFC for the GPS-based PCC CO_2 capture section and CO_2 compression section, that includes the ME costs, freight, bulk material and construction indirect costs, are shown in Tables 6.8 and 6.9, respectively. The TFC for the overall GPS-based PCC plant, totaling at $323.3 million, is shown in Table 6.10.

Table 6.6. GPS PCC CO_2 Capture Section Major Equipment List

VESSELS & TANKS:
========

Plt No.	Item No.	Item Name	Type	Design Conditions PSIG	Design Conditions deg F	Material of Construction	Quantity per Lot	Units	Inside Diameter Ft	Ht or Tan/Tan Length Ft	Width Ft	Length Ft	Number of Lots	2007 Equip Cost $1000
100	C-100	Feed Scrubber	Vert	1	135	304Clad	1	Vessel	48.0	155.5			2	17,994
		- Pall Rings	3.5 inch			304 SS	86859	Ft3					2	
		- Support Plates				304 SS	3619	Ft2	2 @ 48				2	
		- Hold-Down Plates				304 SS	3619	Ft2	2 @ 48				2	
		- Liq Distributors				304 SS	3619	Ft2	2 @ 48				2	
		- Demister Pads				304 SS	3619	Ft2	2 @ 48				2	
100	C-101	Absorption Column	Vert	1	97.071	Kill CS	1	Vessel	46.9	195.0			2	31,912
		- Sulzerpak	170.0 SulzerPak			304 SS	150416	Ft3					2	
		- Pall Rings	3.5 inch			304 SS	15878	Ft3					2	
		- Support Plates				304 SS	5187	Ft2	3 @ 47				2	
		- WW Support Plates				304 SS	1134	Ft2	1 @ 38				2	
		- Hold-Down Plates				304 SS	5187	Ft2	3 @ 47				2	
		- WW Hold-Down Plates				304 SS	1134	Ft2	1 @ 38				2	
		- Liq Distributors				304 SS	5187	Ft2	3 @ 47				2	
		- WW Liq Distributors				304 SS	1134	Ft2	1 @ 38				2	
		- Chimney Trays				304 SS	3458	Ft2	2 @ 47				2	
		- WW Chimney Trays				304 SS	1134	Ft2	1 @ 38				2	
		- WW Demister Pads				304 SS	1134	Ft2	1 @ 38				2	
100	C-103	GPS Column	Vert	73	246.234	Kill CS	1	Vessel	29.0	188.0			1	8,602
		- Sulzerpak	170.0 SulzerPak			304 SS	27812	Ft3					1	
		- Support Plates				304 SS	1987	Ft2	3 @ 29				1	
		- Hold-Down Plates				304 SS	1987	Ft2	3 @ 29				1	
		- Liq Distributors				304 SS	1987	Ft2	3 @ 29				1	
		- Chimney Trays				304 SS	1324	Ft2	2 @ 29				1	
100	C-107	GPS Ovhd CO2 KO Drum	Vert	120	250	304SS	1	Vessel	20.0	13.5			1	337
100	C-110	GPS Stripping Gas KO Drum	Vert	100	250	304SS	1	Vessel	4.0	10.0			1	41

SHELL & TUBE EXCHANGERS AND AIR COOLERS:
==

Plt No.	Item No.	Item Name	Type	Design PSIG Shell	Design PSIG Tube	Des Temp, deg F Shell	Des Temp, deg F Tube	Material Of Construction Shell	Material Of Construction Tube	Duty MMBtu/Hr	Total Bare Tube Area, Ft2	Physical Arrangement In Series	Physical Arrangement In Parallel	Total # Req	Total Equip Cost $1000
100	E-100	Flue Gas Scrubber Cooler	P&F	64	100	375	375		304SS	726	54972	1	4	4	611
100	E-101	1st Absorber Draw Strm 1 Cooler	P&F	30	100	375	375		304SS	263	18735	1	2	2	218
100	E-102	1st Absorber Draw Strm 2 Cooler	P&F	30	100	375	375		304SS	174	13274	1	2	2	162
100	E-103	1st Absorber R/L HX	P&F	87	116	375	375		304SS	3518	520392	1	36	36	5,747
100	E-105	GPS Draw Strm 1 Heater	Weld P&F	50	95	375	375		304SS	921	33166	1	3	3	984
100	E-106	GPS Draw Strm 2 Heater	Weld P&F	50	95	375	375		304SS	85	3059	1	1	1	106
100	E-108	Absorber Lean Solution Cooler	P&F	87	100	375	375		304SS	365	24243	1	2	2	274
100	E-117	GPS Ovhd Cooler 1	Weld P&F	87	100	375	375		304SS	35	1259	1	1	1	49
100	E-118	GPS Ovhd CO2 Cooler	Weld P&F	87	100	375	375		304SS	130	4679	1	1	1	154
100	E-123	GPS Stripping Gas Heater	Weld P&F	100	87	375	375		304SS	13	452	1	1	1	21

COMPRESSORS, BLOWERS & DRIVERS:
==============================

Plt No.	Item No.	Item Name	Type	Design Conditions PSIG	Design Conditions deg F	Material Of Construction Wheel or Impel'r	Material Of Construction Casing	Design Capacity Des Flow SCFM	Design Capacity Inlet PSIA	Design Capacity Delta P PSI	Comp BHP	Driver HP	Driver Type	Total # Req	Total Equip Cost $1000
100	K-100	Flue Gas Blower	Cent.	15	80	304SS	304SS	657199	15.2	0.9	3498	3682	Motor	2	2,449

PUMPS & DRIVERS:
===============

Plt No.	Item No.	Item Name	Type	Design Conditions PSIG	Design Conditions deg F	Material Of Construction Wheel or Impel'r	Material Of Construction Casing	Design Capacity Des Flow GPM	Design Capacity Inlet PSIG	Design Capacity Delta P PSI	Pump BHP	Driver HP	Driver Type	Total # Req	Total Equip Cost $1000
100	G-100	Flue Gas Scrubber Pump	Cent.	94	80	CS	CS	22038	15	76	1510	1589	Motor	6	2378
100	G-101	1st Absorber Draw Strm 1 Pump	Cent.	30	106	CS	CS	30299	15	10	331	348	Motor	4	483
100	G-102	1st Absorber Draw Strm 2 Pump	Cent.	30	103	CS	CS	30302	15	10	329	346	Motor	4	481
100	G-103	Rich Solvent Bottoms Pump	Cent.	238	97	CS	CS	30225	15	208	4582	4823	Motor	3	2961
100	G-104	GPS Column Draw Strm 1 Pump	Cent.	109	229	CS	CS	31783	87	17	400	421	Motor	3	418
100	G-105	GPS Column Draw Strm 2 Pump	Cent.	109	249	CS	CS	31925	87	17	404	425	Motor	3	421
100	G-112	Absorber Ovhd Wash Water Pump	Cent.	38	92	CS	CS	6493	15	21	123	129	Motor	4	233
100	G-113	DFGD Pump	Cent.	64	80	CS	CS	10857	16	44	430	453	Motor	4	590

DUCTING
============================

Plt No.	Item No.	Item Name	Type	Tube Design Cond PSIG	Tube Design Cond deg F	Mat Of Construct	Insulation Thickness Inches	Duct Dimensions Ht, Ft	Duct Dimensions Width, Ft	Duct Dimensions Total Length, Ft	Total # Req	Total Equip Cost $1000
---	--------	--------------------	-------	-------	-------	----------------				-----------		-------
100	L-100	Flue Gas Feed & Exhaust Ducts	Duct	1	450	CS	1	15	15	4140	1	16731

TOTAL EQUIP COST
94355

`Equipment Cost includes Equipment and Installation, excludes Freight, Bulks and Indirect Costs`

REV	DATE	REVISIONS	PROC. ENG	UNIT ENG
2	6/9/2015	Issued for Review	HL	
1	1/28/2013	Issued for Review	AW	
0	9/28/2012	Issued for Report	HL	

DOE/NETL CO2 CAPTURE STUDY - CCS GPS
550 MW NET SUPERCRITICAL POWER PLANT
POST COMBUSTION CO2 CAPTURE BY GPS
CO2 CAPTURE
MAJOR EQUIPMENT LIST

JOB NUMBER	01886-001
DRAWING No.	REV.
DS-EQUIP-100-Design	1

Table 6.7. GPS PCC CO_2 Compression Section Major Equipment List

VESSELS & TANKS:
========

Plt No.	Item No.	Item Name	Type	Design Conditions PSIG	Design Conditions deg F	Material of Construction	Quantity per Lot	Units	Inside Diameter Ft	Ht or Tan/Tan Length Ft	Width Ft	Length Ft	Number of Lots	Total Equip Cost $1000
100	C-111	Feed CO2 KO Drum	Vert	100	250	304SS	1	Vessel	18.0	12.5			1	239
100	C-112	Stage 1 CO2 KO Drum	Vert	200	250	304SS	1	Vessel	15.0	11.0			1	261
100	C-113	Stage 2 CO2 KO Drum	Vert	400	250	304SS	1	Vessel	12.5	10.0			1	294
100	C-114	Stage 3 CO2 KO Drum	Vert	825	250	304SS	1	Vessel	10.5	9.0			1	359
100	C-120	CO2 Product Drum	Horizont	2393	250	304SS	1	Vessel	8.0	31.0			1	890

SHELL & TUBE EXCHANGERS AND AIR COOLERS:
==

Plt No.	Item No.	Item Name	Type	Design PSIG Shell	Design PSIG Tube	Des Temp, deg F Shell	Des Temp, deg F Tube	Material Of Construction Shell	Material Of Construction Tube	Duty MMBtu/Hr	Total Bare Tube Area, Ft2	Physical Arrangement In Series	Physical Arrangement In Parallel	Total # Req	Total Equip Cost $1000
100	E-120	Stage 1 KO Drum Cooler	Weld P&F	175	100	375	375		304SS	38	1355	1	1	1	52
100	E-121	Stage 2 KO Drum Cooler	S&T	475	100	375	375	304SS	304SS	38	9803	1	1	1	266
100	E-122	Stage 3 KO Drum Cooler	S&T	835	100	375	375	304SS	304SS	44	10189	1	1	1	322
100	E-124	Stage 4 KO Drum Cooler	S&T	1447	100	375	375	304SS	304SS	96	9773	1	1	1	387
100	E-126	Supercritical CO2 Cooler	S&T	2400	100	375	375	304SS	304SS	22	3606	1	1	1	225

COMPRESSORS, BLOWERS & DRIVERS:
==============================

Plt No.	Item No.	Item Name	Type	Design Conditions PSIG	Design Conditions deg F	Material Of Construction Wheel or Impel'r	Material Of Construction Casing	Design Capacity Des Flow SCFM	Design Capacity Inlet PSIA	Design Capacity Delta P PSI	Comp BHP	Driver HP	Driver Type	Total # Req	Total Equip Cost $1000
100	K-102	Stage 1 CO2 Compressor	Cent.	200	104	CS	CS	191956	86.992	87.1	13092	13781	Motor	1	2,627
100	K-103	Stage 2 CO2 Compressor	Cent.	375	104	CS	CS	190829	174.048	174.0	12488	13145	Motor	1	2,546
100	K-104	Stage 3 CO2 Compressor	Cent.	725	104	CS	CS	190197	348.096	348.1	11843	12467	Motor	1	2,460
100	K-105	Stage 4 CO2 Compressor	Cent.	1450	104	CS	CS	190048	696.192	696.2	10855	11426	Motor	1	2,327

PUMPS & DRIVERS:
================

Plt No.	Item No.	Item Name	Type	Design Conditions PSIG	Design Conditions deg F	Material Of Construction Wheel or Impel'r	Material Of Construction Casing	Design Capacity Des Flow GPM	Design Capacity Inlet PSIG	Design Capacity Delta P PSI	Pump BHP	Driver HP	Driver Type	Total # Req	Total Equip Cost $1000
100	G-111	Supercritical CO2 Pump	Cent.	2393	124	CS	CS	4476	1300	993	3893	4097	Motor	1	2613

PACKAGED & MISC EQUIPMENT:
============================

Plt No.	Item No.	Item Name	Type	Tube Design Cond PSIG	Tube Design Cond deg F	Mat Of Construct	Design Capacity	Remarks	Total # Req	Total Equip Cost $1000
---	--------	--------------------	-------	-------	-------	---------------	----------------------------------	----------------------------------		-------
100	V-100	TEG Dehydration Package	Pkg						1	1728

TOTAL EQUIP COST
17595

Equipment Cost includes Equipment and Installation, excludes Freight, Bulks and Indirect Costs

Nexant						**DOE/NETL CO2 CAPTURE STUDY - CCS GPS**	**JOB NUMBER**	**01886-001**
	2	6/8/2015	Issued for Review	HL		**550 MW NET SUPERCRITICAL POWER PLANT**	**DRAWING No.**	**REV.**
	1	1/28/2013	Issued for Review	AW		**POST COMBUSTION CO2 CAPTURE BY GPS**		
	0	9/28/2012	Issued for Report	HL		**CO2 COMPRESSION**	**DS-EQUIP-200-Design**	**1**
	REV	DATE	REVISIONS	PROC. ENG	UNIT ENG	**MAJOR EQUIPMENT LIST**		

Table 6.8. GPS PCC CO_2 Capture Section Total Field Cost

PROJECT DESCRIPTION: **Post Combustion CO2 Capture Study**
CLIENT: **Carbon Capture Scientific**
NEXANT JOB: **01886-001**
FILE: **DOE/NETL GPS PCC Cost Estimate.xls**
LOCATION:
SHEET:
QTY BY: **N/A**
AREA/SITE: **550 MW Supercritical Pulverized Coal Power Plant**
EST BY: **N/A**
PLANT: **GPS CO2 Capture Section**
DATE: **June 09, 2015**
ACCOUNT: **2007 Cost Estimate Summary**
CHECK:
SUBJECT: **2007 Cost Estimate Details**

COST CODE	DESCRIPTION	QTY	MEAS Unit	UNIT COSTS MATL	LABOR	SC/Other	D HIRE UNIT MH	TOTAL MHRS * S/C	D HIRE	COSTS IN U.S.$1000 Equipment	BULK	LABOR	SC/Other	TOTAL
	PROCESS EQUIPMENT & DUCTWORK													
C	COLUMNS & TOWERS	6	EA							33,477		25,030		58,507
G	PUMPS & DRIVERS	31	EA							7,190		774		7,964
C	VESSELS, TANKS & STORAGE FACILITIES	2	EA							359		20		379
E	HEAT EXCHANGERS	53	EA							8,238		87		8,325
K	COMPRESSORS, BLOWERS, FANS & DRIVERS	2	EA							2,235		214		2,449
V	PACKAGED EQUIPMENT		EA											
L	DUCTWORK		EA								8,588	8,143		16,731
HT														
	FREIGHT	5.00	%							2,618				2,618
	TOTAL PROCESS EQUIPMENT & DUCTWORK		EA							54,116	8,588	34,268		96,972
	INSTRUMENTS													12,752
	PIPING													44,043
	STEELWORK													6,955
	INSULATION													5,412
	ELECTRICAL													22,794
	CONCRETE													8,628
	BUILDING													
	SITEWORK													10,945
	PAINTING													541
	TOTAL OTHER DIRECT COSTS													112,070
	SUBTOTAL DIRECT COSTS													209,042
	SUBTOTAL CONSTRUCTION INDIRECT COSTS													68,189
	SUBTOTAL FIELD COSTS													277,232
	TOTAL (2007 BASIS)													277,232

Total 1 Train Required for Operation
Total Installed Cost is calculated from Subtotal Field Costs based on factors from DOE/NETL Report

REV	DATE	REVISIONS	PROC. ENG	UNIT ENG
2	6/9/2015	Issued for Review	HL	
1	1/28/2013	Issued for Review	AW	
0	9/28/2012	Issued for Report	HL	

DOE/NETL CO2 CAPTURE STUDY - CCS GPS
550 MW NET SUPERCRITICAL POWER PLANT
POST COMBUSTION CO2 CAPTURE BY GPS
CO2 CAPTURE
CAPITAL COST SUMMARY (Details)

JOB NUMBER	**01886-001**
DRAWING No.	**REV.**
DS-COST-100-COMPRESSORS **(Page 6 of 7)**	**1**

Table 6.9. GPS PCC CO_2 Compression Section Total Field Cost

PROJECT DESCRIPTION: **Post Combustion CO2 Capture Study**
CLIENT: **Carbon Capture Scientific**
NEXANT JOB: **01886-001**
FILE: **DOE/NETL GPS PCC Cost Estimate.xls**
LOCATION:
SHEET:
QTY BY: **N/A**
AREA/SITE: **550 MW Supercritical Pulverized Coal Power Plant**
EST BY: **N/A**
PLANT: **CO2 Compression Section**
DATE: **June 09, 2015**
ACCOUNT: **2007 Cost Estimate Summary**
CHECK:
SUBJECT: **2007 Cost Estimate Details**

COST CODE	DESCRIPTION	QTY	MEAS Unit	UNIT COSTS MATL	UNIT COSTS LABOR	UNIT COSTS SC/Other	D HIRE UNIT MH	TOTAL MHRS * S/C	TOTAL MHRS * D HIRE	COSTS IN U.S.$1000 Equipment	COSTS IN U.S.$1000 BULK	COSTS IN U.S.$1000 LABOR	COSTS IN U.S.$1000 SC/Other	COSTS IN U.S.$1000 TOTAL
	PROCESS EQUIPMENT & DUCTWORK													
C	COLUMNS & TOWERS		EA											
G	PUMPS & DRIVERS	1	EA							2,541		72		2,613
C	VESSELS, TANKS & STORAGE FACILITIES	5	EA							1,920		122		2,042
E	HEAT EXCHANGERS	5	EA							1,225		27		1,252
K	COMPRESSORS, BLOWERS, FANS & DRIVERS	4	EA							8,481		1,479		9,959
V	PACKAGED EQUIPMENT	1	EA							1,114		614		1,728
L	DUCTWORK		EA											
	FREIGHT	5.00	%							748				748
	TOTAL PROCESS EQUIPMENT & DUCTWORK		EA							16,029		2,314		18,343
	INSTRUMENTS													1,487
	PIPING													5,913
	STEELWORK													818
	INSULATION													801
	ELECTRICAL													4,924
	CONCRETE													2,427
	BUILDING													1,122
	SITEWORK													1,681
	PAINTING													160
	TOTAL OTHER DIRECT COSTS													19,334
	SUBTOTAL DIRECT COSTS													37,676
	SUBTOTAL CONSTRUCTION INDIRECT COSTS													8,375
	SUBTOTAL FIELD COSTS													46,051
	TOTAL (2007 BASIS)													46,051

Total of 1 Train Required for Operation
Total Installed Cost is calculated from Direct Installed Cost based on factors from DOE/NETL Report

REV	DATE	REVISIONS	PROC. ENG	UNIT ENG
2	6/9/2015	Issued for Review	HL	
1	1/28/2013	Issued for Review	AW	
0	9/28/2012	Issued for Report	HL	

DOE/NETL CO2 CAPTURE STUDY - CCS GPS
550 MW NET SUPERCRITICAL POWER PLANT
POST COMBUSTION CO2 CAPTURE BY GPS
CO2 CAPTURE
CAPITAL COST SUMMARY (Details)

JOB NUMBER	**01886-001**	
DRAWING No.		**REV.**
DS-COST-100-Design (Page 1 of 7)		**1**

Table 6.10. GPS-Based PCC Total Field Cost

PROJECT DESCRIPTION: **Post Combustion CO2 Capture Study**
CLIENT: **Carbon Capture Scientific**
NEXANT JOB: **01886-001**
FILE: **DOE/NETL GPS PCC Cost Estimate.xls**
LOCATION:
SHEET:
QTY BY: **N/A**
AREA/SITE: **550 MW Supercritical Pulverized Coal Power Plant**
EST BY: **N/A**
PLANT: **GPS Overall PCC**
DATE: **June 09, 2015**
ACCOUNT: **2007 Cost Estimate Summary**
CHECK:
SUBJECT: **2007 Cost Estimate Details**

COST CODE	DESCRIPTION	QTY	MEAS Unit	UNIT COSTS			D HIRE UNIT MH	TOTAL MHRS *		COSTS IN U.S.$1000				
				MATL	LABOR	SC/Other		S/C	D HIRE	Equipment	BULK	LABOR	SC/Other	TOTAL
	PROCESS EQUIPMENT & DUCTWORK													
	GPS CO2 CAPTURE TRAIN 1	1	Train							51,498	8,588	34,268		94,355
	GPS CO2 COMPRESSION TRAIN 1	1	Train							15,281		2,314		17,595
	FREIGHT	5.00	%							3,366				3,366
	TOTAL PROCESS EQUIPMENT & DUCTWORK		EA							70,145	8,588	36,582		115,315
	INSTRUMENTS													14,239
	PIPING													49,956
	STEELWORK													7,773
	INSULATION													6,213
	ELECTRICAL													27,718
	CONCRETE													11,055
	BUILDING													1,122
	SITEWORK													12,626
	PAINTING													701
	TOTAL OTHER DIRECT COSTS													131,404
	SUBTOTAL DIRECT COSTS													246,718
	SUBTOTAL CONSTRUCTION INDIRECT COSTS													76,565
	SUBTOTAL FIELD COSTS (2007 BASIS)													323,283
	TOTAL (2007 BASIS)													323,283

Total 1 Train Required for Operation
Total Installed Cost is calculated from Subtotal Field Cost based on factors from DOE/NETL Report

2	6/9/2015	Issued for Review	HL		DOE/NETL CO2 CAPTURE STUDY - CCS GPS	**JOB NUMBER** **01886-001**
1	1/28/2013	Issued for Review	AW		550 MW NET SUPERCRITICAL POWER PLANT	**DRAWING No.** / **REV.**
0	9/28/2012	Issued for Report	HL		POST COMBUSTION CO2 CAPTURE BY GPS OVERALL CO2 CAPTURE AND COMPRESSION	**DS-COST-100-Design** **(Page 1 of 7)** / **1**
REV	DATE	REVISIONS	PROC. ENG	UNIT ENG	CAPITAL COST SUMMARY (Details)	

6.3.4 Supercritical PC Plant with GPS-Based PCC Performance Summary

Figures 6.1 and 6.3 show the pre- and post-PCC flow schemes for the supercritical power plant steam and condensate streams respectively to produce nominally 550 MWe of net power. The stream flows for Figure 6.1 (under Section 6.2.1.4) correspond to the Case 11 supercritical power plant without PCC of the DOE/NETL report. Figure 6.3 represents the steam and condensate flows for a supercritical PC plant with the same coal firing rate as Case 12 of the DOE/NETL report and equipped with GPS-based PCC. There are, however, certain differences between this plant and the DOE/NETL report's Case 12 supercritical PC plant with benchmark MEA-based PCC:

- The 138 psia steam extraction rate for the PC plant with GPS-based PCC is 0.99 million lbs/hr vs 1.82 million lbs/hr for Case 12.
- The benchmark MEA-based unit uses 138 psia steam that is directly extracted at the Case 12 PC plant's IP to LP crossover line. The GPS PCC plant, however, only requires saturated steam at 60 psia to recover CO_2. In this case, a letdown or backpressure steam turbine (BPST), denoted as BP in Figure 6.2, is added to the PC plant to lower the extracted steam pressure to the required supply pressure of 60 psia to the PCC plant. The turbine recovers some energy, in the form of electric power, from the steam letdown and increases the PC plant's gross output, although the trade-off is an increase in the PC plant capital cost due to the additional BPST.

The net power output and efficiency of the supercritical PC plant with GPS-based CO_2 capture is 646.5 MWe and 32.2%, respectively. Table 6.11 summarizes the performance and efficiency of the overall PC plant with GPS-based PCC.

Figure 6.3. Post-GPS PCC Steam and Condensate Flow Scheme

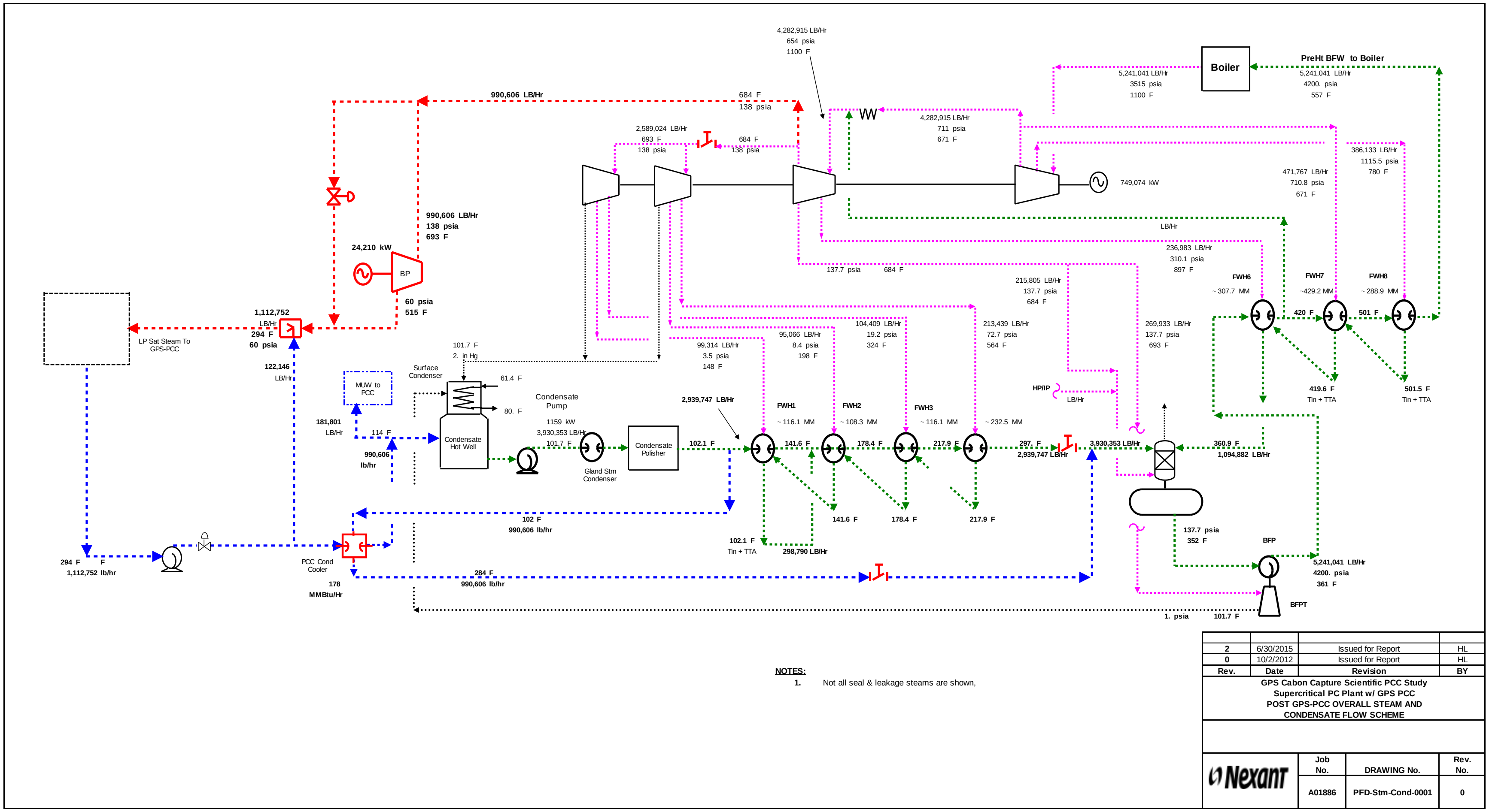

Table 6.11. Supercritical PC Plant with GPS-Based PCC Performance Summary

POWER SUMMARY (Gross Power at Generator Terminals, kWe)	
TOTAL POWER, kWe:	**761,909**
AUXILIARY LOAD SUMMARY, kWe:	
Coal Handling and Conveying	490
Limestone Handling & Reagent Preparation	1,270
Pulverizers	3,990
Ash Handling	760
Primary Air Fans	1,870
Forced Draft Fans	2,380
Induced Draft Fans	10,120
SCR	70
Baghouse	100
FGD Pumps and Agitators	4,250
Miscellaneous Balance of Plant	2,000
Amine CO2 Capture Plant Auxiliaries	22,420
CO2 Compression	42,223
Steam Turbine Auxiliaries	400
Condensate Pumps	630
Cooling Water Circulation Pumps	15,356
Cooling Tower Fans	4,424
Transformer Losses	2,641
TOTAL AUXILIARIES, kWe	**115,394**
NET POWER, kWe	**646,514**
Net Plant Efficiency (HHV)	32.2%
Net Plant Heat Rate (Btu/kWh)	10,587
COOLING TOWER LOADS, MMBtu/hr:	
Surface Condenser Duty	2,402
Closed Cycle Cooling Duties	114
Amine CO2 Capture Plant Cooling Duties	1,693
CO2 Compression Cooling Duties	242
TOTAL COOLING TOWER LOADS, MMBtu/hr	**4,450**
CONSUMABLES	
As-Received Coal Feed, lb/h	586,627
Limestone Sorbent Feed, lb/h	58,054
Thermal Input (HHV), MMBtu/hr	6,845
Makeup Water, gpm	8,650
OVERALL MAKEUP WATER BALANCE, gpm	
FGD Makeup	779
BFW Makeup	105
Boiler Blowdown	(105)
CO2 Capture & Compression Makeups	240
CO2 Capture & Compression Condensate Purges	(1,171)
Cooling Tower Makeup	8,802
TOTAL, gpm	**8,650**

6.3.5 Supercritical PC Plant with GPS-Based PCC Capital Cost Estimate

The cost estimating methodology for the overall supercritical PC plant with GPS-based PCC was described previously in Section 6.2.3. Table 6.12 shows the TPC organized by cost account following the format of the DOE/NETL report. The engineering, construction management and home office fees, as well as project and process contingencies are applied to the TFC (Bare Erected Cost in the DOE/NETL report) to arrive at the total supercritical PC plant with PCC capital cost. The TPC for this case is $1,617 million.

6.3.6 Supercritical PC Plant with GPS-Based PCC O&M Cost Estimate

The annual O&M costs consist of two components: fixed O&M, which is independent of power generation; and variable O&M, which is proportional to power generation and is estimated based on 85% annual capacity factor.

The costs of consumables are escalated to 2010, the year when construction is completed. The annual escalation factor for all consumables, excluding fuel, is 1.87%. For the fuel, Illinois No 6 coal, the annual escalation factor is 2.35%.

The annual variable O&M costs, including consumables such as fuel, water and chemicals, as well as waste disposal costs, are determined based on the rates of consumption, the unit cost of each commodity, and total annual operating hours. Water expenditure was based on net raw water makeup from the overall plant water balance. PC plant related chemical expenditures are independent of the PCC and follow the NETL/DOE report Case 12 consumptions.

PCC-dependent chemicals include: MDEA-PZ solvent mixture and active carbon for the MDEA filter. The solvent replacement cost is estimated based on the total amine degradation rate. For this study, deep FGD is included in the PCC to minimize amine degradation due to SOx. It is assumed that the amine degradation rate is the same as MEA on a molar basis, however, since MDEA has almost double the molecular weight of MEA, the degradation on a mass basis (lb/ton of CO_2 recovered) is also doubled. Compared with the MEA degradation rate of 0.2 lb/ton of CO_2 recovered in Case 12 of the DOE/NETL report, the MDEA degradation rate for the GPS PCC case is about 0.4 lb/ton of CO_2 recovered. Corrosion inhibitor is not required due to the assumption that MDEA is less corrosive than MEA.

The total estimated annual O&M costs for supercritical PC plant with GPS-based PCC is $153 million. Table 6.13 shows the breakdown of the O&M costs in a similar format to the DOE/NETL Case 12 report.

Table 6.12. Supercritical PC Plant with GPS-Based PCC Capital Cost Estimate

Acct		Equip	Material	Labor		Sales	Bare Erect	Eng'g CM	Contingency		
No.	**Plant Description**	**Cost**	**Cost**	**Direct**	**Indirect**	**Tax**	**Cost**	**H.O. & Fee**	**Process**	**Project**	**Total Plt Cost**
1	COAL & SORBENT HANDLING	19,316	5,215	11,691	0	0	36,222	3,246	0	5,920	45,388
2	COAL & SORBENT PREP & FEED	13,126	758	3,326	0	0	17,210	1,508	0	2,808	21,526
3	FEEDWATER & MISC BOP SYSTEMS										
	Feedwater System	22,090	0	7,230	0	0	29,320	2,567	0	4,783	36,670
	Water Makeup & Pretreating	6,527	0	2,099	0	0	8,626	809	0	1,887	11,321
	Other Feedwater Subsystems	6,826	0	2,896	0	0	9,722	866	0	1,588	12,176
	Service Water Systems	1,495	0	807	0	0	2,302	214	0	503	3,019
	Other Boiler Plant Systems	8,357	0	8,175	0	0	16,532	1,551	0	2,713	20,796
	FO Supply & Nat Gas	267	0	329	0	0	596	55	0	98	749
	Waste Treatment Equipment	5,103	0	2,923	0	0	8,026	778	0	1,761	10,565
	Misc Equip (Cranes, Air Comp, etc)	2,768	0	853	0	0	3,621	348	0	794	4,763
4	PC BOILER	190,969	0	107,678	0	0	298,647	28,927	0	32,757	360,331
5	FLUE GAS CLEANUP	101,747	0	34,963	0	0	136,710	12,990	0	14,970	164,670
5B1	GPS CO2 REMOVAL SYSTEM	60,069	82,968	134,195	0	0	277,232	26,311	55,446	71,798	430,786
5B2	GPS CO2 COMPRESSION & DRYING	18,112	11,457	16,482	0	0	46,051	4,372	0	10,084	60,508
6	COMBUSTION TURBINE/ACCESSORIES	N/A	N/A	N/A	0	0	0	0	0	0	0
7	HRSG, DUCTING & STACK	17,889	981	12,221	0	0	31,091	2,840	0	4,457	38,388
8	STEAM TURBINE GENERATOR										
	Steam TG & Accessories	57,927	0	7,749	0	0	65,676	6,288	0	7,196	79,160
	Turbine Plant Auxiliaries	397	0	850	0	0	1,247	121	0	137	1,504
	Condenser & Auxiliaries	6,842	0	2,406	0	0	9,248	879	0	1,012	11,140
	Steam Piping	23,127	0	11,424	0	0	34,551	2,883	0	5,615	43,049
	TG Foundations	0	1,265	2,013	0	0	3,278	308	0	717	4,303
	Back Pressure TG & Accessories	5,242	0	701	0	0	5,943	569	0	651	7,164
9	COOLING WATER SYSTEM										
	Cooling Tower	12,909	0	4,023	0	0	16,932	1,607	0	1,854	20,392
	Circulating CW Pump	3,340	0	242	0	0	3,582	307	0	389	4,278
	Circulating CW Syst Aux	771	0	103	0	0	874	82	0	95	1,052
	Circulating CW Piping	0	6,220	5,933	0	0	12,153	1,120	0	1,991	15,263
	Makeup Water System	624	0	828	0	0	1,452	138	0	239	1,828
	Closed CW System	792	0	626	0	0	1,418	133	0	232	1,783
	Circ CW Syst Foundations & Structures	0	3,303	5,285	0	0	8,587	809	0	1,879	11,275
10	ASH/SPENT SORBENT HANDLING SYS	5,154	162	6,854	0	0	12,170	1,158	0	1,371	14,699
11	ACCESSORY ELECTRIC PLANT	22,250	11,282	32,266	0	0	65,798	5,873	0	9,131	80,802
12	INSTRUMENTATION & CONTROL	9,195	0	9,662	0	0	18,857	1,726	943	2,648	24,174
13	IMPROVEMENT TO SITE	3,162	1,818	6,421	0	0	11,401	1,120	0	2,504	15,025
14	BUILDING & STRUCTURES	0	23,760	22,735	0	0	46,495	4,189	0	7,603	58,287
	TOTAL COST	**626,394**	**149,188**	**465,988**			**1,241,569**	**116,692**	**56,389**	**202,186**	**1,616,835**

Table 6.13. Supercritical PC Plant with GPS-Based PCC O&M Costs

ANNUAL O&M EXPENSES		Capacity Factor:	85
		Cost Base	2010
FIXED OPERATING COSTS			Annual Cost $
Annual Operating Labor Cost			$6,108,823
Maintenance Labor Cost			$10,606,440
Administration & Support Labor			$4,178,816
TOTAL FIXED OPERATING COSTS			**$22,634,078**
VARIABLE OPERATING COSTS			
Maintenance Material Cost			**$15,909,660**
Consumables	Consumption /Day	Unit Cost	
Water/(1000 gallons)	10,587	1.03	**$3,383,309**
Chemicals			
MU & WT Chemicals (lb)	42,381	0.16	$2,103,793
Limestone (ton)	697	20.6	$4,454,632
Carbon for Mercury Removal (lb)	0	1	$0
MDEA Solvent (ton)	3.07	2142.4	$2,040,031
NaOH (tons)	7.36	412.96	$942,969
H2SO4 (tons)	7.18	132.15	$294,377
Corrosion Inhibitor	0.0	3.5	$0
Act Carbon for MDEA Filter (lb)	1,679	1	$520,779
Ammonia (28% NH3) ton	116	123.6	$4,448,240
Subtotal Chemicals			**$14,804,821**
Other			
SCR Catalysts (ton)	0.62	5500	$1,057,953
Subtotal Other			**$1,057,953**
Waste Disposal:			
Flyash (ton)	137	15.45	$656,691
Bottom Ash (ton)	546	15.45	$2,617,176
Subtotal-Waste Disposal			**$3,273,867**
TOTAL VARIABLE OPERATING COSTS	**$130,398,368**		**$38,429,609**
Fuel (ton)	7040	42.11	**$91,968,759**
TOTAL ANNUAL OPERATING COSTS			**$153,032,446**

6.3.7 Supercritical PC Plant with GPS-Based PCC LCOE

Using the methodology as described in Section 6.2.4, the estimated LCOE for the supercritical PC plant with GPS-based PCC, as evaluated by the PSFM and ***not including*** CO_2 transport, storage and monitoring (TS&M), is **97.4 mills/kWh**. This is 152% of the LCOE of the supercritical PC plant without CO_2 capture (63.9 mills/kWh).

6.3.8 Supercritical PC Plant with GPS-Based PCC LCOE Sensitivity Analysis

Consistent with the DOE/NETL report Case 12 supercritical PC plant, the supercritical PC plant with GPS-based PCC utilizes a deep FGD that reduces SOx level in the flue gas to < 1 ppmv before it enters the CO_2 absorber. At such low SOx concentrations, amine degradation losses due to SOx are minimized.

Total amine loss normally includes additional allowance for thermal, NOx and oxygen degradation on top of amine degradation due to SOx. The total amine loss allowance may be as high as 4 to 6 lbs/ton of CO_2 recovered.

A sensitivity analysis is provided in Figure 6.4, which shows how the LCOE varies with total amine degradation loss to allow correction to higher degradation rates if desired.

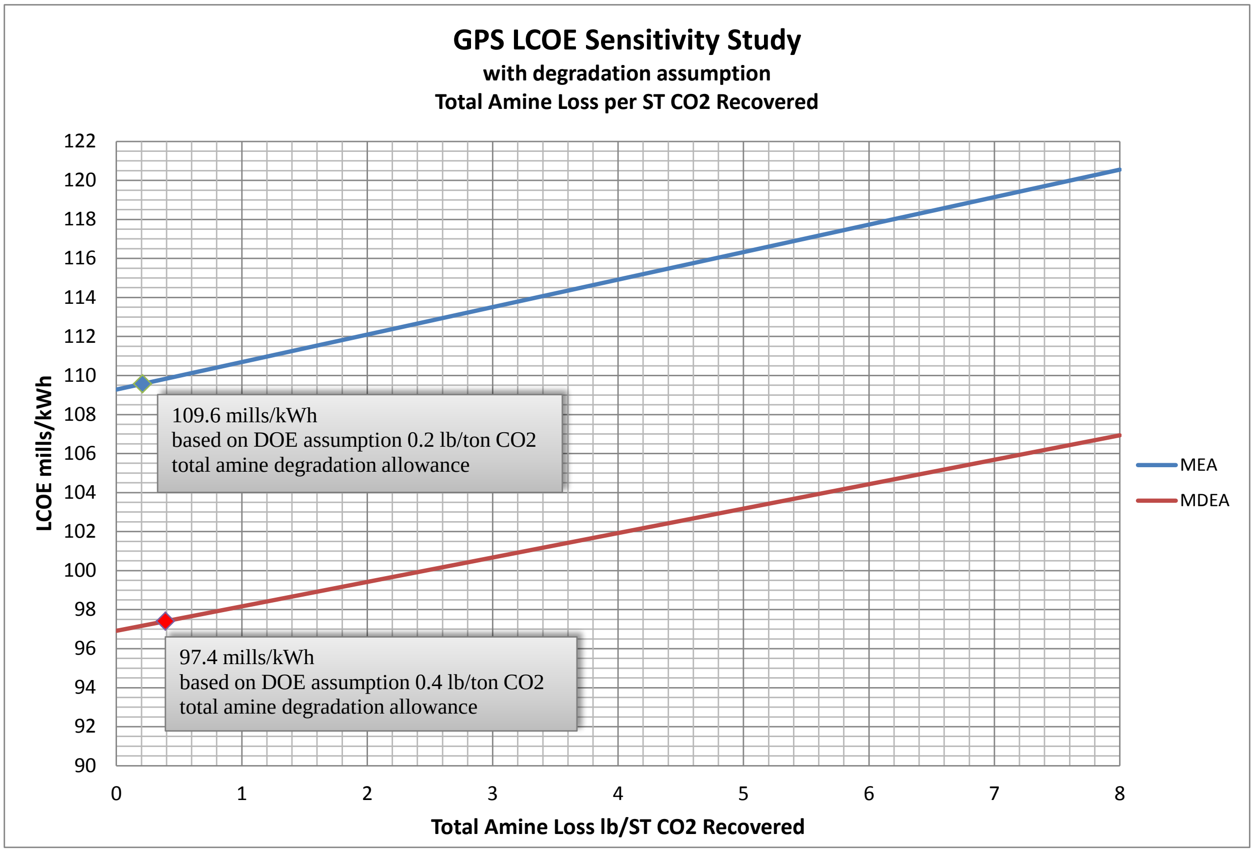

Figure 6.4. Sensitivity Analysis for Impact of Amine Degradation on LCOE

6.4 Summary

6.4.1 Overall Performance, Cost and LCOE Comparison

Table 6.14 compares the power outputs, capital and O&M cost estimates and LCOE among the cases of interest for this study. These are namely: the DOE/NETL report Case 11 supercritical PC plant without CO_2 capture, the DOE/NETL report Case 12 supercritical PC plant with benchmark MEA-based PCC, and the nominal 550 MWe supercritical PC plant using GPS-based PCC.

The net power produced in the supercritical PC plant with GPS-based PCC is 647 MW, greater than the MEA-based design. This higher efficiency is mainly due to the GPS process' much lower reboiling steam requirement and smaller CO_2 compression auxiliary power consumption. The 20-year LCOE for the supercritical PC plant with GPS-based PCC, ***not considering*** CO_2 TS&M, is 97.4 mills/kWh, or 152% of the Case 11 supercritical PC plant without CO_2 capture.

Compared to the DOE/NETL Case 12 supercritical PC plant with benchmark MEA-based CO_2 capture, the supercritical PC plant with GPS-based CO_2 capture has a higher capital cost. This is due to the much lower CO_2 compression section cost in the DOE/NETL Case 12 PC plant, which DOE/NETL has subsequently revised higher in updated versions of the report.

6.4.2 Sensitivity Analysis of Amine Degradation on LCOE

A sensitivity analysis was conducted on the supercritical PC plant with GPS-based PCC to determine what the impact of amine degradation is on its LCOE. The base assumption is that the deep FGD reduces the SOx level in the flue gas to < 1 ppmv before it enters the CO_2 absorber, minimizing amine degradation due to SOx. However, the MDEA losses are assumed to be 0.4 lb/ton of CO$_2$ removed due to its molecular weight being twice as high as MEA. The total amine loss could be as high as 4 to 6 lbs/ton of CO$_2$ recovered, as losses due to thermal, NOx and oxygen degradation are further considered on top of amine degradation due to SOx.

The LCOE varies linearly with amine degradation rates of up to 8 lbs/ton of CO$_2$. It is estimated that the GPS LCOE increases by about 1.2 mill/kWh for every amine degradation increment of 1 lb/ton CO$_2$ recovered.

Table 6.14. Performance, Cost and LCOE Comparison.

Levelised Cost of Energy (LCOE) Summary			
Post-Combustion Case Description	Supercritical PC w/o CO2 Capture	Supercritical PC w/ CO2 Capture	
Case Number	**Case 11**	**Case 12**	**GPS**
Type of CO2 Capture Technology	**N/A**	**Econoamine**	**MDEA/PZ**
Power System Financial Model (PSFM)	Nexant PSFM	Nexant PSFM	
Power Production, MW			
Gross Power	580	663	762
Net Power	550	546	647
Capital Cost, $MM			
Power Plant	866.4	1109.9	1125.5
PCC Plant	0.0	410.8	430.8
CO2 Compression and Drying	0.0	46.4	60.5
Start Up Costs (2% TPC before Contingency)	15.5	26.4	27.2
Total Capital Cost, $MM	**881.9**	**1,593.5**	**1,644.0**
Operating Cost excl Fuel, $MM/yr			
Fixed Operating Cost	13.8	20.5	22.6
Variable Operating Cost			
Non PCC related Opt Cost	20.0	33.6	34.6
NaOH		0.9	0.9
H2SO4		0.3	0.3
Amine M/U		1.0	2.0
Active Carbon		0.6	0.5
Corrosion Inhibitor/Solvent MU		0.0	0.0
Total Operating Cost excl Fuel, $MM/yr	**33.8**	**56.9**	**61.1**
Fuel Cost, $MM/yr	**64.5**	**92.0**	**92.0**
LCOE (excl CO2 TS&M), mills/kWh	**63.9**	**112.0**	**97.4**
% of Case 11 LCOE (FOA Target = 135%)			
% of Case 11 LCOE - Compare to 2007	**100%**	**175%**	**152%**

7. PRELIMINARY ENVIRONMENTAL, HEALTH AND SAFETY RISK ASSESSMENT

7.1 Introduction

Consistent with the TEA for this project, the EH&S assessment was also conducted for the GPS process fully-integrated with a 550 MWe (net) PC power plant. The PCC plant is designed as an integral part of the supercritical PC plant to recover up to 90% of the CO_2 in the flue gas. The description of the GPS-based PCC is provided in Section 6.3.1 and the flow diagram of the full-scale GPS-based PCC design is already shown in Figure 6.2. The stream table for the primary streams is demonstrated in Table 6.3. The primary unit operations for the EH&S purpose include:

- To reduce solvent loss caused by non-reversible reactions between emission components NO_2 and SO_2 and the amine solvent so as to prevent the accumulation of heat stable salts (HSS), a flue gas sulfur scrubber is used before the absorber to further reduce NO_2 and SO_2 in the flue gas.
- To avoid solvent loss due to mechanical entrainment and evaporation and reduce amine emissions from the clean flue gas, an overhead water wash section is applied to the top section of the absorption column.
- To remove high-boiling nonvolatile impurities (HSS), volatile acids and iron products from the circulating solvent solution, a solvent stripper reclaimer is employed for a small slipstream of the lean solvent from the stripper bottom.

7.2 EH&S Risk Assessment Methodology

The EH&S risk assessment followed the well-established DOE guidelines for assessment of EH&S risks to assess the environmental friendliness and safety of the materials and process. The elements and actions in this report include:

- Identify and quantify any potential ancillary or incidental air and water emissions, and solid wastes produced from the skid.
- Collect and summarize a concise but complete and comprehensible description of the various toxicological effects and chemical/physical properties of the substances identified in the process.
- Address the compliance and regulatory implications of the GPS-based processes.
- Conduct an engineering analysis and describe possible engineering controls and other mitigation strategies.

Identify precautions for safe handling and conditions for safe storage, examine waste treatment and offsite disposal options, and discuss accidental release measures.

7.3 Identification of EH&S Risks and Summary of Mitigating Approaches

7.3.1 Engineering Analysis and Engineering Control

Because the emission control, wastewater treatment and disposal of solid wastes of the PC plant are well described in the NETL Report No. DOE/NETL-2007/1281, this EH&S assessment focuses on the GPS-based full-scale PCC plant only. The PCC plant is used to remove 90 percent of the CO_2 in the flue gas exiting the FGD unit, purify it, and compress it to a supercritical condition. The PCC plant is comprised of the flue gas supply, SO_2 polishing, CO_2 absorption, solvent stripping and reclaiming, and CO_2 compression and drying, as illustrated in Figure 6.2 and Table 6.3.

The emission control system of the PCC plant is an overhead water wash section in the absorber, which is used to minimize solvent losses due to mechanical entrainment and evaporation. The flue gas from the top of the CO_2 absorber is contacted with a re-circulating stream of water for the removal of most of the lean solvent. The clean flue gas, along with unrecovered solvent, exit the top of the wash section for discharge to the atmosphere via the vent stack. The water stream from the bottom of the wash section is collected on a chimney tray. A portion of the water collected on the chimney tray spills over to the absorber section as water makeup for the lean solvent. The wash water level is maintained by wash water makeup. Simulation results by ProTreat™ show that the maximum concentration of total amine components in the clean flue gas stream after water wash is less than 1 ppmv.

The wastewater generated from the PCC plant includes runoff, cleaning wastes, blowdown, backwash water, and discharge from the flue gas scrubber. This water is collected by a water collection basin, which is a synthetic membrane-lined earthen basin. The collected wastewater is pumped to an on-site water treatment facility to be treated to within the U.S. EPA standards for suspended solids, oil and grease, pH, and miscellaneous metals. The waste treatment system consists of a water collection basin, raw waste pumps, an acid neutralization system, an oxidation system, flocculation, clarification/thickening, and sludge dewatering. Because the wastewater treatment facilities are used for FGD wastewater, which are more complicated than the PCC wastewater, the on-site treatment facilities are sufficient for the PCC wastewater treatment. A conventional secondary wastewater treatment process can generally fulfill for this purpose.

The waste liquid from the PCC plant comes from the solvent stripper reclaimer. A small slipstream of the lean solvent is fed to the solvent reclaimer for the removal of high-boiling nonvolatile impurities, including HSS, volatile acids and iron products from the circulating solvent solution. To minimize the accumulation of HSS, the flue gas exiting the FGD system passes through an SO_2 scrubber to reduce SO_2 concentration to 10 ppmv or less. The scrubber uses a 20 wt% solution of sodium hydroxide (NaOH) to remove at least 75 percent of SO_2 emissions from the FGD outlet to 10 ppmv. The scrubber proposed for this application has been demonstrated in numerous industrial applications throughout the world and can achieve removal efficiencies of over 95 percent, if necessary. The solvent bound in the HSS is recovered by reaction with caustic and heating with steam. The solvent reclaimer system reduces corrosion, foaming and fouling in the solvent system. The reclaimed solvent is returned to the stripper and the spent solvent is pumped to a solvent reclaimer drain tank for appropriate disposal. Because the make-up solvent is 3.07 ton per day, the same amount of spent solvent is assumed to be generated from the reclaimer. According to ElMoudir et al. (2013)[15] and Natural Scotland and Scottish Environmental Protection Agency (2015)[16], the concentration of equivalent spent solvent is 50 wt% or more. Therefore, the estimated maximum waste stream is below 10 metric ton/day.

7.3.2 EH&S Risk Identification and Associated Mitigation Approaches

The potential risks of the process effluent streams for the major EH&S issues arising from operating the GPS-based PCC plant are identified and corresponding mitigation measures are summarized, which are listed in Table 7.1. The mitigation approaches and actions to satisfy all existing EH&S regulations and guidelines related to the GPS-based CO_2 capture process design, operation and maintenance are summarized in Table 7.2.

Table 7.1. Summary of EH&S Risks and Mitigation measures for effluent streams

Risk	Mitigation Measures	Comments
Amines carry over from the system	The emission control system of the PCC plant is an overhead water wash section in the absorber, which is used to minimize solvent losses due to mechanical entrainment and evaporation.	Estimated maximum concentration of amines from the power plant stack to atmosphere is less than 1 ppmv.
Wastewater	Be collected by a water collection basin, which is a synthetic-membrane-lined earthen basin. Be pumped to an on-site water treatment facility to be treated to within the U.S. EPA standards. The waste treatment system	Wastewater includes runoff, cleaning wastes, blowdown wastewater, backwash water, and discharge from the flue gas scrubber. Because the wastewater treatment facilities are used for FGD wastewater, which are more complicated than the PCC wastewater, the on-site

	consists of a water collection basin, raw waste pumps, an acid neutralization system, an oxidation system, flocculation, clarification/thickening, and sludge dewatering.	treatment facilities are sufficient for the PCC wastewater treatment.
Spent solvent and accumulated heat stable salts	To minimize the accumulation of HSS, the flue gas exiting the FGD system passes through an SO_2 scrubber to reduce SO_2 concentration to 10 ppmv or less. A small slipstream of the lean solvent is fed to the solvent reclaimer for the removal of high-boiling nonvolatile impurities, including HSS, volatile acids and iron products from the circulating solvent solution.	The solvent bound in the HSS is recovered by reaction with caustic and heating with steam. The solvent reclaimer system reduces corrosion, foaming and fouling in the solvent system. The estimated maximum waste stream is below 10 metric ton/day.

Table 7.2. EH&S risks and mitigation approaches for design, operation and maintenance

Risk	Mitigation approach
Safety issues due to improper design and operation/maintenance requirements not identified at design period	Comprehensive design hazard review. A hazard and operability (HAZOP) analysis.
Process operation safety	Safety instrumented systems. Flow restriction and safety interlocks. Automatic safe shutdown capacity incorporated.
Chemical exposure	Multiple eye wash and emergency showers. Safe locations of vents and blow downs. Proper sizing of relief valve and similar devices.
Solvent handling	Rigorous operating procedures including mandatory usage of personal protection equipment.
Solvent storage (regulatory requirements)	OSHA and EPA regulated chemicals with threshold storage volume for process safety management checked. Confirmed solvent is not part of the classified chemicals list with threshold volume.

7.4 Solvent Properties and Toxicological Effects

The solvent is an aqueous solution of blended amines of MDEA and PZ, which were developed for energy-efficient CO_2 recovery from low-pressure flue gas streams. The primary component is MDEA. Because the solvent is composed of diluted aqueous solution of MDEA, PZ and water, and hence, the actual toxicological effects are smaller than the raw blended solution of MDEA, PZ and water. Therefore, solvent properties and toxicological effects are discussed in MDEA solution and raw blended solution of MDEA, PZ and water, respectively. Table 7.3 summarizes properties and toxicological effects for MDEA and Table 7.4 lists properties and toxicological effects for raw blended solution of MDEA, PZ and water.

Table 7.3. Solvent properties and toxicological effects for MDEA solution

Property/Effects	**Solvent Data/Guidelines**
Composition	98-100%wt of MDEA, 0.1-0.5%wt of water
Appearance/Color /Odor	Pale yellow liquid, amine odor
Emergency overview/ Precautions	- May cause eye damage - Severely irritating to eyes, skin, and respiratory tract - May be harmful if swallowed

	- May be harmful if absorbed through skin. - May cause sensitization by inhalation. - May cause sensitization by skin contact - Avoid contact with eyes, skin, and clothing - Avoid inhalation of mists/vapors
Potential health effects	**Primary routes of exposure:** Inhalation, ingestion, eye contact and skin contact. **Acute:** see additional Exposure control. *Inhalation:* At room temperature, exposures to vapors are minimal but vapor concentrations may be generated when heated, which may cause adverse effects. Vapors or mists are irritating to the respiratory tract. *Ingestion:* Low oral toxicity but swallowing large amounts can cause irritation of the digestive tract with abdominal and chest pain, nausea, vomiting and diarrhea. *Skin*: A single short-term exposure may be irritating to the skin. If skin is cut or scratched then irritation may be severe. *Eyes*: Direct contact with concentrated MDEA liquid will cause severe eye irritation. Serious damage may result if treatment is delayed. **Chronic:** see additional Toxicological information. *Inhalation:* Prolonged or repeated overexposure to mists or vapors may result in damage to the respiratory tract. *Skin:* Prolonged or repeated contact with concentrated MDEA may cause severe skin irritation and possible second-degree burn.
Medical conditions aggravated by exposure	Repeated skin contact may aggravate an existing dermatitis. Repeated inhalation may aggravate respiratory conditions, such as asthma and bronchitis, and inflammatory or fibrotic pulmonary disease.
First aid measures	**Inhalation:** Remove from exposure to fresh air immediately. Keep victim at rest. If breathing is difficult, trained personnel may administer oxygen. If breathing has stopped, give artificial respiration. Get immediate medical attention. **Ingestion:** Do not induce vomiting. Get immediate medical attention. If vomiting occurs naturally, have victim lean forward to reduce the risk of aspiration; rinse the mouth. Quickly transport the victim to an emergency care facility. Never give anything by mouth if victim is unconscious, rapidly losing consciousness or convulsing. **Eye Contact:** immediately flush the contaminated eye(s) with lukewarm flowing water for at least 20 minutes while holding the eyelids open. Neutral saline rinsing solution may be used as soon as it is available. Do not interrupt flushing. Take care not to rinse contaminated water into the unaffected eye or the face. Get immediate medical attention. **Skin Contact:** Immediately flush the affected areas with plenty of flowing water or a safety shower for at least 20 minutes. Remove contaminated clothing and shoes while flushing. Do not interrupt flushing. Seek immediate medical attention if irritation persists or if blistering occurs.
Fire fighting measures	**Flammability:** This material can burn if strongly heated. **LFL:** Not available. **UFL:** Not available. **Flash point:** 131°C by Closed Cup. **Extinguishing Media:** Water fog or fine spray, carbon dioxide, alcohol-resistant foam or dry chemical. Use water spray to cool fire-exposed containers. Violent steam generation or eruption may occur upon application of direct water stream. **Fire Fighting Instructions:** Evacuate the area and fight fire from a safe distance or a protected location. Approach the fire from upwind to avoid hazardous vapors. Burning liquids may be extinguished by dilution with water. Do not use direct water stream, it may spread fire. Water spray may be used to flush spills away from ignition sources. Avoid all contact with this material during fire fighting operations. Wear chemical resistant clothing (chemical splash suit) and positive-pressure self-contained breathing apparatus. **Hazardous Combustion Products:** During a fire smoke may contain the original material in addition to unidentified toxic and/or irritating compounds. Hazardous combustion products may include and are not limited to: nitrogen oxides, carbon monoxide, and carbon dioxide.

Accidental release measures	**Personal precautions:** Wear adequate personal protective equipment. **Air release:** Evacuate the area. Ventilate the area. Extinguish all ignition source. Notify occupational and environmental authorities. **Environmental precautions:** Do not discharge into drains/surface waters/groundwater. **Land spill**: Isolate the area; keep people away. Do not touch spilled material. Clean up should be conducted by trained personnel only. Evacuate the area. Ventilate the area. Extinguish all ignition source. Prevent the material from entering sewers, groundwater or surface water. Contain the spill with earth, sand, or suitable absorbent. Collect waste in suitable containers, which can be labeled and sealed. Flush the area with water. Notify occupational and environmental authorities. **Water spill:** Contain spills to prevent contamination of surface water and ground water. Notify occupational and environmental authorities.
Handling and storage	**Handling:** Avoid contact with eyes, skin and clothing. Avoid breathing vapors. Ensure that engineering controls are operating and protective equipment requirements are being followed. Avoid generating vapors and mists. Inspect container leaks before handling. Keep container closed when not in use. Do not use with incompatible materials (see stability and reactivity) **Storage:** Keep storage area away from work areas Store away from incompatible materials **(**see stability and reactivity**).** Store in a cool, dry, well-ventilated area away from sunlight, heat, and ignition sources.
Exposure control and personal protection	**Engineering control:** Good general ventilation is normally sufficient. In places where vapors or mists of this material are created local exhaust ventilation is recommended. **Hygiene measures:** Remove contaminated clothing promptly. Keep contaminated clothing in closed containers; discard or launder before re-wearing. Do not eat, drink or smoke in work areas. Wash hands thoroughly and promptly after handing this material. **Personal Protection:** **Respiratory protection:** Respiratory protection should not be necessary unless the product is heated to release vapors or mist is created. For likely exposure, wear a NOISH/MSHA approved full-face mask, self-contained breathing apparatus. **Skin protection:** Wear chemical protective gloves, coveralls and boots. Protective clothing should be made of butyl rubble, neoprene, or nitrite rubber. If skin is scratched or cut, impervious gloves must be worn even for brief exposures. **Eye protection:** Tightly-fitting safety goggles (chemical goggles). Wear face shield if splashing hazard exists.
General safety and hygiene measures	Handle in accordance with good industrial hygiene and safety practice. Females of childbearing age should not come into contact with the product. Avoid contact with skin. Avoid contact with eyes. Do not breathe spray. Eye wash fountains and safety showers must be easily accessible.
Stability and Reactivity	**Stability:** Stable under normal temperature and pressure**.** **Incompatible materials and conditions to avoid:** Product can decompose at elevated temperatures. Avoid direct sunlight. Avoid contact with nitrites, strong acids, strong oxidizing agents and halogenated hydrocarbons. **Hazardous decomposition products:** May include nitrogen oxides, ammonia, irritating aldehydes and ketones. Hazardous decomposition products depend upon temperature, air supply and presence of other materials. **Hazardous polymerization:** Mixing with nitrite containing materials may cause nitrosamine formation. **Other reactivity concerns:** Contact with nitrosating agents, under acidic conditions such as nitrous acid, nitrite or nitrogen oxides, can form nitrosamines some of which are potent carcinogens.
Toxicological Information	**Acute toxicity:** LD_{50} (oral) 1.945 mg/kg (rat); LD_{50} (dermal) 5.990 mg/kg (rabbit). **Irritation / corrosion:** Severely irritating to eyes; prolonged contact is irritating to the skin. Inhalation of mists or vapors is irritating to the respiratory tract. **Sensitization:** NA. **Reproductive toxicity: NA.** **Toxicologically synergistic effects**: MDEA may react with nitrites, under acid conditions to form nitrosamines some of which are potent carcinogens.

	Carcinogenicity: No data are listed in ACGIH, IARC, NTP, OSHA concerning carcinogenic effects.
Ecological Information	**Ecotoxicity:** Product is practically non-toxic to aquatic organisms on an acute basis. Acute 96 hour LC50 for Fathead Minnow (*Pimephales promelas*) is 1200 mg/L. Acute 96 hour LC50 for water flea (*Daphnia magna*) is 250 mg/L. Growth inhibition EC50 for marine copepod Arcatia tonsa is 84 mg/L. **Environmental mobility:** NA. **Persistence and degradability:** Product is expected to biodegrade readily under aerobic conditions. Theoretical oxygen demand (ThOD) is calculated to be 2.29 p/p. 28-day biochemical oxygen demand is 20-59 of ThOD. 5-day biochemical oxygen demand is below detectable limits. Bioaccumulative potential: is low (BCF<100 and log P_{ow}<3).
Disposal considerations	**Waste disposal method:** Do not dump into any sewers, on the ground or into any body of water. Store material for disposal as indicated in Handling and storage. For unused, uncontaminated product, the preferred options include sending to a licensed, permitted recycler, reclaimer, incinerator or other thermal destruction device. Dispose of in accordance with local, state and federal laws and regulations.
Regulatory information	**NFPA Hazard rating:** Acute health: 1; Flammability: 1; Reactivity: 0; **HMIS Hazard rating:** Acute health: 1; Flammability: 1; Reactivity: 0; **Clean Air Act:** None **Clean Water Act:** None of the chemicals in this product are listed as hazardous substances, priority pollutants or toxic pollutants under CWA.

Table 7.4. Solvent properties and toxicological effects for MDEA and PZ blended solution

Property/Effects	**Solvent Data/Guidelines**
Composition	45-50%wt of MDEA, 30-35%wt of PZ and 10-30%wt of water
Appearance/Color /Odor	Colorless/ yellow, liquid, fishy odor
Emergency overview/ Precautions	- Severe respiratory tract irritant. May cause respiratory sensitization. - May cause skin sensitization. Severe skin irritant. Corrosive to skin. - Severe eye irritant. Corrosive to eyes. - Corrosive to respiratory system.
Potential health effects	**Primary routes of exposure:** Eye and skin contact. Skin absorption. **Acute:** Product vapor in low concentrations can cause lacrimation, conjunctivitis and corneal edema when absorbed into the tissue of the eye from the atmosphere. Corneal edema may give rise to a perception of "blue haze" or "fog" around lights. The effect is transient and has no known residual effect. Burns of the eye may cause blindness. Contact of undiluted product with eyes or skin quickly causes severe irritation and pain and may cause burns, necrosis and permanent injury. Inhalation of vapors may severely damage contacted tissue and produce scarring. Inhalation of aerosols and mists may severely damage contacted tissue and produce scarring. Product is absorbed through the skin and may cause nausea, headache, and general discomfort. **Chronic:** This substance may cause respiratory sensitization and chronic lung toxicity to exposed workers. Repeated and/or prolonged exposures may cause allergic reaction/sensitization. Repeated and/or prolonged exposures may result in: adverse respiratory effects (such as cough, tightness of chest or shortness of breath), adverse eye effects (such as conjunctivits or corneal damage), and adverse skin effects (such as rash, irritation or corrosion). Effects from inhalation of vapors may be delayed. Repeated and/or prolonged exposure to low concentrations of vapor may cause: sore throat, which is transient.
Medical conditions aggravated by exposure	Asthma Chronic respiratory disease (e.g. Bronchitis, Emphysema) Eye disease Skin disorders and Allergies Not a carcinogen.
First aid measures	**Inhalation:** Move patient to fresh air. If breathing has stopped or is labored give assisted respiration (e.g. mouth-to-mouth). Supplemental oxygen may be indicated. Prevent aspiration of vomit. Turn victim's head to the side. Seek medical advice. **Ingestion:** In the event of ingestion, administer 3-4 glasses of milk or water. DO NOT INDUCE VOMITING. Seek medical advice. **Eye Contact:** Hold eyelids apart and immediately flush eyes with plenty of water for at least 15 minutes. Seek medical advice. **Skin Contact:** Remove product and immediately flush affected area with water for at least 15 minutes. Remove contaminated clothing and shoes. Destroy contaminated leather apparel. Cover the affected area with a sterile dressing or clean sheeting and transport for medical care. Do not apply greases or ointments. Control shock, if present. Launder contaminated clothing prior to reuse.
Fire fighting measures	**Flash point:** >100°C by Closed Cup. **Extinguishing Media:** Ignition will give rise to a Class B fire. In case of large fire use: water spray, alcohol foam. In case of small fire use: carbon dioxide (CO_2), dry chemical, dry sand or limestone. **Fire Fighting Instructions:** A face shield should be worn. Firefighters should wear butyl rubber boots, gloves, and body suit and a self-contained breathing apparatus. Retain expended liquids from fire fighting for later disposal. **Unusual fire and explosion hazards:** May generate toxic or irritating combustion products. Contact of liquid with skin must be prevented. Sudden reaction and fire may result if product is mixed with an oxidizing agent. May generate carbon monoxide gas. May generate toxic nitrogen oxide gases. May generate ammonia gas. Personnel in vicinity and downwind should be evacuated.

Accidental release measures	Containment Techniques (Removal of ignition sources, diking, etc.) Stop the leak, if possible. Ventilate the space involved. Reduce vapor spreading with a water spray. Shut off or remove all ignition sources. Construct a dike to prevent spreading (includes molten liquids until they freeze). **Clean-Up Procedures:** If recovery is not feasible, admix with dry soil, sand, or non-reactive absorbent and place in an appropriate chemical waste container. Transfer to containers by suction, preparatory for later disposal. Place in metal containers for recovery or disposal. Flush area with water spray. Clean-up personnel must be equipped with self-contained breathing apparatus and butyl rubber clothing. For large spills, recover spilled material with a vacuum truck. **Other:** Open enclosed spaces to outside atmosphere. Wear protective clothing, boots, gloves, and eye protection
Handling and storage	**Handling:** Avoid contact with skin or eyes. Avoid breathing of vapors. Handle in well ventilated work space. When handling, do not eat, drink, or smoke. Emergency showers and eye wash stations should be readily accessible. Adhere to work practice rules established by government regulations (e.g. OSHA). Do not use sodium nitrite or other nitrosating agents in formulations containing this product. Cancer- causing nitrosamines could be formed. **Storage:** Keep away from: acids, oxidizers. Keep in cool, dry, ventilated storage and in closed containers. Store in steel containers preferably located outdoors, above ground, and surrounded by dikes to contain spills or leaks. Do not store in reactive metal containers.
Exposure control and personal protection	**Engineering control:** No specific controls needed. **Protective Equipment:** Full-face shield with goggles underneath for *eye protection*. For *hand protection*, apply neoprene rubber gloves, impermeable gloves, cuffed butyl rubber gloves or nitrile rubber gloves. For *respiratory protection*, not required under normal conditions in a well-ventilated workplace. An organic vapor respirator National Institute for Occupational Safety and Health (NIOSHA) approved for organic vapors is recommended under emergency conditions. *Protective clothing* includes impervious clothing, slicker suit, rubber boots, full rubber suit (rain gear) and butyl or latex protective clothing. **Exposure Guidelines/Other:** Provide readily accessible eyewash fountains and safety showers. Wash at the end of each work shift and before eating, smoking or using toilet. Promptly remove clothing that becomes contaminated. Discard contaminated leather articles.
Stability and Reactivity	**Stability:** Stable**.** **Conditions to avoid:** Not applicable. **Incompatibility/materials to avoid:** Mineral acids (i.e. sulfuric, phosphoric, etc.). Organic acids (i.e. acetic acid, citric acid etc.). Oxidizing Agents (i.e. perchlorates, nitrates etc.). Sodium or Calcium Hypochlorite. CAUTION!! N-Nitrosamines, many of which are known to be potent carcinogens, may be formed when the product comes in contact with nitrous acid, nitrites or atmospheres with high nitrous oxide concentrations. Product slowly corrodes copper, aluminum, zinc and galvanized surfaces. Reaction with peroxides may result in violent decomposition of peroxide possibly creating an explosion. Nitrites, nitrosating agents. A reaction accompanied by large heat release occurs when the product is mixed with acids. Heat generated may be sufficient to cause vigorous boiling creating a hazard due to splashing or splattering of hot material. **Hazardous decomposition products:** Nitrogen oxide can react with water vapors to form corrosive nitric acid. [TLV=2] Carbon Monoxide in a fire. Carbon Dioxide in a fire. Ammonia when heated. Nitrogen oxides in a fire. Irritating and toxic fumes at elevated temperatures. Nitric acid in a fire. Nitrosamines. The oxides of nitrogen gases (except nitrous oxide) emitted on decomposition are highly toxic. **Hazardous polymerization:** Will not occur.
Toxicological Information	**Acute toxicity:** Estimated LD_{50} (oral) >2000.00 mg/kg (rat); Estimated LD_{50} (dermal) >4000.00 mg/kg (rabbit).

	Inhalation toxicity LD_{50} for rat: no data.
Ecological Information	No data.
Disposal considerations	Comply with all Federal, State, and Local Regulations.
Regulatory information	US Federal Regulations: TOXIC SUBSTANCES CONTROL ACT (TSCA)- All components are included in the EPA Toxic Substance Control Act (TSCA) Chemical Substance Inventory. OSHA Hazard Communication Standard (28CFR1910.1200) hazard class(es): Corrosive, Sensitizer EPA SARA Title III Section 312 (40CFR370) hazard class: Immediate Health Hazard. Delayed Health Hazard. EPA SARA Title III Section 313 (40CFR372) toxic chemicals above "de minimis" level are none.

7.5 Summary

A preliminary EH&S assessment has been completed to identify possible EH&S risks, to summarize corresponding mitigation measures, and to collect information for solvent properties and toxicological effects. This topical report summarizes the key EH&S concepts and approach, as well as the implementation of risk mitigation measures. This assessment is anticipated to provide a strong basis for EH&S risk handling in further scale-up and commercialization of the GPS process for post-combustion CO_2 capture. The primary summaries and conclusions of the EH&S assessment are:

- Results from engineering analysis and engineering control for the full-scale GPS-based PCC process show that: 1) the gaseous emission control system of the GPS-based process does not increase the current emissions of the power plant regulated matters, such as SO_2, NOx, particulate matter, and mercury; 2) the maximum concentration of amines emitted with the flue gas through the stack of the power plant would be below 1 ppmv; 3) the wastewater from the PCC plant can be collected and treated by an onsite water treatment facility to within the U.S. EPA standards; 4) the waste liquid of the PCC plant is heat stable salts, volatile acids and iron products from the circulating solvent solution from the solvent reclaimer; and 5) the estimated maximum waste stream is below 10 metric ton/day, which can be appropriately disposed by the power plant onsite facilities, or by an outside waste handling facility.
- The potential risks of the GPS-based process effluent streams for the major EH&S issues arising from operating the process are identified and corresponding mitigation approaches and actions are summarized, which satisfy all existing EH&S regulations and guidelines related to the GPS-based CO_2 capture process design, operation and maintenance. The properties and toxicological effects of the blended amine solvent solution of MDEA, PZ and water are also summarized.
- The properties and toxicological effects of the blended amine solvent solution of MDEA, PZ and water are summarized.

8. PROJECT FINAL STATUS

The milestones set for this project have been successfully achieved. Table 8.1 summarizes the milestone log.

Table 8.1. Milestone log summary

	Task	Title/Description	Planned Completion Date	Actual Completion Date	Verification Method
BP1	1	Submit Project Management Plan	10/31/2011	9/16/2011	Project Management Plan file
	2	GPS column study and optimization to achieve thermal efficiency of 60% or greater	9/30/2012	7/9/2012	Design review with NETL / Presentation of data
	9	Solvent loss due to degradation of solvent is less than 3 kg/ton CO_2	9/30/2012	7/9/2012	Design review with NETL / Presentation of data
BP2	1	Host site agreement executed	6/30/2013	6/30/2013	Written notification from NCCC
	3	Overall energy performance column and solvent less than or equal to 0.22 kwh/kg CO_2	9/30/2013	12/30/2012	Design review with NETL / Presentation of data
	7	GPS column efficiency experimental measured at 50% or greater	9/30/2013	2/25/2013	Design review with NETL / Presentation of data
	8	Overall energy performance of system less than or equal to 0.20 kwh/kgCO_2	9/30/2014	2/25/2013	Design review with NETL / Presentation of data
	16	Complete design of bench-scale GPS test unit for conventional columns	4/30/2013	5/20/2013	Design report
	16	Completion of the fabrication and shakedown of the skid-mounted GPS system using water and air	3/31/2014	5/23/2014	Review with NETL/presentation of data
	16	Complete installation of 500 SLPM column-based GPS bench unit at NCCC	5/31/2014	8/10/2014	Review with NETL / NCCC
BP3	12	Completion of Preliminary EH&S Assessment	9/30/2015	10/5/2015	Topical Report
	15	Completion of techno-economic analysis of the GPS system using NCCC field test data	9/30/2015	9/30/2015	Topical Report
	17	Complete commissioning of the skid-mounted GPS system at NCCC	9/30/2014	2/27/2015	Review with NETL / NCCC
	17	Completion of the parametric tests of GPS system at NCCC and identify optimal operating conditions for long-term test	12/31/2014	3/27/2015	Review with NETL /NCCC
	17	Long-term operation of the GPS skid for >2000 hours of cumulative run-time on coal-derived flue gas	8/31/2015	8/10/2015	Review with NETL / NCCC
	17	Completion of equipment tear down and return to CCS facilities	9/30/2015	9/10/2015	Review with NETL /NCCC
BP1 to BP3	1	Quarterly report	Each quarter	As required due date	Quarterly Report files
	1	Draft Final report	10/31/2015	10/20/2015	Draft Final Report file

9. CONCLUSIONS AND RECOMMENDATION

9.1 Conclusions

The GPS-based PCC process developed in this project presents a unique approach that uses a gas pressurized technology for CO_2 stripping at an elevated pressure to overcome the energy use and other disadvantages associated with the benchmark MEA process. The project was aimed at performing laboratory- and bench-scale experiments to prove its technical feasibility and generate process engineering and scale-up data, and conducting a TEA to demonstrate its energy use and cost competitiveness over the MEA process.

A combination of experimental, process simulation, and cost analysis studies were performed to obtain detailed information to address the technical challenges described in Section 1.3. The major conclusion of the project is that the GPS-based PCC process is energy-efficient and cost-effective compared with the benchmark MEA process. For integration of the GPS process into a 550-MWe PC-fired power plant, the increase in COE is approximately 23% lower than that for the benchmark MEA process. More detailed results and conclusions from those studies are summarized below.

9.1.1 Simulation study and optimization of the GPS-based process.

- Favorable configuration and operating conditions for the GPS column were identified, which shows that: 1) high heat efficiency can be achieved when the side-heating units are placed in the top half of the GPS column and maximum of four heating units is recommended; 2) high operating pressure is favorable for high thermal efficiency and high GPS effluent CO_2 pressure, but results in high capital and operational cost; 3) higher operating temperature is favorable for better GPS column performance, but subject to solvent thermal stability; and 4) GPS column thermal efficiency exceeds 60% for the selected commercial solvents.
- Absorption-based CO_2 capture processes use heat to separate CO_2 from flue gas and to compress CO_2 thermally. Optimization study of GPS-based process shows that thermal compression does not increase the heat efficiency of low-pressure steam applications comparing to that for direct power generation. Meanwhile, there is an optimal operating pressure range based on balancing reductions in CO_2 compression work, pumping work, and capital equipment costs. This optimum range is 20 bar or less.
- For a modified GPS-based PCC process design with a split gaseous stream from the GPS column, this split gaseous stream includes 20% of the overall recovered CO_2 and goes through the second absorption cycle. The remaining 80% of the overall recovered CO_2 is compressed directly as part of the CO_2 product. The overall energy performance for this modified GPS process is less than 0.22 kWh/kg CO_2.
- An alternative separation method for GPS column product stream was also developed, which integrates a compound compression/refrigeration process into the GPS-based PCC process. This process further improves energy efficiency with overall energy performance of 0.198 kWh/kg CO_2.
- The latest optimization of the GPS-based process is a simplified GPS process without requirement of GPS product stream separation, i.e., one absorption/desorption cycle through reducing the operating pressure of the GPS column to 6 bar. The performance of this latest GPS-based process was investigated in detail at the NCCC with real post-combustion flue gas and via a TEA, which are described in Sections 5 and 6.

9.1.2 Solvent properties study at high temperature and high CO_2 loading.

- The VLE data were measured for various concentrations of the CO_2/PZ/MDEA/H_2O system and compared with ProTreat™ software simulation results. The experimental data exhibit reasonable agreement with the simulation results at low-to-moderate CO_2 loadings, indicating that use of the simulation results provides a reasonable representation of equilibrium behavior. Better agreement between the measured and predicted results is observed as the temperature is increased. At higher CO_2 loadings (i.e., greater than ~0.6 mol/mol amine), the measured equilibrium CO_2 partial pressures become markedly greater than the simulation results.

- Thermal stability study of the solvents demonstrates that the estimated solvent loss is significantly less than the control target of 3 kg solvent/ton CO_2.
- Oxidative stability tests of the solvents show the estimated solvent loss is significantly less than the control target of 3 kg solvent/ton CO_2.
- Corrosion test of the solvents indicate that while the corrosion rate depends on the material type, the overall rates are relatively low. For all types of materials, corrosion rates are less than 1.0 mils/year for temperatures less than 100°C, thereby suggesting that carbon steel could be used in equipment components that do not exceed 100°C. In comparison, equipment components that exceed processing temperatures of 80°C may benefit from being fabricated from stainless steel. This type of design could assist in decreasing the overall capital cost.

9.1.3 Lab-Scale experimental testing of GPS process performance

- A lab-scale packed-bed first absorption column of 9 feet in packing height and 4 inches in internal diameter with two inter-stage cooling zones was fabricated to test the performance of the selected solvents. Results show that 90% CO_2 capture can be achieved at gas flow rates of less than 20 liters/min, but the percentage of CO_2 capture decreases with increasing feed gas flow rate. When the lean loading decreases from 3.8 to 3.3 wt%, the 90% capture target can be achieved at gas flow rates up to 30 L/min. Similarly, at flow rates less than 15 L/min, 90% capture can be achieved for lean loadings up to 4.0 wt%.
- A lab-scale packed-bed GPS column of 6 feet in packing height and 1 inches in internal diameter was fabricated to test its performance with the selected solvents. The GPS column has multiple heating locations along the column depth. Results show that: 1) at constant operating pressure of 6 bar, the target lean loading (4 wt%) was achievable over a large range of solvent flow rates, but the CO_2 purity reduces with increasing solvent flow rate, which indicates that less than 150 g/min of solvent flow rate is required to achieve 95% purity of CO_2 product; 2) to achieve target lean loading, the required stripping gas/solvent ratio increases with increasing column operating pressure; 3) introducing the slipstream still enables the GPS column to be operated at the anticipated CO_2 working capacity and CO_2 purity, which indicates that use of a slipstream from the GPS column can assist in achieving process performance goal for product purity; and 4) the thermal efficiency of the GPS column, a ratio of the theoretical minimum heat duty to the actual heat duty, is 64%, which is much higher than that of a traditional columns (typical 20% or less).
- The second absorption column is fabricated by modifying the GPS column, because both columns have similar operating conditions. Results show that the CO_2 concentration in the outlet gas stream is much less than the target CO_2 concentration of less than 5% though the CO_2 concentration in the outlet gas stream increases with increasing operating temperature at the top of the column. This good performance is a combination of the large driving force of mass transfer at the bottom of the column and the ability to achieve thermodynamic equilibrium at the top of the column.
- Flasher tests using a 970-mL autoclave were conducted to verify the predictions from ProTreat simulations. The results measured experimentally agree well with the data collected at 10 and 20 bar. At operating pressures of 40 and 60 bars, however, the measure CO_2 pressure was greater than those by corresponding simulation because of increased difficulty in accurately sampling.

- To seek a low capital cost alternative, a lab-scale standard RPB was evaluated at anticipated absorption and stripping operating conditions. The results indicate that the use of RPB could effectively reduce the equipment footprint by 20 times or more, hence greatly reduce capital cost of the columns.

9.1.4 Continuous skid testing of a bench-scale GPS based process

A nominal 500 SLPM skid-mounted, column-based GPS bench unit was evaluated at the NCCC host site. The skid has dimensions of 10’6” length and 8’ width. The absorber has 8’’ ID and 32’ height and the GPS column has 6” ID and 30’ height. The skid was equipped with PLC control system and able to run without manual intervention. Parametric test results showed that:

- With the increase of total flue gas flow rate, the CO_2 removal rate in the absorber is reduced while CO_2 purity from the stripper is reduced slightly;
- With the increase of G/L volume ratio, the CO_2 removal rate is reduced and CO_2 purity was not affected;
- With the increase of stripper operating pressure, both the CO_2 product purity from the stripper and CO_2 removal rate in the absorber are reduced; and
- With the increase of N_2 flow rate into the stripper, the CO_2 product purity is reduced but CO_2 removal rate increased.

These results are expected and agreed with those obtained from the lab scale individual unit tests and the computer simulation. After the parametric tests, the skid was transitioned to the long-term test under 24-hour operation mode. The operating conditions were maintained at which 90% CO_2 removal rate in the absorber is achieved and CO_2 product with 95% purity from the stripper is produced. These operating conditions were determined from the parametric tests. The pressure in the stripper was kept around 6 bar absolute. The long-term test started from May 23 and ended in August 10, 2015.

During the long term tests, solvent loss was also measured. However, since the bench scale skid system was not equipped with a solvent recovery system, the solvent loss was high at an estimated net loss rate range of 2.9-3.2 kg/day.

Energy consumption test was conducted to evaluate the performance of the GPS technology. Excluding the sensible heat, the average of measured sum of reaction and stripping heat is 1586 kJ/kg CO_2 captured, which is quite close to 1570 kJ/kg CO_2 captured, the result of computer simulation.

Both parametric tests and long term tests at NCCC have demonstrated that GPS process is able to achieve 90% CO_2 removal from typical coal derived flue gas. GPS process is also able to produce high pressure CO_2 product with required purity. Additionally, the energy consumption of the GPS process is much lower than that of the DOE MEA baseline case.

9.1.5 Techno-economic study of GPS-based PCC process

Comparison of the power outputs, capital and O&M cost estimates, and LCOE was conducted among the DOE/NETL report Case 11 supercritical PC plant without CO_2 capture, the DOE/NETL report Case 12 supercritical PC plant with benchmark MEA-based PCC, and the nominal 550 MWe supercritical PC plant using GPS-based PCC. The results shown that the net power produced in the supercritical PC plant with GPS-based PCC is 647 MW, greater than the MEA-based design. This higher efficiency is mainly due to the GPS process’ much lower reboiling steam requirement and smaller CO_2 compression auxiliary power consumption. The 20-year LCOE for the supercritical PC plant with GPS-based PCC, ***not considering*** CO_2 TS&M, is 97.4 mills/kWh, or 152% of the Case 11 supercritical PC plant without CO_2 capture, which is also 23% less than that with benchmark MEA-based PCC.

A sensitivity analysis was conducted on the supercritical PC plant with GPS-based PCC to determine what the impact of amine degradation is on its LCOE. The base assumption is that the DFGD reduces the SOx level in the flue gas to < 1 ppmv before it enters the CO_2 absorber, minimizing amine degradation due to SOx. However, the MDEA losses are assumed to be 0.4 lb/ton of CO_2 removed due to its molecular weight being twice as high as MEA's. The total amine loss could be as high as 4 to 6 lbs/ton of CO_2 recovered, as losses due to thermal, NOx and oxygen degradation are further considered on top of amine degradation due to SOx. The LCOE varies linearly with amine degradation rates of up to 8 lbs/ton of CO_2. It is estimated that the GPS LCOE increases by about 1.2 mill/kWh for every amine degradation increment of 1 lb/ton CO_2 recovered.

9.1.6 Preliminary environmental, health and safety risk assessment

Results from engineering analysis and engineering control for the full-scale GPS-based PCC process show that: 1) the gaseous emission control system of the GPS-based process does not increase the current emissions of the power plant regulated matters, such as SO_2, NOx, particulate matter, and mercury; 2) the maximum concentration of amines emitted with the flue gas through the stack of the power plant would be below 1 ppmv; 3) the wastewater from the PCC plant can be collected and treated by an onsite water treatment facility to within the U.S. EPA standards; 4) the waste liquid of the PCC plant is heat stable salts, volatile acids and iron products from the circulating solvent solution from the solvent reclaimer; and 5) the estimated maximum waste stream is below 10 metric ton/day, which can be appropriately disposed by the power plant onsite facilities, or by an outside waste handling facility.

The potential risks of the GPS-based process effluent streams for the major EH&S issues arising from operating the process are identified and corresponding mitigation approaches and actions are summarized, which satisfy all existing EH&S regulations and guidelines related to the GPS-based CO_2 capture process design, operation and maintenance. The properties and toxicological effects of the blended amine solvent solution of MDEA, PZ and water are also summarized.

9.2 Recommendations

The following activities are recommended in future work:

- Scale-up testing of an integrated system. The design and testing of an integrated GPS-based PCC plant at a pilot-scale using a slipstream of actual flue gas is recommended. The plant is recommended to install water wash solvent recovery unit at top of absorber to avoid solvent loss and emission to atmosphere, to install a condenser or an equivalent heat recovery unit for the GPS product stream to recover solvent, and to install a flue gas scrubber to reduce amine solvent degradation.
- Quantification of solvent degradation and study on solvent reclamation process are recommended to generate engineering and design data for future scaling-up.
- Performance of GPS-based PCC process using alternative commercial solvents, such as AMP, is suggested to be studied to compare solvent performance and stability, especially during long-term, continuous testing.

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