CO₂ Capture by Absorption with Potassium Carbonate

Quarterly Progress Report

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Abstract

The objective of this work is to improve the process for CO₂ capture by alkanolamine absorption/stripping by developing an alternative solvent, aqueous K₂CO₃ promoted by piperazine. The baseline campaign with 30% MEA has given heat duties from 40 to 70 kcal/gmol CO₂ as predicted by the stripper model. The Flexipak 1Y structured packing gives significantly better performance than IMTP 40 duped packing in the absorber, but in the stripper the performance of the two packings is indistinguishable. The FTIR analyzer measured MEA volatility in the absorber represented by an activity coefficient of 0.7. In the MEA campaign the material balance closed with an average error of 3.5% and the energy balance had an average error of 5.9.

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Introduction

The objective of this work is to improve the process for CO₂ capture by alkanolamine absorption/stripping by developing an alternative solvent, aqueous K₂CO₃ promoted by piperazine. This work expands on parallel bench-scale work with system modeling and pilot plant measurements to demonstrate and quantify the solvent process concepts.

Gary Rochelle is supervising the bench-scale and modeling work; Frank Seibert is supervising the pilot plant. Five graduate students (Babatunde Oyenekan, Ross Dugas, Jennifer Lu, John McLees, Andrew Sexton) have received support during this quarter for direct effort on the scope of this contract. Two students supported by other funding have made contributions this quarter to the scope of this project (Eric Chen – EPA Star Fellowship; Marcus Hilliard – Industrial Associates).

Experimental

Subtask 1.1 describes experimental methods for measuring CO₂ solubility in the aqueous solvent at stripper temperature.

Subtask 2.2 describes modifications to be made to the pilot plant for Campaign 4.

Subtask 2.5 describes the changes in the analytical methods used in the pilot plant for the second campaign.

Subtask 3.4 describes methods to use the FTIR to analyze the absorber off-gas from the pilot plant.

Results and Discussion

Progress has been made on six subtasks in this quarter:

Subtask 1.1 – Modify Vapor-Liquid Equilibrium (VLE) Model

Existing experimental apparatus at the Norwegian University of Science and Technology has been used successfully to duplicate the Tosh et al. (1959) data on CO₂ solubility in 20 wt% potassium carbonate at 110°C.

Subtask 1.10a – Simulate MEA Baseline Stripper Performance

Stripper performance data from Campaigns 2 and 3 were analyzed and simulated by the ACM model. The measured stripper heat duty in Campaign 2 with 5 m K⁺/2.5 m PZ varied from 75 to 140 kcal/gmol CO₂. The predicted heat duty varied from 40 to 95 kcal/gmol CO₂. The high measured heat duty may result from the difficulty in preheating the stripper feed in Campaign 2. In Campaign 3 with 30% MEA the rich feed was more completely preheated. The measured stripper heat duty varied from 40 to 140 kcal/gmol CO₂. The Aspen Custom Modeler (ACM) model accurately predicted reboiler heat duty in about 50% of the runs. In the others it underpredicted the heat duty by 30 to 50%. There appears to be no significant difference in stripper performance with the structured (Flexipac 1Y) or dumped (IMTP 40) packing.

Subtask 2.2 – Design Modifications, Order Equipment and Packing Materials

Modifications have been designed in preparation for Campaign 4. They include a cross-exchanger for rich solution preheating, steam injection for absorber gas heating, a stainless-steel line for the absorber feed gas, and additional capabilities for CO₂ analysis.

Subtask 2.5 – Pilot Plant – Campaign 2

The liquid samples from Campaign 2 have been re-analyzed for CO₂ loading. The total alkalinity has been determined by a correlation with measured on-line solution density. The apparent mass transfer coefficients (K_G) agree well with values predicted from the bench-scale measurements.

Subtask 2.7 – Pilot Plant – Campaign 3 – MEA Baseline

The CO₂ loading was successfully correlated to the solution density. The average mass balance error was 3.5% between the CO₂ absorbed via the liquid analysis and the CO₂ released from the stripper via an annubar flow meter. The average energy balance error between the predicted reboiler duty and the measured reboiler duty was -2.3% with an absolute average error of 5.9%.

In a preliminary mass transfer analysis executed for the absorber, it was determined that the Flexipac 1Y exhibited higher K_{Ga} values than IMTP-40. For both packings, higher gas rates resulted in higher K_{Gas} .

Subtask 3.4 – Amine Volatility

The high-temperature FTIR was used to analyze absorber off-gas from the last two weeks of the MEA pilot plant campaign. The CO₂ analysis agrees well with the online Vaisala, suggesting that the FTIR may be used as a back-up analyzer. The measured water leaving the absorber was strongly correlated with temperature and was 10 to 20% lower than the expected vapor pressure of water. MEA concentration was 10 to 170 ppm and was correlated with temperature to give MEA activity coefficients of 0.6 to 1.0. Ammonia concentration in the absorber off-gas was as high as 1300 ppm, because the gas was recycled and there was no designed bleed of ammonia from the system.

Conclusions

1. IMTP 40 and Flexipac 1Y packing appear to give equivalent performance in the stripper.
2. Measured on-line density is a more reliable indicator of total solution alkalinity than pH titration of potassium/pz solvents.
3. The average value of K_G for 5 m K⁺/2.5 m PZ is 0.0055 m/s at 0.45 mol CO₂/equiv alkalinity and 0.0035 at 0.495 mol CO₂/equiv alkalinity.
4. MEA volatility in the absorber off-gas corresponded to a liquid phase activity coefficient of 0.7.
5. The FTIR analyzer is a reliable instrument for gas analysis in the pilot plant.

6. Ammonia accumulates in the pilot plant system to as high as 1300 ppm in the absorber off-gas.
7. In the MEA campaign, the material balance closed with an average error of 3.5% and the energy balance had an average error of 5.9%.
8. In the MEA campaign, the Flexipac 1Y packing consistently gives 2 times higher values of K_{ga} than the IMTP 40 packing.

Future Work

We expect the following accomplishments in the next quarter:

Subtask 1.1 – Modify Vapor-Liquid Equilibrium (VLE) Model

The VLE apparatus at the Norwegian University of Science and Technology will be used to measure CO_2 solubility at 100 to 120°C in potassium carbonate/piperazine solvents.

Subtask 1.5 – Simulate Base Case Pilot

The absorber data from Campaigns 1 and 2 will be simulated with the spreadsheet model.

Subtask 1.10 – Simulate MEA Baseline Stripper performance

The absorber and stripper data from Campaign 3 will be simulated with the Freguia model in AspenPlus/Ratefrac.

Subtask 2.2 – Design Modifications, Order Equipment and Packing Materials

The following major pilot plant modifications will be completed before Campaign 4 with K+/PZ:

- A new stainless-steel reboiler will be installed.
- The solvent preheat system will be upgraded by installing a new lean/rich cross exchanger.
- The PVC absorber feed gas line will be replaced with stainless steel.

Subtask 2.6 – Pilot Plant Campaign 4, Optimization of System Parameters

The final pilot plant campaign is scheduled to begin in September 2005.

Subtask 3.4 – Amine Volatility

The FTIR analyzer will be calibrated for piperazine and used in Campaign 4 to determine piperazine volatility. A bench-scale system will be constructed to measure amine volatility.

Task 1 – Modeling Performance of Absorption/Stripping of CO₂ with Aqueous K₂CO₃ Promoted by Piperazine

Subtask 1.1 – Modify Vapor-Liquid Equilibrium (VLE) Model

by Marcus Hilliard
(Supported by the Industrial Associates Program)

Summary

The work presented in this subtask is part of a collaborative effort between The University of Texas and the Norwegian University of Science and Technology to verify the partial pressure of carbon dioxide (CO₂) over a salt solution at 110°C.

Experimental Section

Sample solutions of potassium carbonate (K₂CO₃) and potassium bicarbonate (KHCO₃) were prepared from Flucka and Sigma-Aldrich, respectfully, without further purification and deionized water. CO₂ and nitrogen (N₂) gasses were obtained from AGA Gas GmbH at a purity of >99.99 mol% and >99.999 mol%, respectfully.

As a baseline for blended salt/amine systems, we conducted a preliminary CO₂ solubility study using 20 mass% K₂CO₃ at 110°C and over a range in loading from 0.2 to 0.5. For this study, loading is defined as the moles of CO₂ per mole of K₂CO₃.

Experimental Methods

Solubility of CO₂ was determined using a vapor-liquid equilibrium apparatus with recirculation of the gas phase as shown in Figure 1. The apparatus was designed to operate at pressures up to 700 kPa and temperatures up to 130°C. The use of this apparatus to explain CO₂ solubility in amine solutions has previously been described by Ma'mun et al. (2005); therefore, only a few essentials are given here.

In an experiment, three 300 cm³ stainless-steel cells (equilibrium cells 1, 2, and 3) are filled with a known amount of preloaded sample solution. Within equilibrium cell one, 200 cm³ of sample solution is fed into the cell, while cells two and three only contain 150 cm³ of sample solution. The cells are located within a thermostated box where the temperature of each cell is measured within $\pm 0.1^\circ\text{C}$ and controlled through the use of three separate oil baths. Initially, the cells are pressurized to 300 kPa to minimize vaporization of the loaded solution during the initial heating of the apparatus. When the experimental temperature is reached, the system is pressurized to 700 kPa and the vapor is then allowed to circulate. Equilibrium is obtained when the temperature, CO₂ concentration in the vapor phase, and the equilibrium pressure are constant. This process normally takes two to three hours. When equilibrium is achieved, a 75 cm³ liquid sample is withdrawn from cell 3 into an evacuated sampling cylinder and then allowed to cool to ambient temperature before the sample is removed and analyzed.

Figure 1. Experimental Apparatus Block Flow Diagram

A vapor bleed stream from the main vapor phase recycle line is cooled to 13°C with cooling water to allow water to condense. The stream is then sent to a Fisher-Rosemount nondispersive IR CO₂ analyzer (Model: BINOS 100) to determine the volume percent of CO₂ within the vapor bleed stream consisting of N₂, CO₂, and a small amount of H₂O. Thus, the partial pressure of CO₂ can be calculated as

$$P_{CO_2} = y_{CO_2}^{IR} \left[P - (P_{H_2O} - P_{H_2O}^{IR}) \right] \quad (1)$$

where

P is the total pressure, kPa,

$y_{CO_2}^{IR}$ is the volume percent of CO₂ from the IR analyzer, %,

P_i is the partial pressure of component i , kPa.

The CO₂ loading analysis was performed by using two parallel liquid samples each titrated for CO₂ and total alkalinity (K⁺) using BaCl₂ precipitation and H₂SO₄, respectively. The relative standard uncertainty in the loadings was $\pm 2\%$.

CO₂ Analysis Procedure

Sample Preparation

1. Take a 250 ml Erlenmeyer flask and dispense 25 ml of 0.5 M BaCl₂ and 50 ml of 0.1 M NaOH from the automatic dispensers.
2. Weigh the flask and tare the scale.
3. Use an automatic pipette and dispense 0.25 ml of sample into the Erlenmeyer flask and weight.
4. Record the weight of the sample.
5. Seal the flask with a stopper with vapor tube.
6. Place the flask on the warming plate and bring to a boil.
7. Boil for ~4 minutes. BaCO₃ will precipitate out of the solution by the given reaction:

8. After four minutes, transfer the flask to the cooling tray and wait five minutes.
9. After five minutes, replace the stopper with a square of paraffin wax and seal the flask.
10. After 5 minutes, the flask should be at room temperature and can then be transported to the vacuum filtration apparatus.

CO₂ Filtration

1. Take a silicone filter and place it in the center of the vacuum filter. The thickness of the filter is 0.6 micrometer with a diameter of 47 millimeters.
2. Start the vacuum filter.
3. Wet the filter with a little bit of DI water.
4. Place the top of the filter and clamp the apparatus together.
5. Pour your cooled solution into the middle of the filter.
6. Use DI water to get the last drop of solution from the flask rim.
7. Go through three 100 ml washings of the flask.
8. Carefully take off the top of the vacuum filter and place it onto the work bench.
9. Remove the filter and place it into a 100 ml beaker.
10. Place the top of the vacuum filter on top of the 100 beaker and rinse the top with 50 ml of DI water.
11. Turn off the suction.

CO₂ Titration

1. Weigh the flask and tare the scale.
2. For Samples A and B, dispense 40 ml of a 0.1 N HCl solution using the automatic dispenser.
3. For the Blank, dispense 10 ml of a 0.1 N HCl solution using the automatic dispenser.
4. Barium carbonate will then react with the hydrochloric acid liberating CO₂ into the solution by the following reaction:

5. Record the weight of the acid.
6. Place on the magnetic stirrer and allow the BaCO₃ to dissolve completely.
7. After the BaCO₃ has completely dissolved, place the flask on the autotitrator.
8. Titrate the solution with 0.1 M NaOH until the pH = 5.2. A method has been programmed into the autotitrator to stop automatically after measuring a pH = 5.2 for a given period of time.
9. Rinse the electrode and the NaOH dispenser with DI water.
10. Tap dry with a paper towel.
11. Push the dose button twice to clear the line.
12. Push the fill button to fill the reservoir.
13. Place the flask on the magnetic stirrer and lower the electrode into the solution.
14. Be careful not to allow the electrode to touch the magnetic stirrer.
15. Push Start.
16. After the titration is complete, record the final amount of NaOH.
17. Use the following equation to calculate the CO₂ concentration:

$$CO_2 (mole / kg) = \frac{1}{20} \cdot \frac{HCl (gm) - NaOH (ml) - [Blank HCl (gm) - Blank NaOH (ml)]}{Sample (gm)}$$

Total Alkalinity Analysis Procedure

Sample Preparation

1. Take a 100 ml beaker and dispense 60 ml of DI water from the automatic dispenser.
2. Weigh the beaker and tare the scale.
3. Use an automatic pipette and dispense 0.5 ml of sample into the beaker and weight.
4. Record the weight of the sample.
5. Place the beaker on the autotitrator with a magnetic stir rod in the bottom of the beaker.
6. Titrate the solution with 0.1 M H₂SO₄ until the pH = 2.75. A method has not been programmed into the autotitrator to stop automatically, so you will have to monitor the titration results.
7. Rinse the electrode and the H₂SO₄ dispenser with DI water.
8. Tap dry with a paper towel.
9. Push the dose button twice to clear the line.
10. Push the fill button to fill the reservoir.
11. Place the flask on the magnetic stirrer and lower the electrode into the solution.
12. Be careful not to allow the electrode to touch the magnetic stir rod.
13. Push Start.
14. After the titration is complete, record the final amount of H₂SO₄.
15. Use the following equation to calculate the total alkalinity:

$$\text{Total Alkalinity}(\text{mole} / \text{kg}) = \frac{H_2SO_4(\text{ml}) \cdot 0.2}{\text{Sample}(\text{gm})}$$

Results

Experimental CO₂ solubility data for 20 mass% K₂CO₃ were measured at 110°C and we can also compare the experimental points to CO₂ solubility as reported by Tosh et al. (1959) and CO₂ solubility predictions as reported by Hilliard (2005) as shown in Figure 2.

Through liquid analysis procedures given above, it was found that the water condensate collected from the vapor bleed stream during the experiment did contain trace amounts of dissolved CO₂ and implies that CO₂ is absorbing into the water condensate as the gas stream passes over the saturated coils during the experiment and is not entering into the vapor bleed stream before it reaches the CO₂ analyzer. Please refer to Table 1 for further information.

From the analysis in Table 1, we could conclude that the experimental points were not affected from the amount of CO₂ found within the water condensate since the water condensate carbonate concentration was within the experimental error of the liquid analysis measurements.

Future Work

Work is underway to complete the full description of potassium/piperazine solvent from 100 to 120°C at loadings from 0.5 to 0.7. We are also underway to measure other amine based solvents at high temperature.

Figure 2. Comparison of Tosh et al. (1959) CO_2 Solubility and Hilliard (2005) CO_2 Solubility Predictions to Current Work in Loaded 20 Mass% K_2CO_3 Solutions at 110°C

Table 1. Overall Results for 20 Mass% Series

Solution Weighted Amounts

Solution	K ⁺ (m)	□ (gm/L)	TC (equ/kg soln)	TA (equ/kg soln)	K ⁺ (m)
1	3.62	1185.40	1.4561	2.8766	3.59

Pre-experiment Solution Analysis

Experimental Observed Results

Solution	Temp (°C)	TP (kPa)	CO ₂ (%)	H ₂ O Con (ml)
1-1	110.03	748.08	0.404	4
1-2	110.06	729.19	1.103	2
1-3	110.07	737.22	3.945	1

Liquid Sample Analysis

Solution	TC (equ/kg soln)	TA (equ/kg soln)	K ⁺ (m)
1-1	1.6461	2.7992	3.52
1-2	1.8402	2.7999	3.56
1-3	2.0273	2.7660	3.54

Calculated Values

Ldg (TC/TA)	P _{CO2} (kPa)	P _{CO2} (Pa)
0.1761	2.470	2470
0.3145	6.541	6541
0.4659	23.733	23733

H₂O Condensate Analysis

Solution	TC (equ/kg soln)	TC (ppm)
1-1	0.0000	0
1-2	0.0097	428
1-3	0.0004	19

Ldg = mole CO₂/mole K₂CO₃

Subtask 1.10a – Simulate MEA Baseline Stripper Performance

by Babatunde Oyenekan
(Supported by this contract)

Summary

In this quarter, the results of the second pilot plant campaign were revisited and analysed. In Campaign 2, the solvent was 5m K+ / 2.5m PZ and the stripper was equipped with CMR #2 packing. Campaign 3 was carried out in this quarter. The solvent was 7m monoethanolamine (MEA). In the first half of the campaign, the stripper was equipped with IMTP #40 and in the second half, Flexipac 1Y was used. We report the data obtained during Campaigns 2 and 3. These include CO₂ concentrations in the rich and lean solutions, temperature profiles in the column, and steam flow and rates when the stripper is operated at different pressures. The stripper model was run and the results compared to those obtained from the pilot plant tests.

Experimental

Data Collection

The online stripper inlet and outlet CO₂ concentrations were measured with Vaisala GM CO₂ analyzers. The Vaisala probes were ranged from 0 to 1%, 0 to 5% and 0 to 20% CO₂. The online absorber middle concentration was measured using a Horiba PIR-2000 CO₂ analyzer, which had a range of 0 to 5 % CO₂. The Horiba analyzer could be readily switched to sample the inlet, outlet, or middle of the absorber. The Vaisala measurements were confirmed by the Horiba. The CO₂ analyzers were calibrated before the start of the campaign. At higher CO₂ concentrations, the Horiba analyzer was over-ranged and could not read certain absorber middle concentrations.

Liquid samples of the stripper middle and lean solutions were taken to represent the mid-section and lean concentrations, respectively, while the data from the absorber rich was taken and assumed to be representative of the stripper rich solution. The pH was recorded for each offline sample with a handheld pH meter. Thermocouples were used to obtain the temperatures in six sections in the stripper. Piperazine and potassium concentrations were determined by titration with hydrochloric acid and sodium hydroxide, and the total was reported as total alkalinity. CO₂ loading was determined by a total organic carbon analyzer (TOC) operating in the mode that gives inorganic carbon. Piperazine and potassium concentration was verified by TOC and inductively coupled plasma (ICP) analysis, respectively. Vanadium and total iron were determined by ICP.

Table 2. Campaign 2 Stripper Data

Sample Number	Column Pressure (atm)	Rich Conc. (m)	Lean Conc. (m)	Liquid Rate (kg/s)	CO ₂ Removed (gmol/s)	T Approach (K)	Feed T (K)	Stripper Bottoms T (K)	Cooling Water Flow (gpm)	Cooling Water Inlet T (K)	Cooling WaterOutlet T (K)
2.1	1.55	6.38	4.31	0.60	0.69	38.39	354	392	202.62	287	291
2.2	1.58	2.42	0.76	0.59	0.56	39.22	353	393	202.15	286	291
2.3	1.60	5.98	4.82	0.68	0.43	42.07	351	393	201.71	283	284
2.4	1.58	5.95	4.83	0.82	0.52	45.37	347	392	201.48	284	285
2.5	1.54	1.41	0.41	0.85	0.47	45.06	346	391	201.55	284	285
2.6	1.61	5.86	4.93	0.93	0.49	43.15	349	393	201.55	284	285
2.7	1.63	6.02	5.10	0.96	0.52	43.14	350	393	201.55	285	285
2.8	1.52	6.14	5.02	1.01	0.63	41.55	349	391	201.89	285	286
2.9	1.74	5.68	4.66	0.64	0.38	44.46	351	395	201.25	283	283
2.10	1.53	5.62	4.71	0.87	0.46	42.41	349	391	200.65	284	285
2.11	1.50	5.59	4.73	0.87	0.43	37.64	353	391	201.43	284	285
2.12	1.57	5.87	4.96	0.90	0.47	41.03	351	392	201.33	284	286
2.13	3.37	5.99	5.00	0.76	0.43	70.27	347	417	201.01	283	283
2.14	0.31	6.05	5.19	0.38	0.18	35.42	312	347	202.01	281	282
2.15	0.36	5.61	4.79	0.44	0.21	28.43	322	350	202.32	281	282
2.16	0.33	5.67	4.80	0.42	0.21	27.77	320	348	201.92	281	282
2.17	0.35	5.71	5.19	0.60	0.18	21.26	328	350	202.52	281	283
2.18	0.36	5.76	5.28	0.75	0.20	12.95	338	351	202.59	281	283
2.19	1.71	5.63	4.60	1.55	0.92	49.74	343	393	201.83	285	286
2.20	1.79	5.97	4.98	1.66	0.95	51.40	344	395	202.22	287	287
2.21	1.83	6.08	5.01	1.66	1.01	51.78	344	396	201.95	287	287
2.22	1.61	6.05	4.75	1.15	0.86	43.26	349	392	202.43	285	287
2.23	1.67	5.88	4.50	1.14	0.92	45.92	348	394	202.71	287	290

Sample Number	Qreb (kcal/s)	Qbottoms (kcal/s)	Qfee d (kcal/s)	Qsens (kcal/s)	Qcond (kcal/s)	Qdes (kcal/s)	Qloss (kcal/s)	Q(actual) (kcal/s)	Energy Efficiency (%)	Q from Pilot Plant (kcal/gmol CO ₂)	Q from ACM Model (kcal/gmol CO ₂)
2.1	106.90	0.00	-31.20	31.20	54.26	10.36	11.08	95.81	90	138.77	39
2.2	122.15	0.00	-34.34	34.34	68.35	8.42	11.04	111.11	91	197.94	Not converged
2.3	57.57	0.00	-26.46	26.46	8.64	6.46	16.01	41.56	72	96.57	56
2.4	64.25	0.00	-30.66	30.66	12.26	7.82	13.51	50.73	79	97.34	61
2.5	64.19	0.00	-26.57	26.57	11.04	7.11	19.48	44.72	70	94.38	Not converged
2.6	68.39	0.00	-24.85	24.85	13.13	7.39	23.02	45.37	66	92.11	66
2.7	68.42	0.00	-26.36	26.36	10.82	7.78	23.45	44.97	66	86.66	67
2.8	76.16	0.00	-35.08	35.08	15.76	9.45	15.86	60.30	79	95.67	58
2.9	46.34	0.00	-22.63	22.63	6.23	5.71	11.78	34.57	75	90.84	63
2.10	72.57	0.00	-22.20	22.20	18.20	6.90	25.27	47.30	65	102.85	66
2.11	72.59	0.00	-18.47	18.47	20.04	6.47	27.60	44.99	62	104.25	63
2.12	83.95	0.00	-20.05	20.05	21.64	7.12	35.15	48.80	58	102.85	65
2.13	62.43	0.00	-37.99	37.99	-0.20	6.52	18.12	44.31	71	101.90	92
2.14	32.73	0.00	-7.71	7.71	10.81	2.75	11.46	21.27	65	116.22	95
2.15	36.27	0.00	-6.84	6.84	14.23	3.17	12.04	24.23	67	114.76	58
2.16	31.58	0.00	-6.83	6.83	8.37	3.16	13.22	18.36	58	87.14	55
2.17	38.83	0.00	-4.69	4.69	13.44	2.66	18.04	20.79	54	117.22	63
2.18	44.66	0.00	-2.82	2.82	22.70	3.00	16.14	28.52	64	142.73	49
2.19	101.41	0.00	-50.06	50.06	3.65	13.80	33.91	67.50	67	73.39	68
2.20	108.29	0.00	-51.47	51.47	3.85	14.23	38.73	69.55	64	73.29	72
2.21	108.21	0.00	-57.53	57.53	4.75	15.17	30.75	77.45	72	76.57	69
2.22	94.55	0.00	-46.27	46.27	22.19	12.83	13.26	81.29	86	95.06	53
2.23	126.25	0.00	-50.47	50.47	42.82	13.80	19.16	107.09	85	116.42	67

Results and Discussion

Stripper Performance

Table 2 shows the stripper data obtained during Campaign 2 at 0.31 to 3.40 atm at varying CO₂ concentrations in the rich and lean streams. The energy required for stripping was computed as follows.

Q_{reboiler} was calculated from steam tables in the Delta V program.

The reboiler duty is made up of the following energy contributions:

$$Q_{\text{reboiler}} \text{ (kcal/s)} = Q_{\text{sens}} + Q_{\text{cond}} + Q_{\text{des}} + Q_{\text{loss}} \quad (2)$$

The enthalpy of the stripper bottoms was computed as:

$$Q_{\text{bottoms}} \text{ (kcal/s)} = L * C_p * (T_{\text{bottoms}} - T_{\text{ref}}) \quad (3)$$

L is the Stripper lean liquid rate (kg/s)

C_p is the heat capacity of the lean solution ~ 1 kcal/kg °C

T_{bottoms} is the temperature of the stripper bottoms temperature

T_{ref} was equal to the stripper bottoms

The enthalpy of the feed was calculated as:

$$Q_{\text{feed}} \text{ (kcal/s)} = LF * C_p * (T_{\text{feed}} - T_{\text{ref}}) \quad (4)$$

LF is the Stripper feed liquid rate (kg/s)

C_p is the heat capacity of the lean solution ~ 1 kcal/kg °C

T_{feed} is the temperature of the stripper rich feed after preheating

T_{ref} was equal to the stripper bottoms temperature

The sensible heat requirement was calculated as:

$$Q_{\text{sens}} \text{ (kcal/s)} = Q_{\text{bottoms}} - Q_{\text{feed}} \quad (5)$$

The heat of condensing steam is calculated as:

$$Q_{\text{cond}} \text{ (kcal/s)} = \text{CWflow} * (T_{\text{out}} - T_{\text{in}}) \quad (6)$$

CWflow is the cooling water flow in gpm

T_{out} is the temperature of the cooling water out (K)

T_{in} is the temperature of the cooling water in (K)

The heat of desorption was calculated with the expression:

$$Q_{\text{des}} \text{ (kcal/s)} = \text{CO}_2 \text{ removed} * H_{\text{des}} \quad (7)$$

CO₂ removed is the amount of CO₂ removed (gmol/s)

H_{des} is the heat of desorption of CO_2 from 5m K^+ /2.5m PZ ~ 15 kcal/gmol

The actual heat used in stripping is given by:

$$Q_{\text{actual}} \text{ (kcal/s)} = Q_{\text{sens}} + Q_{\text{cond}} + Q_{\text{des}} \quad (8)$$

The normalized energy for stripping:

$$Q \text{ from pilot plant (kcal/gmol CO}_2\text{)} = Q_{\text{actual}} / \text{CO}_2 \text{ removed} \quad (9)$$

Figure 3 compares the normalized energy requirement for stripping from the second pilot plant campaign to that obtained from the ACM Model. The ACM model is of the form described in previous reports but the Murphree efficiency for CO_2 was specified as 10% while the efficiency of water and temperature were assigned efficiencies of 100%. The number of stages has been adjusted to six instead of ten.

The energy efficiency is computed as:

$$\text{Energy Efficiency} = \left[\frac{Q_{\text{reb}} - Q_{\text{loss}}}{Q_{\text{reb}}} \right] * 100\% \quad (10)$$

Figure 3. Comparison of Normalized Energy Requirement from Pilot Plant and ACM Model for Campaign 2 (Solvent: 5m K^+ /2.5m PZ, IMTP # 40 Packing)

The ACM Model tracks the trend observed in the pilot plant tests but underpredicts the steam requirement. The mass transfer modeling is currently being done and will be available in the next report. The transfer of water and heat may play a major role in these data and may not be represented well by the existing model.

The results for Campaign 3 are presented in Table 3. The analyses in this campaign were done with the same methodology as that of Campaign 2. For Campaign 3, the heat of desorption of CO₂ from the 7m MEA solution was assumed to be 22 kcal/gmol CO₂. The reference temperature was chosen as 68°F. However, the heat losses were calculated with an equation for heat losses from the stripping column based on past distillation tests. Some reboiler vapour temperatures were high due to a possible leak. As such, 3°F was added to the reboiler liquid temperature. This was about the average excluding the high vapor temperature runs.

The heat losses for the third campaign was calculated as

$$Q_{\text{loss}} \text{ (kcal/s)} = 650 * (T_{\text{bottoms}} + 3 - T_{\text{amb}}) * (0.00007/60) \quad (11)$$

T_{amb} is the average ambient air temperature during the run.

Table 3. Campaign 3 Stripper Data (Packing: IMTP # 40)

Sample Number	Column Pressure (atm)	Rich Conc. (m)	Lean Conc. (m)	Liquid Rate (kg/s)	CO ₂ Removed (gmol/s)	T Approach (K)	Feed T (K)	Stripper Bottoms T (K)	Cooling Water Flow (gpm)	Cooling Water Inlet T (K)	Cooling Water Outlet T (K)
3.1	1.6	3.19	1.36	0.34	0.31	19.65	372	390	203.53	281	282
3.2	1.6	3.07	1.32	0.34	0.84	19.44	372	390	203.38	281	282
3.3	1.6	3.46	1.22	0.24	0.83	19.52	373	391	203.44	280	281
3.4	1.6	3.29	1.23	0.24	0.99	20.17	372	391	203.62	281	281
3.5	1.6	3.98	1.36	0.53	0.99	23.78	368	391	203.66	281	283
3.6	1.6	3.97	1.38	0.53	0.89	22.22	369	391	203.70	281	283
3.7	1.6	3.76	1.35	0.67	0.89	41.81	349	391	157.63	284	285
3.8	1.6	3.74	1.30	0.67	0.80	41.17	350	390	157.77	284	285
3.9	1.6	4.03	1.14	0.52	0.82	33.46	357	391	157.71	284	286
3.10	1.6	4.04	1.12	0.52	0.83	33.32	358	391	157.70	284	286
3.11	1.6	4.07	1.12	0.44	0.81	27.96	364	391	157.66	284	286
3.12	1.6	4.14	1.09	0.44	0.92	28.10	363	391	157.71	283	285
3.13	1.6	3.84	2.45	1.02	0.92	41.21	345	387	159.82	284	284
3.14	1.6	3.85	2.49	1.02	0.78	41.34	345	386	159.63	284	284
3.15	1.6	3.74	2.73	1.46	0.53	39.99	345	385	159.93	285	285
3.16	1.6	3.76	2.71	1.46	0.51	38.91	346	385	159.88	285	285
3.17	1.6	3.73	2.82	1.45	0.51	38.71	345	384	159.80	286	285
3.18	1.6	3.84	2.03	0.51	0.48	26.31	363	389	157.82	282	282
3.19	1.6	3.75	2.12	0.51	0.44	26.57	363	389	157.48	282	282
3.20	1.6	4.08	2.09	0.43	0.45	18.98	371	389	157.64	282	282
3.21	1.6	4.10	2.14	0.41	0.68	18.79	371	389	157.63	282	282
3.22	1.6	4.20	2.07	0.36	0.00	20.17	370	389	157.32	281	281
3.23	1.6	4.23	2.03	0.36	0.97	20.04	370	389	157.50	281	281
3.24	1.6	3.83	2.12	0.67	0.91	38.20	351	389	157.58	283	282

Table 3. Campaign 3 Stripper Data (Packing: IMTP #40) [Cont'd.]

Sample Number	Qreb (kcal/s)	Qbottoms (kcal/s)	Qfee d (kcal/s)	Qsens (kcal/s)	Qcond (kcal/s)	Qdes (kcal/s)	Qloss (kcal/s)	Q(actual) (kcal/s)	Energy Efficiency (%)	Q from Pilot Plant (kcal/gmol CO ₂)	Q from ACM Model (kcal/gmol CO ₂)
3.1	35.88	2.72	-2.71	5.43	13.28	8.68	9.03	26.85	75	68.09	N/C
3.2	35.95	2.67	-2.68	5.35	13.50	8.31	9.08	26.87	75	71.22	N/C
3.3	27.20	1.86	-1.84	3.70	9.26	7.26	9.19	18.01	66	54.64	N/C
3.4	30.60	1.91	-1.92	3.83	12.70	6.75	9.19	21.41	70	69.83	N/C
3.5	57.47	5.04	-5.01	10.05	18.00	18.60	9.27	48.20	84	57.04	N/C
3.6	56.39	4.64	-4.70	9.34	18.39	18.18	9.13	47.26	84	57.23	N/C
3.7	79.16	11.31	-11.17	22.49	18.56	21.80	8.72	70.44	89	71.13	N/C
3.8	78.27	11.15	-11.04	22.19	19.72	21.71	8.49	69.78	89	70.74	N/C
3.9	72.81	6.98	-6.86	13.84	25.05	19.56	7.78	65.03	89	73.20	N/C
3.10	69.96	6.89	-6.83	13.72	23.82	19.56	7.83	62.13	89	69.92	N/C
3.11	67.67	4.96	-4.91	9.88	27.90	17.51	7.88	59.79	88	75.19	N/C
3.12	56.01	5.00	-4.84	9.84	18.94	17.96	8.02	47.99	86	58.82	N/C
3.13	66.16	16.83	-16.76	33.59	2.55	18.34	8.08	58.08	88	69.71	48
3.14	65.56	16.89	-16.84	33.73	2.62	17.80	8.06	57.50	88	71.12	49
3.15	87.24	23.47	-23.36	46.83	2.72	20.31	8.25	79.00	91	85.61	58
3.16	85.01	22.55	-22.68	45.23	3.14	20.17	7.85	77.17	91	84.21	56
3.17	82.57	22.45	-22.41	44.85	2.39	17.12	7.47	75.10	91	96.58	61
3.18	32.84	5.41	-5.39	10.80	3.53	11.59	7.86	24.98	76	47.46	48
3.19	33.24	5.48	-5.44	10.91	3.29	11.33	7.93	25.30	76	49.17	46
3.20	27.31	3.16	-3.22	6.38	4.29	11.23	8.05	19.26	71	37.74	40
3.21	26.96	3.11	-3.03	6.14	4.21	10.54	8.18	18.78	70	39.22	38
3.22	24.51	2.94	-2.88	5.81	3.76	9.76	8.59	15.92	65	35.92	39
3.23	24.50	2.90	-2.87	5.77	3.60	9.87	8.61	15.90	65	35.46	41
3.24	49.70	10.26	-10.21	20.47	2.78	14.92	8.45	41.25	83	60.86	123

Table 4. Campaign 3 Stripper Data (Packing : Flexipac 1Y)

Sample Number	Column Pressure (atm)	Rich Conc. (m)	Lean Conc. (m)	Liquid Rate (kg/s)	CO ₂ Removed (gmol/s)	T Approach (K)	Feed T (K)	Stripper Bottoms T (K)	Cooling Water Flow (gpm)	Cooling Water Inlet T (K)	Cooling WaterOutlet t T (K)
3.25	1.6	2.93	2.13	1.88	0.97	46.03	255	390	170.78	288	288
3.26	1.6	2.85	2.10	1.87	0.91	47.21	342	390	170.69	287	287
3.27	1.6	3.13	2.18	1.48	0.90	41.92	341	393	170.76	286	286
3.28	1.6	3.13	2.17	1.49	0.91	42.86	346	393	170.76	286	286
3.29	1.6	3.40	2.18	0.99	0.75	38.45	345	394	170.55	284	284
3.30	1.6	3.44	2.15	0.99	0.78	38.84	349	394	170.36	284	284
3.31	1.6	3.23	2.10	0.72	0.45	28.76	349	398	170.31	283	283
3.32	1.6	3.24	2.09	0.72	0.45	28.07	358	400	170.25	283	283
3.33	1.6	3.20	2.13	0.76	0.44	28.84	359	409	170.11	283	283
3.34	1.6	3.18	2.10	0.76	0.45	28.79	357	409	170.27	283	283
3.35	1.6	3.15	2.13	0.76	0.44	29.69	357	396	167.66	283	283
3.36	1.6	3.22	2.14	0.77	0.48	28.92	357	397	167.29	283	283
3.37	1.6	3.06	2.11	0.89	0.44	31.83	358	408	168.20	283	283
3.38	1.6	3.05	2.10	0.97	0.48	33.39	354	407	167.70	283	283
3.39	1.6	2.78	1.73	1.49	0.98	42.64	353	392	198.92	285	286
3.40	1.6	2.81	1.75	1.49	0.99	42.66	347	393	198.24	285	286
3.41	1.6	3.28	1.76	1.02	0.91	38.36	347	391	167.43	284	285
3.42	1.6	3.26	1.75	1.01	0.90	37.76	351	391	170.24	284	285
3.43	1.6	3.73	1.77	0.70	0.83	36.44	351	391	198.31	283	283
3.44	1.6	3.73	1.78	0.70	0.82	36.57	352	391	198.36	283	283
3.45	0.68	3.29	2.15	1.09	0.78	14.72	353	371	167.64	286	292
3.46	0.68	3.23	2.15	1.09	0.74	14.92	352	371	170.83	286	292
3.47	0.68	4.09	2.20	0.53	0.58	9.17	352	367	197.69	283	286
3.48	0.68	4.07	2.19	0.54	0.60	10.31	357	367	197.65	283	286

Table 4. Campaign 3 Stripper Data (Packing: Flexipac 1Y) [Cont'd.]

Sample Number	Qreb (kcal/s)	Qbottoms (kcal/s)	Qfee d (kcal/s)	Qsens (kcal/s)	Qcond (kcal/s)	Qdes (kcal/s)	Qloss (kcal/s)	Q(actual) (kcal/s)	Energy Efficiency (%)	Q from Pilot Plant (kcal/gmol CO ₂)	Q from ACM Model (kcal/gmol CO ₂)
3.25	112.18	35.23	-35.11	70.34	2.51	21.40	7.56	104.61	93	107.63	85
3.26	111.97	36.21	-36.04	72.25	2.23	20.11	7.58	104.39	93	114.29	92
3.27	84.75	25.26	-25.08	50.34	3.44	19.78	8.27	76.48	90	85.14	70
3.28	87.45	25.86	-25.77	51.63	3.17	20.03	8.28	79.17	91	87.02	71
3.29	60.94	15.43	-15.29	30.72	2.77	16.60	8.30	52.63	86	69.81	56
3.30	60.93	15.46	-15.46	30.92	2.76	17.22	8.32	52.61	86	67.28	55
3.31	37.44	8.49	-8.41	16.90	3.28	9.87	7.59	29.85	80	66.56	62
3.32	36.39	8.30	-8.20	16.49	2.41	9.94	7.44	28.96	80	64.15	62
3.33	36.75	8.94	-8.82	17.76	2.82	9.71	7.24	29.51	80	66.93	62
3.34	36.76	8.94	-8.81	17.75	1.97	9.98	7.30	29.47	80	64.99	64
3.35	36.75	9.28	-9.14	18.42	2.87	9.78	8.19	28.56	78	64.30	64
3.36	37.09	9.04	-8.95	17.99	2.94	10.64	8.22	28.88	78	59.76	61
3.37	39.58	11.52	-11.45	22.97	0.23	9.68	7.51	32.07	81	72.90	70
3.38	47.00	13.20	-13.11	26.32	4.13	10.63	7.39	39.61	84	82.03	72
3.39	99.36	26.03	-25.92	51.95	10.45	21.62	7.78	91.58	92	93.26	N/C
3.40	97.94	25.97	-25.86	51.83	9.31	21.86	7.73	90.21	92	90.86	N/C
3.41	72.16	15.78	-15.74	31.52	8.04	20.01	7.61	64.55	89	71.00	N/C
3.42	72.14	15.57	-15.43	31.00	9.10	19.91	7.56	64.57	90	71.41	N/C
3.43	50.22	10.17	-10.17	20.34	4.58	18.21	8.61	41.61	83	50.32	N/C
3.44	50.05	10.22	-10.17	20.38	4.92	18.02	8.56	41.49	83	50.70	N/C
3.45	110.94	6.51	-6.46	12.98	67.35	17.22	5.92	105.03	95	134.26	56
3.46	111.46	6.57	-6.54	13.11	69.30	16.33	5.64	105.82	95	142.63	58
3.47	48.98	1.96	-1.93	3.90	29.56	12.77	5.36	43.63	89	75.21	36
3.48	51.43	2.15	-2.19	4.34	33.33	13.30	5.41	46.02	89	76.20	36

The energy requirement for stripping obtained from the pilot plant using the two packings – IMTP #40 and Flexipac 1Y – are compared in Figures 4 and 5. The results show that the ACM model predicts the energy requirement fairly well. There were, however, some cases in which the ACM model did not converge. The model is being revised to fit the entire range of CO₂ concentrations.

Figure 4. Comparison of Normalized Energy Requirement from Pilot Plant and ACM Model for Campaign 3 (Solvent: 7m MEA, Packing: IMTP #40)

Figure 5. Comparison of Normalized Energy Requirement from Pilot Plant and ACM Model for Campaign 3 (Solvent: 7m MEA, Packing: Flexipac 1Y)

Comparison of samples 3.24 and 3.44 which have equivalent run conditions but IMTP #40 and Flexipac 1Y, respectively, show a 17% reduction in energy requirement when Flexi-Pac 1Y is used. This suggests that the structured packing (Flexi-Pac) 1Y requires less stripping energy than the random packing (IMTP #40).

Conclusions and Future Work

In this quarter, the results from the second pilot plant campaign were revisited. The energy requirement was compared to that of the ACM Model. Campaign 3, with 7m monoethanolamine as solvent, was completed and the results analysed. The ACM model predicts the energy requirement for the third campaign fairly well but underpredicts the energy requirement for Campaign 3. Mass transfer modeling of the pilot plant results is in progress. The ACM model is also being revised to better capture the transfer of water and heat transfer.

Task 2 – Pilot Plant Testing

by Eric Chen

(Supported by EPA Star Fellowship)

Introduction

In this quarter additional modifications have been made to the pilot plant system. In addition, a search for new CO₂ analyzers, a cross exchanger, and an air heater was initiated and formal quotations have been obtained.

Experimental – Equipment Modifications

All of the 8-inch PVC gas lines were replaced with 8-inch 304 L stainless steel pipe. In addition, any remaining PVC pipe was replaced with stainless steel, which included 3 and 4-inch pipes. A control valve was installed on the cooling water to the air cooler. In the next campaign, the air cooler will be operated to minimize the amount of water vapor in the outlet gas stream and protect the Vaisala CO₂ probes. The condensate from the air cooler will be sent a 4-inch reboiler, converted to steam, and re-injected into the inlet gas stream, downstream of the inlet CO₂ analyzers. The steam will be used to heat and saturate the inlet gas to 60°C in order to simulate flue gas. An existing 4-inch reboiler will need to be retrofitted and connected to the pilot plant system.

The in-situ Vaisala CO₂ gas analyzers currently used for the inlet and outlet gas stream of the absorber have a temperature limitation of 60°C and cannot be operated in a condensing environment. Therefore, a search for alternative in-situ CO₂ probes was initiated. The goal was to find an economical CO₂ analyzer that could measure multiple gas streams and components. It was found that industrial stack gas analyzers were cost prohibitive (~\$30,000 to \$80,000). Approximately half of the cost was associated with the sample conditioning units. In all of the units, the water had to be removed prior to analysis. As a result of the high cost of a new CO₂ analyzer and the desire to measure multiple gas components, it was decided the existing FTIR would be retrofitted to measure only the outlet gas stream. A dual sample stream analysis unit that could be used with the FTIR would cost approximately \$20,000. A new heated line, approximately 100 feet in length and a MODBUS card used to connect the FTIR computer to the Delta V system will both need to be procured. The cost should be approximately \$10,000 to \$15,000.

During the MEA campaign, the air cooler was operated. However, the temperature of the inlet gas stream was too low and was not representative of a typical inlet gas stream (~55 to 60°C). The inlet gas stream needed to be heated and a process air heater from Chromalox was specified. The total cost would be approximately \$10,000 to \$15,000. Because of the high cost, it was decided that an existing 4-inch reboiler would be re-commissioned. The tentative plan is to take the water condensed from the air cooler and from the condensate return off the stripper to feed to the reboiler. The steam generated from the reboiler would be fed to the inlet absorber gas, downstream of the CO₂ analyzers. The retrofit of the 4-inch reboiler will require the installation of 1" pipe

from the air cooler and condensate return to the reboiler and from the reboiler to the inlet gas line.

Due to the inadequate preheat of the stripper feed, a new cross-exchanger will be procured. The cross-exchanger will take the hot lean stream from the reboiler and use it to heat the cold rich solution from the outlet of the absorber. The existing feed preheater will be used as a trim heater and will be installed either in parallel or in series with the cross-exchanger. If the cross-exchanger is installed in parallel, it will more closely resemble a commercial configuration, but will require additional flow and temperature instrumentation. The installation of the cross-exchanger in series will simplify instrumentation and thus reduce costs. A plate and frame cross-exchanger, which is typically used in commercial absorber/stripper systems, has been quoted from Alfa Laval. The cost of the cross-exchanger alone will be approximately \$7,000 and has been sized for a 10°C approach and a pressure drop of 15 psi. The cross-exchanger will be constructed out of 304 stainless steel with EPDM gaskets.

A new reboiler for the stripper has been procured. The existing reboiler was constructed out of carbon steel and it was suspected that there was a slow leak. The new reboiler is constructed of 316 stainless steel and was designed to replicate the existing reboiler. The reboiler should be installed and insulated in July.

Subtask 2.5a – Campaign 2 Pilot Plant - Results for Absorber

by Eric Chen

(Supported by EPA Star Fellowship)

Experimental – Campaign 2 Data Analysis

Due to the inconsistent method of CO₂ loading analysis, the absorber lean, middle, and rich samples were re-analyzed with a more rigorous method. The samples were diluted 40:1 with chilled DI water. 100 ppm standards were made up daily and were analyzed after every six samples. The CO₂ loading was measured using a Shimadzu TOC 5050A, which has an autosampler. The diluted liquid samples were transferred to the sample tubes and covered with parafilm prior to analysis. It was determined that the diluted piperazine/potassium carbonate samples absorbed up to 10% CO₂ when left open to the atmosphere overnight.

Also, for the second campaign, the concentration of potassium and piperazine (total alkalinity) was initially obtained by the titration method initially developed and used in Campaign 1. However, in Campaign 2, the titration method was conducted on samples that had been diluted 4:1. The results seem to consistently underpredict the total alkalinity of the solution. This may have been due to a change in the indicator endpoint resulting from sample dilution.

In order to obtain preliminary values of total alkalinity for Campaign 2, a total alkalinity/density correlation was developed based on the data from Campaign 1. The lean density from Campaign 1 was correlated with total alkalinity and gave a fit with a R² of 0.99 (Figure 6). The lean density numbers from Campaign 2 were inserted into the correlation to give values of total alkalinity. The total alkalinity correlation is given by the following equation:

$$TotalAlkalinity = -7.95x^2 + 128.89x + 734.76$$

We are in the process of developing an analytical method based on ion chromatography that will give us piperazine and potassium concentration to validate total alkalinity correlation. The potassium method appears to work well, but the piperazine method requires further refinement.

Figure 7 shows that lean loading can be correlated to the online pH measurements and is inversely related to pH. However, it appears that pH was better correlated to capacity (Figure 8). The figure also shows that the majority of the runs were conducted with a capacity of about 0.5 mol CO₂/kg solvent. This reflects the indirect relationship between capacity and lean loading, since the lean loading was maintained approximately constant between 0.42-0.44 mol CO₂/K+2PZ.

Figure 6. Campaign 1 Total Alkalinity

Figure 7. Absorber Lean Loading

Figure 8. Absorber Solvent Capacity

Some preliminary data analysis was undertaken using the data obtained from the second campaign. Gas-phase mass transfer coefficients (K_G) were calculated for the top and bottom beds and for the overall column with the following equation:

$$K_G = \left(\frac{G}{a_{eff}} \right) \frac{\ln \left[\frac{CO_{2,IN} - CO_{2,IN}^*}{CO_{2,OUT} - CO_{2,OUT}^*} \right]}{\left((CO_{2,IN} - CO_{2,IN}^*) - (CO_{2,OUT} - CO_{2,OUT}^*) \right)}$$

where, G is the gas rate, a_{eff} is the effective wetted area, and the last term is the log mean driving force across the bed(s). CO_2^* is the partial pressure of CO_2 in equilibrium with the loading of the solution. The effective area was calculated based on a correlation developed from the results of absorbing ambient CO_2 in a solution of 0.1N potassium hydroxide, which was conducted in the first campaign. The correlation is based on mass flows and does not account for the effects of viscosity, surface tension, and density.

The K_G calculation also does not account for the changes in temperature across the column. Variations in temperature across the column will affect the kinetics and vapor-liquid equilibrium and hence the absorption rates of CO_2 .

Figure 9 illustrates the significant temperature bulges across the absorber column for inlet CO_2 concentrations at 8 and 12 mole%. At high CO_2 concentrations, the temperature bulge varied between 18 to 33°C, but for an inlet of 3% CO_2 , the temperature

bulge varied between 1 and 10°C. The figure also shows that at low liquid-to-gas ratios (L/G), the temperature bulge occurs near the top of the column. However, as the L/G increases, the temperature bulge moves down the column and the bulge occurs near the bottom of the column for high L/G ratios.

Figure 9. Absorber Temperature Profile

In order to calculate the equilibrium partial pressure of CO_2 , VLE data is required. A correlation was developed using data generated from the bench-scale wetted wall column. In the analysis of the pilot data, it was discovered that the absorber was pinched at different locations of the column for some of the runs. A plot of the pinched absorber data correlates well with the 40°C VLE (Figure 10). Therefore, the pinch analysis validates the VLE data generated by the bench-scale apparatus and may be used for the preliminary K_G calculations.

Finally, the mass transfer rate from the pilot plant was compared to bench-scale results at 60°C (k_g'). K_G was plotted against the average loading across the packed bed for each particular run. Figure 11 shows that the average K_G of the top (large blue triangle) and bottom (large red diamond) was about 10% higher than the wetted wall column. However, the average K_G of the overall column (large green square) was approximately 80% higher than the bench-scale results. The small points represent the values of K_G calculated for each of the different runs.

Figure 10. Pilot Absorber Pinches

Figure 11. Pilot Plant Mass Transfer Comparison

The preliminary rate analysis does not account for the temperature bulges that occur in the column. A rigorous adiabatic absorber model will be used to reconcile the pilot plant and wetted wall data. This should help resolve the discrepancies associated with the temperature variations in the column. Significant foaming was occasionally

observed which limited the hydraulic rates. Antifoam was added periodically which eliminated the problem for 10 to 20 hours of operation. The foaming tendency appeared to increase with the higher carbon dioxide concentration, presence of significant temperature bulge and high gas rates.

Conclusions and Future Work

The second pilot plant campaign successfully demonstrated reliable operation of the piperazine promoted potassium carbonate in an absorber/stripper system at a capacity of 0.5 mol CO₂/kg of solvent. A pH correlation was developed for lean loading and for capacity, which showed that pH was inversely related to loading and directly related to the capacity. Also, temperature bulges are significant in the piperazine/potassium carbonate system. Pinched pilot plant data was used to validate the VLE data from the bench-scale work. Finally, the average top and bottom gas-phase mass transfer coefficient approximately matched the wetted-wall data, while the overall K_G was about 80% higher. A rigorous modeling effort will be needed to confirm the preliminary results and to account for the temperature bulges.

Subtask 2.7 – MEA Baseline Campaign

by Ross Dugas
(Supported by this contract)

Introduction

This report contains the results of the monoethanolamine (MEA) baseline campaign completed in April 2005. The report contains material balance, heat balance, mass transfer, and pressure drop data obtained from the Separation Research Program's (SRP) pilot plant at the University of Texas at Austin.

General Information and Operating Conditions

The MEA baseline campaign utilized a 30wt% monoethanolamine solution and consisted of 48 runs, liquid sample collections, at 23 operating conditions. Liquid samples were collected from the absorber feed, middle, and outlet and also from the stripper middle and outlet. Usually two runs were executed for each operating condition. The absorption/stripping system was maintained at steady state for about an hour before liquid samples were taken. After this initial sampling, the system was held steady for another hour until the second set of samples was taken at the condition. After this second sampling, a new operating condition was attempted. These 48 runs consist of runs 44-91. Run numbers 1-43 were not used to avoid confusion with samples obtained from campaigns 1 and 2 involving the piperazine/potassium carbonate solvent. In addition to the liquid sampling, instantaneous online measurements were recorded for approximately 70 variables. These variables contain readings such as gaseous CO₂ concentrations, temperatures, pressures, densities, flow rates, and liquid levels. These values were logged into a spreadsheet with a recording interval of one minute. For calculation purposes, these values were averaged around the sample time including the 10 minutes before and after the sampling time. This dampens any fluctuations caused by the actual sample taking. This raw data, as well as three diagrams detailing the location of all the measurement devices, can be seen in Appendix A.

The MEA baseline campaign consisted of using two different packings in the absorber and stripper. Originally Flexipac 1Y, a structured packing, was used in the absorber with IMTP-40, a random metal packing, in the stripper. Halfway through the campaign, the Flexipac 1Y was moved to the stripper while the IMTP-40 was added to the absorber. With each packing orientation, lean loadings of 0.2 and 0.3 moles CO₂/mole MEA were attempted. Controlling and measuring this CO₂ loading was difficult and operating errors were made. For each lean loading, two gas rates were run. The higher gas rate was near flooding and the lower was approximately half the higher. For each of these gas rates, three liquid rates were attempted. Liquid rates were controlled such that the CO₂ removal from the inlet flue gas would be approximately 70, 85, and 95%. At the end of the campaign, a few runs with vacuum stripping were performed. The actual operating conditions performed can be seen below in Table 5.

Table 5. Actual Operating Conditions of MEA Campaign

Sample	Packings (Absorber/Stripper)	Lean Loading (mole _{CO2} /mole _{MEA})	Gas Rate (ACFM)	Liquid Rate (GPM)	CO ₂ Removal (%)
44,45	Flexipac 1Y / IMTP-40	0.19	250	5.0	99%
46,47	Flexipac 1Y / IMTP-40	0.17	250	3.5	99%
49,51	Flexipac 1Y / IMTP-40	0.19	500	10.0	96%
52,53	Flexipac 1Y / IMTP-40	0.16	500	7.8	87%
54,55	Flexipac 1Y / IMTP-40	0.16	500	6.8	75%
56,57	Flexipac 1Y / IMTP-40	0.35	450	15.0	62%
59,60	Flexipac 1Y / IMTP-40	0.40	355	21.2	94%
61,62	Flexipac 1Y / IMTP-40	0.29	200	7.5	95%
63,64	Flexipac 1Y / IMTP-40	0.30	200	6.1	87%
65,66	Flexipac 1Y / IMTP-40	0.30	200	5.4	72%
67	Flexipac 1Y / IMTP-40	0.30	317	10.4	92%
68,69	IMTP-40 / Flexipac 1Y	0.30	400	27.5	93%
70,71	IMTP-40 / Flexipac 1Y	0.31	400	21.7	86%
72,73	IMTP-40 / Flexipac 1Y	0.31	400	14.5	70%
74,76	IMTP-40 / Flexipac 1Y	0.30	200	10.7	95%
75,77	IMTP-40 / Flexipac 1Y	0.31	200	11.3	80%
78,79	IMTP-40 / Flexipac 1Y	0.31	204	11.3	95%
82,83	IMTP-40 / Flexipac 1Y	0.25	400	22.0	94%
84,85	IMTP-40 / Flexipac 1Y	0.25	399	15.0	87%
86,87	IMTP-40 / Flexipac 1Y	0.25	400	10.4	72%
88,89	IMTP-40 / Flexipac 1Y	0.31	300	16.1	96%
90,91	IMTP-40 / Flexipac 1Y	0.31	300	8.0	69%

Experimental

Originally the CO₂ loading was controlled using ionic conductivity. Equations were developed to predict the loading using ionic conductivity, temperature, and MEA concentration. However, the two ionic conductivity meters began malfunctioning a week into the campaign and were determined to be inoperable. After sample 60, density was used as the controlling parameter for CO₂ loading. Since no correlations had been determined for density beforehand, the density was varied until a satisfactory CO₂ loading was obtained. A Shimadzu total organic carbon (TOC) analyzer located at the J.J. Pickle Research Center (PRC) was used to determine the CO₂ loading. The TOC analysis put the plant operations on hold and the loading results had less than average reproducibility. In the end, the lean loadings were held at steady values, but the actual value of the loadings was not always the desired magnitude. Referring back to Table 5, it can be seen that a loading of 0.25 was used instead of the attempted loading of 0.20 for runs 82-87.

The loading was more accurately linked to the solution density once the campaign had come to a close. After all the samples were analyzed by the PRC TOC for CO₂ content, the CO₂ concentrations for the absorber rich and lean samples were plotted to solution density. The results can be seen in Figure 12.

Figure 12. CO₂ Loading Correlation for MEA Solutions

Each point on Figure 12 is the average result of two to four TOC measurements for absorber rich and lean samples. The absorber lean stream was controlled near 104°F (40°C). The absorber rich stream exited at varying temperatures but the measured density was adjusted by a factor assuming that these rich solutions have the same thermal expansivity as water. When this temperature-density correction was applied, a linear dependence was observed. Using the equation of this line, all the solution loadings were calculated from their densities. This calculated loading was the loading that was used in all calculations. This technique greatly reduces the reproducibility and accuracy problems that were encountered with the TOC analyzer.

Results and Discussion

Mass Balance

After the liquid analysis was performed, it was possible to reconcile the mass balance. The mass of CO₂ absorbed in the absorber should be the same as the mass of CO₂ released in the stripper at steady state conditions. This mass of CO₂ was calculated three ways. The first way was using the liquid loading analysis of the absorber lean and rich streams. The second way was by analyzing the CO₂ concentration in the gas streams entering and leaving the absorber. The third way was by measuring the CO₂ flow leaving the stripper via an annubar flowmeter. The three CO₂ capacities are illustrated in Figure 13. The values can also be seen in Table A2 of the appendix.

Figure 13. CO₂ Mass Balance Comparison for Three Calculation Methods

For almost all runs, the three CO₂ mass calculations agree very well. It is also observed that the stripper CO₂ flow and the absorber liquid flow agree most closely. The absorber gas capacity also shows good agreement for the middle and end of the campaign but was inaccurate at the beginning. This is most likely due to a faulty air flow measurement for these runs. For runs 44-47 with low gas rates, the flow of CO₂ off the top of the stripper bordered near the minimal flow requirements for the annubar flow measurement. As a result, runs 46 and 47 reported zero gas flow when CO₂ was obviously flowing through the device. For calculation purposes in runs 44-47, the true CO₂ capacity was taken to be the absorber liquid capacity.

Excluding the first four runs from a simple error analysis, the stripper flow and absorber liquid capacities had an average discrepancy of 3.5% of the average of the two values. When the absorber gas capacity was included, the discrepancy increased to 6.5% of the average of the three values. This increased error is the reason that the true CO₂ capacity, used for calculation purposes, was taken as only the average of the stripper flow and the absorber liquid capacity, except for runs 44-47.

Heat Balance

To provide a level of confidence in heat related measurements, a heat balance was performed around the stripper. The limits of the balance include the stripper, reboiler, and the condenser. The boundary limits intersect the rich and lean solution streams, the cooling water streams, and the CO₂ flow leaving the condenser. A simple drawing of the energy balance limits can be seen below in Figure 14.

Figure 14. Schematic of Heat Balance Boundary Limits

Figure 14 also shows the boundary limits intersecting the steam streams but this was not used in the heat balance. Instead, the heat recovered from the steam is directly logged by the pilot plant's computer software. The software uses the temperatures and pressures of the steam and condensate streams and does curve fitting to enthalpy tables to determine the heat load. The heat capacities of the rich and lean solutions were determined by curve fitting heat capacity data obtained from Weiland et al. (1997). The heat capacity of the CO₂ streams leaving was taken as the heat capacity at 80°F (300K). The heat capacity of CO₂ is relatively constant over the relative temperature range of interest. Since the CO₂ heat capacity is relatively constant and such a minor factor in the total heat balance around the stripper, this inaccuracy has been avoided to this point. It will be addressed at a later time. Since the rich and lean solution streams have different heat capacities, the reference temperature is important for determining the enthalpy change. For each run, the reference temperature was taken to be the average of the lean and rich solution temperatures. This same reference temperature was taken for the CO₂ stream. The heat of desorption of the CO₂ should be the heat value at this same reference temperature. The heat of desorption was taken as 22 kcal/gmole. This is a typical value for the heat of reaction in this temperature range. No justification from the literature has been made on this value yet. The energy contribution from the cooling water stream could not be taken directly from the flow rate and temperature readings of the two streams. The flow rate could not be limited to a rate which gave a significant temperature difference in the inlet and outlet water temperatures. Instead, this energy was calculated

via the reflux stream and the CO₂ outlet stream. Whatever energy was dissipated from these two streams was transferred to the cooling water. The final energy term is due to heat losses. An existing equation, developed by SRP, detailed the amount of energy that should be lost by the stripper due to heat losses to the environment. This equation was used to calculate ambient heat losses. The heat balance is presented such that the reboiler duty, the only source of heat input, is compared the calculated energy requirements from heat losses, heat capacities, and heat of reaction. This comparison can be seen below in Figure 15. The numerical values can be seen in Table A3 in Appendix A.

Figure 15. Heat Balance Comparison of Predicted and Measured Reboiler Duties

For all runs, the predicted reboiler duty and actual reboiler duty match up very well. The predicted duty has an average error of -2.3% with respect to the actual heat duty. This means the prediction, on average, underpredicts the actual reboiler duty by 2.3%. This could be due to a systematic error or miscalibration. The campaign runs gave an absolute average error of 5.9%. This means, on average, the predicted and actual reboiler duties differed by an absolute value of 5.9%. With very good agreement in both the mass and energy balances, the data obtained from the pilot plant can be treated with confidence.

Mass Transfer

Mass transfer data was obtained by looking at the driving force at the top and bottom of the column. The inlet Vaisala CO₂ sensor does not encounter saturated gas. The stripper's condenser and the absorber's air cooler prevent the gas sensors from seeing saturated gas. This was designed because the sensors will malfunction when they encounter water. Figures A1 through A3 in Appendix A show the plant's schematic layout which is important in determining the saturated CO₂ concentrations in the column.

For the bottom of the column, the unsaturated air entering the column will immediately become saturated and experiences a temperature drop. The calculated saturated CO₂ concentration was used as part of the driving force. This was calculated by assuming that the air leaving the air cooler is saturated at its temperature. It was also assumed that the gas leaving the condenser is saturated at the exiting temperature. These two streams are mixed before re-entering the bottom of the column. Since the gas leaving the condenser is pure CO₂, with the exception of a tiny bit of water, and the gas leaving the air cooler is analyzed by the outlet CO₂ sensor, we can determine the stoichiometric mixture of these two gases to produce the CO₂ concentration observed by the inlet CO₂ analyzer. Using this ratio of the streams, the water concentration can be determined. Using the water concentration of the inlet gas and the observed temperature in the column where the gas enters, the amount of water vaporized to saturate the gas can be determined. With this calculated new gaseous inventory, the saturated CO₂ concentration can be determined. The other half of the driving force results from the equilibrium vapor pressure of the solvent that the vapor encounters. This is the solvent leaving the column where the CO₂ loading and temperature are known. This equilibrium vapor pressure was determined using a flash calculation in Aspen using the electrolyte NRTL properties and Freguia's Fortran code. This equilibrium simulation was performed for the bottom of the column for all of the runs. The determination of the driving force at the top of the column was similar. The equilibrium vapor pressure was again determined using the same Aspen simulation with the appropriate compositions and temperatures. The saturated CO₂ concentration was calculated by assuming saturation at the top of the column and saturation exiting the air cooler. Similarly to the bottom of the column, these calculations were performed for all the pilot plant runs.

Using the driving forces, in vapor fraction terms, K_{Ga} was determined for the top and the bottom of the column for each run. Using these K_{Gas} , a log mean average K_{Ga} for the column was calculated. It was observed that the Flexipac 1Y packing generally had a larger K_{Ga} value than the IMTP-40. This is expected due to the increased area for mass transfer. K_{Ga} values for the Flexipac 1Y averaged 5.79 lbmole/ft³h compared to 3.96 for the IMTP-40.

Driving factors were calculated to recognize pinches. This driving factor is defined as the operating CO₂ vapor fraction divided by the equilibrium vapor fraction. Pinches can be recognized by this driving factor approaching one. This driving factor analysis showed that there were no lean end pinches. The smallest driving force at the top of the column was approximately 9 and ranged to over 100. On the rich end of the column, pinches were observed. These driving forces were generally single digits. A table of the saturated and equilibrium concentrations, driving factors and K_{Gas} for every run can be seen in Table A4 in Appendix A. Figure 16 distinguishes the mass transfer performance for Flexipac 1Y and IMTP-40 for high and low gas rates.

Figure 16. Mass Transfer Performance of Flexipac 1Y and IMTP-40

Figure 16 demonstrates that the Flexipac 1Y packing has higher K_{Ga} values than IMTP-40. Part of this is likely due to the increased surface area of Flexipac 1Y. Higher gas rates also show more mass transfer than lower gas rates. This is most likely due to the increased wetted area of the packings at higher gas rates. The fraction of wetted packing has yet to be determined.

Pressure Drop

Differential pressure was measured across the top and bottom beds of both the absorber and stripper. In this report, the pressure drop is only analyzed for the absorber. The gas flow in this analysis is based on the absorber inlet gas conditions. It neglects gas volume absorbed by the air to achieve saturation, CO_2 lost due to reaction, and density changes due to changing temperatures and pressures. A pressure drop analysis distinguishing lean loadings and packing type can be seen below in Figure 17.

Figure 17. Pressure Drop Analysis for the Bottom Bed of the Absorber

Flexipac 1Y shows a clear distinction between the high and low lean loadings. This distinction may be due to an increased viscosity of the solutions when more CO₂ is chemically absorbed. For the IMTP-40, no clear distinction exists. In all four cases, the pressure drop trend increased for increasing liquid rate. It does appear that the IMTP-40 is less sensitive to changes in liquid rate. The IMTP-40 also shows less distinction between the different loadings. This is somewhat expected since the Flexipac 1Y testing experienced a greater difference in the two lean loadings than the IMTP-40. This distinction as well as all relevant pressure drop data can be seen in Table A5 in Appendix A. It must be noted that this bottom bed analysis based on lean loading is weakened by the fact that the loadings have drastically changed by the time the solution reaches the bottom bed of the absorber. The loading of the solution in the middle of the column has not been determined since the loading correlation is based on density. It will be calculated by a mass balance using the gaseous CO₂ concentration at the middle of the column.

The same analysis was performed for the top bed of the absorber. Some of the runs using the Flexipac 1Y packing had to be removed due to misleading pressure drop data. Towards the end of the Flexipac 1Y testing, the mesh screen of the liquid collector plate at the bottom of the top bed became clogged with deposited rust. This limited the liquid flow capacity of the column and on occasion caused a liquid level on the collection plate. In these cases a very high pressure drop was observed for only the top bed of the column. During the column change-out, a high flow collector plate was installed and the problem was not encountered with the IMTP-40 packing. A pressure drop analysis of those runs not tainted by the collector plate problem can be observed in Figure 18.

Figure 18. Pressure Drop Analysis for the Top Bed of the Absorber

The top bed of the absorber shows results similar to those of the bottom bed. Again, the Flexipac 1Y packing shows trends for each of the lean loadings. The IMTP-40 again shows little distinction between lean loadings. As stated before, this is at least

partially due to the smaller difference in lean loading and lack of data points at the lower lean loading. It is interesting that the IMTP-40 trends exhibit a decreasing pressure drop with increasing liquid rates. This is intuitionally opposite of what is expected. A temperature near the middle of the top bed was analyzed to see if temperature might play a significant role in explaining this odd behavior. Figure 19 shows how the observed pressure drop compared to a temperature near the middle of the top bed.

Figure 19. Temperature, Pressure Drop Comparison for the Absorber's Top Bed

Figure 19 seems to suggest that the column temperature seems to play a fairly large role in the pressure drop for the IMTP-40 packing. The data points for Flexipac 1Y don't show any significant trend. Typically, higher liquid rates result in lower temperatures near the top of the column since the majority of the reaction will occur near the bottom. At colder temperatures, the gas is more dense and will result in a lower velocity through the packing. This may be a possible explanation for why the IMTP-40 shows this particular behavior. It does not explain why the Flexipac does not seem to be affected. Regardless, the temperature effects, which are a result of the operating conditions, can play a significant role in the pressure drop through the packing. The extent of this effect and why it seems more pronounced with the IMTP-40 packing has not yet been examined. A more detailed analysis involving the temperature profiles throughout the column will be examined.

Conclusions

The CO₂ loading was successfully correlated to the solution density. This enabled the rich and lean loading to be determined more accurately than with the TOC analyzer results. This increased loading accuracy factored into the establishment of accurate mass and energy balances. The average mass balance error was 3.5% between the CO₂

absorbed via the liquid analysis and the CO₂ released from the stripper via an annubar flow meter. The average energy balance error between the predicted reboiler duty and the measured reboiler duty was -2.3% with an absolute average error of 5.9%.

A preliminary mass transfer analysis was executed for the absorber. It was determined that the Flexipac 1Y exhibited higher K_{Ga} values than IMTP-40. For both packings, higher gas rates resulted in higher K_{Ga}. There were only a data points for IMTP-40 with the lower gas rates but the trends still seem to apply.

A simple pressure drop analysis was conducted for the two packings in the absorber. For both beds, the Flexipac 1Y showed trends for each lean loading. These trends showed an increasing $\Delta P/G^2$ for increasing liquid rate and higher pressure drops with richer loadings. The IMTP-40 results with the higher loading somewhat merged with the few points having the lower lean loading. The two lean loadings were closer in the case of the IMTP-40 packing. The trends showed a slight increase in $\Delta P/G^2$ with increasing liquid rate for the bottom bed of the absorber and a slight decrease for the top bed. The $\Delta P/G^2$ value does correspond very well with TT4076 in the top bed of the absorber for the IMTP-40 packings. This implies that temperature plays a significant role in determining the pressure drop characteristics of the IMTP-40 packing.

Future Work

The results from the pilot plant still require further analysis to characterize the mass transfer performance and evaluate the pressure drop data. The pilot plant data also needs to be compared to the Freguia Aspen model. Matching the model to the pilot plant will help in maximizing the efficiency of the process as well as learning why certain phenomena occur. This new understanding will be very useful in the planning of any future pilot plant campaigns using MEA or other solvents.

Subtask 3.4 – Amine Volatility

by John McLees

(Supported by this contract)

Introduction

The main focus of this section is to present the results of the FTIR analysis conducted during Campaign 3. FTIR analysis allows for measuring many different constituents of the pilot plant gas, and results for CO₂, H₂O, NH₃, and MEA are presented here. The development of the method used to deduce the final concentrations of these four compounds will be presented in detail in this section.

Another focus was to design a packed bed reactor system for use in the laboratory for determining such data as equilibrium partial pressures and activity coefficients in amine systems such as MEA and PZ; but the work could be expanded to include several other amines. A variety of commercial packings that have been well characterized were taken under consideration for the reactor design, and their respective properties have been tabulated. Packing height was determined as a product of the height of a gas phase transfer unit (H_G) and the number of transfer units (N_G). After several design cases, a one-inch I.D. jacketed column packed to a height of 12 inches with 0.16-inch Pro-Pak packing (available from Ace Glassware, Inc.) was finally chosen as the initial design, and construction will begin soon.

Future work has begun in generating reference files at various concentrations for PZ in preparation for the upcoming Campaign 4 in the fall. An in-depth discussion as to the current method of generating these files will be presented here.

Experimental Method

FTIR Analysis at UT's Pickle Research Campus (PRC)

During the week of April 6-April 13 of Campaign 3 at PRC, the FTIR, sample pump, and data collection software package were placed on level 2 of the pilot plant for the purpose of analyzing the gas at the top of the absorber column. The actual sample was taken from the vertical section of the 8-inch I.D. pipe, located approximately 6 feet before the cooler. A sample probe was constructed from 0.25-inch stainless-steel tubing, bent at a 90-degree angle and positioned so that the inlet of the probe was pointed down in the same direction of the gas flow so that the gas to be analyzed would have to make a 180-degree turn in order to minimize entrainment in the heated line. Furthermore, the probe was constructed long enough so that the sample could be taken from the center of the pipe so as to minimize wall effects. A line of 3/8-inch plastic tubing was run from the main nitrogen line up to the sample point in order to provide the constant pressure for the analyzer's optics as well as to serve as a purge for the purpose of running new background scans. This nitrogen line was fed into a three-way splitter with one outlet going to the analyzer and the other fed into a globe valve that, when turned on, prohibited flow from the absorber column into the sample line, and thus allowed pure nitrogen to flow into the heated sample line.

The initial background scan was made by flowing nitrogen through the heated line (heated to 180°C) for five minutes. A typical background scan for this study is shown in Figure 1 below. The peaks at 1300 to 1800 cm^{-1} and 3500 to 3900 cm^{-1} range are characteristic of water absorbance and the peak that occurs around 2350 cm^{-1} is due to CO_2 absorbance. These peaks are present because the optics casing is not hermetically sealed, so that even though only N_2 is flowing through the system, some air (containing water and CO_2) will be present. Ideally, the values of the intensity (measured on the y-axis) should fall between 20,000 and 65,000, with the physical saturation limit of the detector being 65,535.

Figure 20. A Typical Background Scan of Pure N_2 through the FTIR during PRC Campaign 3

Once the background scan was completed, the software was programmed to take samples continuously in three-minute intervals, which were automatically saved by the Calmet software into folders that corresponded to the date that the sample was taken. A new background scan had to be performed every time there was a 15° change in ambient temperature, and thus new backgrounds were taken once in the early morning, once around lunchtime, and once in the later evening. The analyzer optics are somewhat temperature sensitive and small changes can be compensated for automatically, but if there is too big a swing in ambient temperature, the calibration could drift and the resulting samples would yield incorrect data with very high residuals.

Samples were taken from mid-day April 6 until the early afternoon of April 8, when the pilot plant was shutdown for the weekend. Upon startup on Monday morning

(April 11), sample collection was resumed until late afternoon on April 13, when the absorber conditions changed to vacuum mode.

Packed-Bed Reactor Design

Our goal for the design of this particular reactor was to specify a gas and liquid flowrate as well as a percent flooding and be able to use these specifications to calculate a column diameter as well as packing height from known correlations. The initial packing we had in mind was the 10-mm stainless steel Interpack, available from Jaeger, Inc. Ideally, we would like to operate the gas anywhere from 5-7 SLPM (as is the current setup in the stirred reactor system), and the liquid flowrate has been considered anywhere from 250 sccm to almost 4 SLPM. Onda et al. (1968) correlated the mass transfer coefficients in both gas and liquid phase in packed columns, and their approach was used to calculate packing heights for different commercially available packings for use in our packed bed reactor system. Our amine-water system, in particular, is gas-film controlled, where the gas phase mass transfer coefficient, k_G , is given by

$$k_G RT / a_t D_G = 5.23 (G / a_t \mu_G)^{0.7} (\mu_G / \rho_G D_G)^{1/3} (a_t D_p)^{-2.0} \quad (12)$$

where R is the universal gas constant ($\text{m}^3\text{-atm/kg-mole K}$), T is the temperature (K), a_t is the surface area of the packing (m^2/m^3), D_G is the gas diffusivity (m^2/hr), G is the gas superficial mass velocity ($\text{kg}/\text{m}^2\text{-hr}$), D_p is the packing size (m), and μ_G and ρ_G are the gas viscosity ($\text{kg}/\text{m-hr}$) and density (kg/m^3), respectively. Once the gas-phase mass transfer coefficient is known, the height of a gas phase transfer unit, H_G , was estimated using the following relation:

$$H_G = \frac{G}{k_G A} \quad (13)$$

Packing height, Z , (in m) was determined as the product of the height of a gas phase transfer unit and the number of transfer units, which was arbitrarily set at 5, as it is known that 5 transfer units yields a 99% approach to equilibrium.

$$Z = H_G N_G \quad (14)$$

Column diameter (and consequently, superficial gas and liquid velocities) were obtained through a correlation from Seader and Henley (1998). Once the gas (G) and liquid (L) molar flowrates (in kgmol/hr) were specified, one could use Equation (15) to calculate the variable on the x-axis, and draw a line to the flooding limit on the y-axis, and thus obtain a superficial gas velocity from Equation (16).

$$X = (LM_L / GM_G)(\rho_G / \rho_L)^{0.5} \quad (15)$$

$$Y = \frac{u_o^2 F_p}{g} \left(\frac{\rho_G}{\rho_{H_2O_L}} \right) f(\rho_L) f(\mu_L) \quad (16)$$

Once the superficial gas velocity was known and the percent of flooding was specified (80% for our study), the column diameter (in inches) was calculated by

$$D_T = \left(\frac{4GM_G}{fu_o\pi\rho_G} \right)^{0.5} \quad (17)$$

Several design scenarios were considered, and the results have been tabulated in Table 6. Most of these designs yielded columns that were too tall to be practical for our laboratory set-up, so other commercially made column and packing systems were then considered. Ace Glassware, Inc. provided us with packing data for both their 0.16-in and 0.24-in Pro-Pak packing, and based on our study of their data, we have chosen a jacketed 1-in I.D. column with packed to a height of 12 inches with the 0.16-in Pro-Pak as our initial system, and we will soon order these materials as well as begin construction of the liquid distribution system. An early schematic of what the system could look like upon completion is shown below in Figure 21.

Table 6. Representative Cases for Construction of the Packed-Bed Reactor System

L (L/min)	G (L/min)	Packing	Column Diameter (in)	Packing Height (cm)
0.25	5	10 mm Interpack	0.85	187
0.75	5	10 mm Interpack	1.15	156
1	5	10 mm Interpack	1.51	132
2	7	10 mm Interpack	1.84	130
3	7	10 mm Interpack	2.13	119

Figure 21. Proposed Schematic Diagram of Laboratory Packed-Bed Reactor System

Generation of PZ Reference Files

In order to be able to use the FTIR for similar analysis on the absorber gas for the next pilot plant campaign this fall, it was necessary to generate reference files for PZ as they were previously unavailable. Normally, reference file generation is a somewhat trivial process for gas-phase components, but liquid- and solid-phase components are not so simple. It is possible to dissolve unknown solids into a solvent in which the absorbance spectrum is known (i.e., methanol or benzene), but this idea was discarded due to the fact that our methanol reference files are dated and probably not as accurate as they should be. Our method, therefore, consisted of taring a 250-ml beaker and placing a known mass of PZ in the beaker. The beaker and PZ were placed inside an air-tight bomb, which was then placed in a heat bath at a temperature of 90°C. The FTIR had been calibrated with pure N₂ at a given flowrate which was controlled by the 15 SLPM mass flow controller, and this same N₂ flowrate was then flowed from the flow controller down the length of the heated tube to heat the N₂ to 180°C, which was then passed over the PZ in the bomb. This gas inside the bomb flowed through another tube in the heated sample line into the analyzer, where samples were taken at three-minute intervals. This process was allowed to run for eight hours, after which the bomb was taken out of the bath, opened, and the beaker and PZ weighed again. With a known mass loss over a known period of time (the evaporation rate assumed constant during the experiment), and a known molar flowrate of N₂ (given by Equation (18)), it is possible to know the concentration of PZ in the gas phase.

$$\begin{aligned} \text{N}_2 \text{ Flowrate (gmol/min)} = & 0.0000221(\text{Controller Setting})^2 \\ & + 0.0068815(\text{Controller Setting}) - 0.0083132 \end{aligned} \quad (18)$$

Our first attempt at this process showed a higher than expected amount of water present, so the PZ was placed in a dessicator for a period of four days, and the same process was repeated. Higher concentrations may be obtained by increasing the bath temperature above the melting point of PZ, to approximately 105°C, which will be carried out in the next few weeks.

Results and Discussion

PRC FTIR Method Development

The initial results of the FTIR analysis came back with very high residuals, meaning that the absorbance peaks of the compounds being measured compared poorly with those peaks in the reference files, and thus many of the values initially reported were deemed suspect. Some causes of this were poor or misplaced reference files, higher than expected concentrations of some compounds, and analyzing for absorbance of compounds in the wrong wave regions. With FTIR analysis, it is possible to re-evaluate results even after the experiment is complete (granted the background scan is good) by changing the wave regions where absorbance is being analyzed for in certain compounds.

The first step of the new method development was to generate new NH₃ reference files, as it was believed the ones that were initially used were dated and possibly inaccurate. To do this, a 1000 ppm NH₃/N₂ blend was mixed with pure N₂ at different flowrates and passed through the heated sample line back in the laboratory. The N₂ flow

was varied to give different NH_3 concentrations. New reference files were generated at 100 ppm, 250 ppm, 500 ppm, 750 ppm, and 1000 ppm, and added to the analysis settings.

Secondly, the analysis regions for different compounds were changed. For NH_3 , absorbances were only 995-1073 and 1096-1250 cm^{-1} . Analysis for NO was turned off, but the results yielded higher residuals than previously found for H_2O , so NO was added back to the list of compounds to be analyzed. For CO_2 , it was found to be impossible to analyze in the region between 980-1130 cm^{-1} , but proved to be insignificant in terms of affecting the concentrations as this region is normally just used for baseline correction purposes. Also, due to the high H_2O residuals, it was not practical to use the region between 3400 and 3800 cm^{-1} for CO_2 , and it was removed. An additional analysis region for MEA was added (2416-2601 cm^{-1}), and another region was experimented with (980-1119 cm^{-1}), but the residuals increased, and this latter region was removed. Another reference file for methanol was added (10 ppm), and the analysis regions were changed to 995-1073 cm^{-1} , 1095-1150 cm^{-1} , and 2450-3180 cm^{-1} . This caused a drop from in MEA concentration from 29.2 ppm to 2.9 ppm for the same sample. Furthermore, an additional region was added for acetaldehyde from 3200-3350 cm^{-1} . Finally, the methylamine analysis regions were changed to 2022-2223 cm^{-1} , 2450-2650 cm^{-1} , and 2800-3203 cm^{-1} , with the first two regions to account for baseline correction. This new method greatly improved the residuals on every compound, with noticeable improvements in CO_2 , H_2O , NH_3 , and MEA.

PRC FTIR Results

One of the most important goals of this FTIR study was to evaluate whether or not FTIR analysis could be a viable alternative to the current Horiba and Vaisala instruments as an in-line analyzer. One way to check this is to compare the concentrations of CO_2 measured at the top of the absorber. Figure 22 presents the measured concentrations of CO_2 by the FTIR (averaged over a period of 15 minutes) and the instantaneous readings of the Vaisala AI404 analyzer. The FTIR value was obtained by finding the time of the FTIR sample that was closest to the time the liquid samples were taken by the operators, and then averaging that value with the FTIR samples that occurred three and six minutes before and after the chosen FTIR sample. The values for the Vaisala analyzer had to be corrected to account for the fact that the gas being analyzed is wet, and since the Vaisala is calibrated with dry gas, the actual values were divided by $(1+\%\text{H}_2\text{O})$ to give the concentrations shown in Figure 22.

Figure 22. Carbon Dioxide Concentrations (volume %) Measured over the Seven-Day Period of the FTIR Analysis

The FTIR is a very adequate instrument for analyzing compositions of wet gases for CO₂ for the majority of the experiment. The values differed on average by approximately 20% for the vast majority of the points not counting the last two, which were drastically influenced by the high temperature conditions. Figure 23 below shows the direct correlation between temperature and H₂O concentration, and because the last two sample points occur at a higher than normal temperature, the H₂O concentration is significantly higher, and thus the measured CO₂ concentrations are not in agreement. Secondly, the sample probe into the column had approximately 4 to 5 inches of exposed stainless-steel tubing, and thus the gas may have cooled 2 to 3 degrees over this short distance, causing some water to condense (along with some CO₂), and this may contribute to the different values, especially at the higher temperature runs.

Figure 23. Water Concentration (volume %) and Temperature (°F) over the Course of the Seven-Day Period

Since there is no other alternative way of measuring concentrations of any other compounds in the gas phase at PRC, the measured vapor pressure of H₂O and MEA was compared to that of pure liquid (Posey, 1994), given by Equations (19a) and (19b) below.

$$\text{H}_2\text{O: } P_{\text{H}_2\text{O}}^*(Pa) = \exp\left(72.55 - \frac{7206.7}{T(K)} - 7.1385 \ln T(K) + 4.046E - 6T(K)^2\right) \quad (19a)$$

$$\text{MEA: } P_{\text{MEA}}^*(Pa) = \exp\left(172.78 - \frac{13492}{T(K)} - 21.914 \ln T(K) + 1.3779E - 5T(K)^2\right) \quad (19b)$$

Figure 24. Experimental and Predicted Values for Water Vapor Pressure (atm) Vs. Inverse Temperature (K^{-1})

Figure 25. Experimental and Predicted Values for MEA Vapor Pressure (atm) Vs. Inverse Temperature (K^{-1})

It is observed that in both cases, the actual measured vapor pressures in a loaded solution for both compounds are somewhat lower than predicted for the unloaded scenario. Apparent activity coefficients for each compound were calculated by Equations (20a) and (20b), and then plotted as a function of absorber lean loading in Figures 26 and 27.

$$\text{H}_2\text{O}: \gamma_{\text{H}_2\text{O}} = \frac{a_{\text{H}_2\text{O}}}{x_{\text{H}_2\text{O}}} \quad (20a)$$

$$\text{MEA}: \gamma_{\text{MEA}} = \frac{P_{\text{MEA},\text{meas}}^*}{P_{\text{MEA},\text{calc}}^*(T) * x_{\text{MEA}} * (1 - 2\alpha)} \quad (20b)$$

where α is the absorber lean loading (mol CO₂/mol MEA), $a_{\text{H}_2\text{O}}$ is the activity of water ($P_{\text{H}_2\text{O},\text{meas}}^*/P_{\text{H}_2\text{O},\text{calc}}^*$), $x_{\text{H}_2\text{O}}$ and x_{MEA} are the mole fractions of free water and MEA, respectively, in unloaded solutions. These values correspond to 55/62 for water, and 7/62 for MEA.

Figure 26. Measured Activity Coefficients for Water as a Function of Absorber Lean Loading for Campaign 3

Chang (1993) and Posey (1994) predict an activity coefficient of approximately 0.96 for water in a binary water-MEA solution, and our data seem to be a scatter with values ranging from approximately 0.5-1, while most are consistently lower than 0.96. The same study also predicts MEA activity coefficients between 0.4 and 0.45 for a binary water-MEA system between the temperatures of 30°C and 60°C. Our studies show that, in this temperature range, we again see a scatter of points at both loading conditions, but the majority of the points are somewhat higher than this prediction. Both of these deviations are accounted for by the fact that the loaded CO₂ decreases the amount of free MEA in the system, and thus the differences in the activity coefficients.

Figure 27. Measured Activity Coefficients for MEA as a Function of Absorber Lean Loading for Campaign 3

It is worth noting, however, that for most of the experiment, NH_3 concentrations at the top of the absorber were very high, some exceeding 1000 ppm. Currently, we cannot measure NH_3 past this limit, and since the FTIR cannot extrapolate values beyond its known references (due to the severe non-linearity of absorbance peaks), the NH_3 concentrations given by the FTIR above 1000 ppm are more than likely significantly underpredicted. This creates a slight problem in that NH_3 absorbs in many of the same places as compounds such as H_2O , CO_2 , and MEA; so if the NH_3 concentrations are incorrect, there's a good chance that some of the other values are not entirely correct.

Future Work

PZ reference files will continue to be produced for various concentrations by the method outlined previously in preparation for FTIR analysis during the last pilot plant campaign this fall. Materials will be ordered soon to begin construction of the packed-bed reactor in the laboratory, and upon completing the construction phase; a known experiment (such as absorption of SO_2 by water) will be run in order to characterize the column and packing. Once the mass transfer characteristics of the system are known, it will be possible to begin using the reactor to generate equilibrium data for different amine systems and compare this experimental data to that predicted by various models.

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Table A1. Summary of Online Measurements from PRC Pilot Plant

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		GAS Press Pressure Drip Bed Temp Bed Temp Bed Temp Bed Temp Bed Temp Bed Temp Bed Temp CO2 In CO2 Mid CO2 Out Column Level Acc Level																													
		PT900		PDT450		PDT451		TT4078		TT4077		TT4076		TT4075		TT4074		TT4073		TT4071		AI406		AI900		AI404		LC201		LC203	
Date/Time	Sample	(PSIG)	(in H2O)	(in H2O)	(F)	(F)	(F)	(F)	(F)	(F)	(F)	(F)	(F)	(F)	(F)	(F)	(F)	(F)	(F)	(F)	(F)	(F)	(F)	(F)	(F)	(F)	(F)	(F)	(F)	(F)	
3/15/05 20:10	44	0.21	0.31	0.32	75.55	171.66	173.17	176.92	168.45	175.57	126.44	12.50	0.29	-0.01	0.08	10.490	9.00														
3/15/05 21:10	45	0.20	0.30	0.29	74.25	115.19	170.76	174.94	166.76	174.04	126.98	11.63	0.22	-0.01	0.06	10.494	9.00														
3/16/05 2:15	46	0.20	0.21	0.26	70.69	167.03	168.04	173.34	165.23	172.41	117.13	12.09	0.16	0.07	0.08	10.519	9.00														
3/16/05 3:15	47	0.20	0.21	0.25	71.06	163.05	165.55	171.44	162.99	170.94	116.97	11.24	0.13	0.06	0.06	10.536	9.00														
3/16/05 10:15	50	0.08	2.05	2.43	137.96	158.89	142.37	141.29	131.64	132.09	134.00	12.30	11.05	2.76	5.02	10.544	9.00														
3/16/05 11:15	48	0.07	1.94	2.32	137.67	161.70	145.86	144.37	134.59	134.46	134.95	11.20	10.48	2.47	4.75	10.501	9.00														
3/18/05 8:35	49	0.58	2.25	2.66	126.58	172.58	165.79	163.22	152.30	146.18	110.14	11.77	5.40	0.44	0.65	10.468	9.00														
3/18/05 9:35	51	0.56	2.21	2.59	125.03	172.99	167.58	165.63	155.02	149.17	111.90	11.82	4.84	0.31	0.50	10.521	9.00														
3/18/05 16:00	52	0.48	1.67	2.10	138.12	165.08	149.17	143.60	132.49	126.94	102.52	11.69	8.71	1.53	1.70	10.509	9.00														
3/18/05 17:00	53	0.49	1.71	2.15	139.31	164.80	148.94	143.17	132.53	126.51	102.72	11.71	8.72	1.61	1.77	10.482	9.00														
3/18/05 17:30	54	0.46	1.60	2.00	140.15	157.61	139.35	134.23	125.35	119.62	98.20	11.70	9.24	2.64	3.06	10.463	9.00														
3/18/05 18:30	55	0.45	1.59	1.96	139.00	155.76	135.98	130.79	121.26	116.70	96.46	11.83	9.81	3.08	3.37	10.503	9.00														
3/22/05 1:15	56	0.56	3.79	5.83	108.79	165.96	157.40	156.58	150.55	146.42	114.67	12.16	8.36	4.18	4.83	9.979	9.00														
3/22/05 2:15	57	0.57	3.83	5.96	107.17	164.71	156.52	156.09	150.29	145.93	114.14	11.90	8.47	4.30	4.99	10.020	9.00														
3/22/05 6:30	58	0.58	5.58	16.49	95.63	105.23	110.60	125.35	126.97	127.66	125.32	12.25	6.23	2.13	2.13	10.014	9.00														
3/22/05 11:30	60	0.65	3.81	11.10	96.56	104.66	107.75	118.73	119.61	127.44	124.82	12.45	4.64	0.73	0.82	10.165	9.00														
3/23/05 17:00	61	0.20	0.64	0.76	101.76	173.72	170.71	170.86	166.42	162.67	114.73	12.37	3.96	0.94	0.71	10.220	9.00														
3/23/05 18:00	62	0.20	0.64	0.67	94.78	172.69	170.84	171.92	167.55	165.13	116.02	11.74	2.78	0.71	0.62	10.183	9.00														
3/23/05 20:55	63	0.18	0.52	0.17	108.73	170.08	158.00	152.14	146.93	142.40	105.99	12.10	8.28	2.35	1.67	10.213	9.00														
3/23/05 21:55	64	0.17	0.51	-0.01	107.28	169.05	155.60	149.34	143.81	139.71	105.13	12.14	8.63	2.60	1.85	10.242	9.00														
3/24/05 3:00	65	0.16	0.47	-0.83	117.30	162.22	143.90	136.96	130.20	127.61	99.08	12.10	9.97	4.45	3.76	10.183	9.00														
3/24/05 4:15	66	0.16	0.47	-0.83	118.09	161.82	142.86	135.54	128.48	125.72	98.64	12.70	10.50	4.81	3.85	10.165	9.00														
3/24/05 7:45	67	0.44	1.54	12.42	110.74	170.52	166.21	163.84	161.52	154.97	110.67	11.07	5.09	1.59	1.03	10.166	9.00														
Column Changeout		Column Changeout																Column Changeout													
4/6/05 16:20	68	0.56	2.49	1.10	100.84	106.92	110.70	111.40	113.61	120.53	124.48	12.23	3.52	0.78	0.97	12.185	10.00														
4/6/05 17:30	69	0.56	2.65	1.18	100.75	105.99	109.31	110.08	112.39	118.60	122.72	11.16	3.12	0.70	0.87	12.249	10.00														
4/7/05 1:00	70	0.58	2.96	0.84	96.94	111.31	117.97	118.25	121.85	132.51	127.08	11.97	4.52	1.48	1.79	10.112	10.00														
4/7/05 2:05	71	0.56	2.84	0.79	96.32	110.82	117.07	117.19	120.12	130.20	125.85	11.78	4.44	1.50	1.79	10.103	10.00														
4/7/05 5:30	72	0.60	2.56	1.95	105.25	154.50	154.35	153.81	154.78	151.75	119.54	11.48	6.42	2.82	3.66	10.132	10.00														
4/7/05 6:30	73	0.61	2.53	2.03	108.40	156.77	155.96	155.15	155.77	152.00	119.56	12.19	6.96	2.99	4.07	10.080	10.00														
4/7/05 10:45	74	0.33	0.45	0.27	89.72	110.87	118.05	115.85	122.96	141.27	126.85	12.13	3.59	0.08	0.65	10.073	10.00														
4/7/05 11:45	76	0.31	0.44	0.25	91.78	113.98	122.49	120.22	127.42	144.52	126.30	12.35	4.39	0.10	0.83	10.070	10.00														
4/7/05 17:00	75	0.20	0.58	0.37	98.89	125.59	132.65	129.62	135.40	143.81	122.86	12.17	7.29	0.31	2.76	10.100	10.00														
4/7/05 18:00	77	0.20	0.58	0.37	99.06	125.63	132.45	129.76	135.43	143.98	122.61	12.32	7.20	0.28	2.73	10.082	10.00														
4/8/05 2:05	78	-0.01	0.47	0.30	90.29	106.65	112.81	110.82	115.24	131.31	126.24	11.01	2.84	0.03	0.48	10.110	10.00														
4/8/05 3:10	79	0.12	0.48	0.32	91.11	109.63	117.49	114.95	119.74	135.76	126.94	11.86	3.83	0.04	0.73	10.122	10.00														
4/8/05 11:00	81	0.34	0.34	-0.09	97.10	110.10	117.20	114.90	117.60	126.50	125.20	11.88	4.49	4.49	0.54	10.100	10.00														
4/8/05 12:00	80	0.47	0.28	0.18	96.00	109.00	114.90	112.90	115.60	124.60	124.20	10.88	4.61	4.61	0.56	10.100	10.00														
4/11/05 11:30	82	0.53	2.46	1.18	95.83	108.17	113.45	114.70	118.05	129.07	130.52	11.86	3.22	0.05	0.79	11.495	10.20														
4/11/05 12:30	83	0.54	2.54	1.08	96.56	108.84	114.29	115.54	118.87	130.37	130.80	12.24	3.44	0.05	0.88	11.496	10.20														
4/11/05 14:30	84	0.50	2.49	2.00	115.38	166.56	165.67	164.76	164.79	160.48	124.81	12.05	4.96	0.12	1.76	11.518	10.20														
4/11/05 15:30	85	0.46	2.50	2.06	118.09	167.31	166.45	165.57	165.46	161.11	125.03	11.88	4.80	0.11	1.65	11.535	10.20														
4/12/05 1:30	86	0.48	2.12	2.08	134.96	160.30	156.05	153.40	151.24	143.18	112.01	11.89	7.27	0.27	3.72	11.511	10.20														
4/12/05 2:30	87	0.49	2.13	2.07	136.65	161.11	156.82	153.82	151.70	143.64	112.50	11.80	7.16	0.26	3.59	11.518	10.20														
4/13/05 10:00	88	0.44	1.27	0.69	96.60	110.36	117.24	116.18	123.57	142.33	134.97	12.17	3.14	0.03	0.67	10.517	10.20														
4/13/05 11:00	89	0.41	1.13	0.64	97.25	109.41	115.25	116.18	119.79	135.42	134.49	11.78	2.70	0.03	0.52	10.493	10.20														
4/13/05 14:45	90	0.29	1.02	1.01	136.73	160.22	154.85	152.18	148.63	142.84	112.35	12.64	8.15	0.25	4.22	10.497	10.20														
4/13/05 15:45	91	0.23	1.06	1.05	134.81	158.67	153.68	151.15	147.64	141.77	111.40	12.03	7.84	0.24	4.07	10.467	10.20														

Date/Time		Sample		Top BOT Temp Bot TOP Temp Bot MID Temp Bot Temp Cond Ret Vapor Inlet Bot Liq to Reb VAP to Condens Org. Out (Cond) CW Inlet CW Outlet CW Flow Feed Temp Reflux Temp																											
				T2078		Bot TOP Temp		Bot MID Temp		Bot Temp		Cond Ret		T208		T219		T216		T225		T224		T226		FT205		TT205		TT220	
				(F)	(F)	(F)	(F)	(F)	(F)	(F)	(F)	(F)	(F)	(F)	(F)	(F)	(F)	(F)	(F)	(F)	(F)	(F)	(F)	(F)	(F)	(F)	(F)	(F)	(F)	(F)	(F)
3/15/05 20:10	44	236.5	236.36	237.6	241.36	262.01	243.98	243.43	197.13	51.63	46.64	47.76	203.53	210.53	134.22																
3/15/05 21:10	45	236.5	236.53	237.6	241.33	262.43	244.07	243.46	197.42	51.54	46.66	47.88	203.38	210.58	131.58																
3/16/05 2:15	46	235.6	235.83	237.2	241.42	261.10	243.87	243.76	193.63	50.00	45.48	46.84	203.44	211.64	149.66																
3/16/05 3:15	47	236.3	237.15	238.0	241.52	260.98	243.95	243.80	198.84	50.01	46.00	46.50	203.62	210.65	136.84																
3/16/05 10:15	50	235.9	235.89	237.9	241.77	269.14	245.42	243.60	191.16	53.27	47.03	49.15	203.66	202.41	117.06																
3/16/05 11:15	48	235.4	235.69	237.9	241.82	269.78	245.68	243.63	191.67	53.34	46.90	49.20	203.70	204.75	119.60																
3/18/05 8:35	49	236.2	237.07	238.6	241.67	284.79	245.78	243.51	189.30	56.66	51.56	53.45	157.63	169.17	91.67																
3/18/05 9:35	51	236.7	236.95	238.5	241.69	284.56	245.93	243.48	190.79	57.94	52.07	54.32	157.77	170.50	95.89																
3/18/05 16:00	52	237.5	237.96	239.1	242.14	286.76	246.88	243.89	201.40	68.77	51.93	54.81	157.71	183.86	111.93																
3/18/05 17:00	53	237.8	237.78	239.0	242.21	285.22	246.81	243.97	201.35	64.74	51.66	55.21	157.70	184.54	114.30																
3/18/05 17:30	54	237.8	238.32	239.2	242.26	284.54	246.83	244.01	200.42	71.06	51.19	54.99	157.66	195.46	113.34																
3/18/05 18:30	55	237.6	237.36	238.7	242.14	278.94	246.45	244.08	204.74	58.74	50.77	53.85	157.71	194.72	118.50																
3/22/05 1:15	56	171.5	170.85	176.3	235.25	273.61	243.94	236.42	139.34	55.81	51.60	51.58	159.82	162.40	216.45																
3/22/05 2:15	57	171.2	170.06	173.2	234.78	272.73	243.83	235.92	137.78	55.95	52.31	51.63	159.63	161.88	212.96																
3/22/05 6:30	58	172.3	171.12	173.4	232.97	282.15	243.84	233.13	134.82	56.97	53.94	54.21	159.93	161.33	188.25																
3/22/05 10:10	59	173.4	172.31	174.7	232.71	281.32	243.67	233.32	137.60	58.21	54.39	54.29	159.88	163.25	178.68																
3/22/05 11:30	60	172.6	171.44	172.9	230.73	281.26	243.59	231.18	135.91	58.14	54.52	53.84	159.80	161.36	186.03																
3/23/05 17:00	61	207.3	208.24	221.4	239.12	260.66	243.15	240.64	168.08	54.70	48.84	48.91	157.82	194.14	204.03																
3/23/05 18:00	62	202.9	203.05	217.3	238.80	260.43	243.14	240.27	165.51	53.87	48.35	48.39	157.48	193.29	205.34																
3/23/05 20:55	63	206.6	207.48	214.3	238.95	259.66	243.07	240.78	171.37	52.07	47.46	47.50	157.64	208.06	199.15																
3/23/05 21:55	64	203.4	204.34	207.6	238.45	259.49	242.79	240.56	169.74	51.89	47.34	47.37	157.63	207.96	192.10																
3/24/05 3:00	65	204.0	206.08	203.7	238.51	258.74	242.62	240.62	165.39	50.58	46.79	46.74	157.32	205.80	215.21																
3/24/05 4:15	66	205.7	207.64	205.8	238.78	259.13	242.90	241.00	166.16	50.84	47.19	47.24	157.50	206.44	209.33																
3/24/05 7:45	67	192.8	194.38	222.6	239.13	264.62	244.31	240.58	146.00	53.30	49.46	48.48	157.58	172.31	216.00																
Column Changeout		Column Changeout																				Column Changeout									
4/6/05 16:20	68	200.0	203.22	211.4	239.14	279.53	242.51	239.12	138.15	62.29	58.33	58.32	170.78	155.97	150.24																
4/6/05 17:30	69	205.3	210.08	225.2	239.22	279.87	242.64	239.52	138.19	61.80	57.74	57.69	170.69	154.40	144.79																
4/7/05 1:00	70	209.1	214.08	218.9	237.20	282.28	247.63	238.62	143.21	58.40	54.87	54.86	170.76	163.23	170.37																
4/7/05 2:05	71	206.1	212.14	217.2	237.74	282.74	247.86	238.82	141.89	58.36	55.08	54.90	170.76	162.16	174.61																
4/7/05 5:30	72	210.3	216.19	218.9	236.54	275.19	249.97	237.39	140.98	55.44	51.77	51.76	170.55	168.07	162.78																
4/7/05 6:30	73	215.5	220.69	222.7	238.23	275.66	249.94	237.71	140.64	55.04	51.37	51.58	170.36	168.18	167.87																
4/7/05 10:45	74	196.2	196.69	209.5	234.00	276.04	257.07	236.68	157.74	55.17	50.08	50.36	170.31	185.50	198.53																
4/7/05 11:45	76	195.8	195.25	205.6	233.21	280.53	261.25	236.36	160.22	55.44	50.02	50.20	170.25	186.09	203.28																
4/7/05 17:00	75	188.9	187.95	183.7	232.51	293.69	276.15	235.03	156.15	56.02	49.99	50.33	170.11	182.99	209.38																
4/7/05 18:00	77	189.2	188.72	189.4	231.21	294.48	276.40	235.26	156.93	55.95	49.91	50.39	170.27	183.92	213.38																
4/8/05 2:05	78	199.1	199.11	211.4	232.61	270.05	252.58	236.90	159.55	54.30	49.71	50.32	167.66	183.32	213.10																
4/8/05 3:10	79	196.0	196.08	202.9	232.79	274.55	255.99	236.44	160.98	53.67	49.16	49.78	167.29	184.56	219.39																
4/8/05 11:00	81	189.6	189.40	190.4	224.50	275.50	275.50	235.90	161.50	55.50	50.30	50.70	168.20	178.60	231.20																
4/8/05 12:00	80	186.5	185.70	187.1	219.40	272.90	272.90	235.40	159.50	55.50	50.10	50.60	167.70	175.50	215.90																
4/11/05 11:30	82	233.7	234.58	235.8	241.02	300.33	246.66	241.90	177.57	59.13	54.36	54.99	198.92	165.03	100.18																
4/11/05 12:30	83	233.2	234.14	235.2	240.84	300.05	247.39	241.81	174.12	59.01	54.07	55.90	198.24	165.14	102.67																
4/11/05 14:30	84	231.0	232.59	233.4	240.05	282.91	244.25	241.06	173.05	58.07	52.39	53.66	167.43	172.26	130.80																
4/11/05 15:30	85	232.6	233.30	233.9	239.83	281.36	244.01	241.11	177.29	57.42	51.48	52.99	170.24	173.02	135.92																
4/12/05 1:30	86	225.1	226.47	232.0	241.03	265.23	243.93	241.07	160.26	53.87	49.70	50.00	198.31	174.97	206.87																
4/12/05 2:30	87	225.7	226.08	232.3	240.91	265.69	243.84	241.07	163.04	53.79	49.82	50.41	198.36	175.26	211.66																
4/13/05 10:00	88	196.1	196.65	197.6	200.39	284.39	207.69	201.93	176.02	100.83	55.35	66.47	167.64	174.97	112.58																
4/13/05 11:00	89	196.4	196.64	197.6	200.41	276.72	207.59	201.88	177.03	100.32	55.77	66.78	170.83	175.01	114.76																

Date/Time		Steam Pressure		Steam Flow	Steam Temp	Heat Balance	ABS Press	Pre-Heat	Steam	Annubar	Pres	Pre-Heat	Sim	Pre-Ht Duty	Pre-Ht Cnd Temp	ABS Lean Temp	ABS Rich Temp
		PT202	(psia)	(lb/hr)	(F)	HB202	inH2O	FC210	TIME	(psia)	(lb/hr)	FT210	MMBTU/hr	(F)	FT210	Ttcon	A403_T
Sample						%		%								(F)	(F)
3/15/05 20:10	44	131.63	529.05	347.53	36.76	5.95	55.00	131.63	269.00	0.3293	104.93			104.93	104.93	122.34	
3/15/05 21:10	45	132.51	530.05	348.12	37.33	5.77	55.00	132.51	263.13	0.3246	105.01			105.01	105.01	123.24	
3/16/05 2:15	46	132.12	399.98	347.72	29.93	6.02	#DIV/0!	132.12	196.89	0.2658	105.02			105.02	105.02	113.83	
3/16/05 3:15	47	132.48	450.04	348.08	32.78	5.96	13.49	132.48	187.74	0.2559	105.21			105.21	105.21	114.83	
3/16/05 10:15	50	124.91	856.12	342.96	41.49	0.31	100.00	124.91	345.04	0.3825	104.77			104.77	104.77	128.14	
3/16/05 11:15	48	124.53	839.90	343.16	38.02	0.04	100.00	124.53	343.48	0.3769	105.23			105.23	105.23	130.63	
3/18/05 8:35	49	122.87	1200.01	342.08	50.94	13.23	100.00	122.87	349.34	0.3798	103.44			103.44	103.44	103.80	
3/18/05 9:35	51	122.82	1184.76	342.28	50.46	12.77	100.00	122.82	345.06	0.3777	103.03			103.03	103.03	104.64	
3/18/05 16:00	52	122.35	1105.68	342.41	48.66	11.46	100.00	122.35	330.24	0.3698	103.97			103.97	103.97	97.90	
3/18/05 17:00	53	123.02	1059.72	342.66	48.18	11.63	100.00	123.02	330.10	0.3697	104.69			104.69	104.69	98.29	
3/18/05 17:30	54	123.34	1024.82	342.87	46.71	10.96	100.00	123.34	312.46	0.3596	104.60			104.60	104.60	96.14	
3/18/05 18:30	55	124.28	842.26	343.47	43.33	10.73	100.00	124.28	323.09	0.3657	104.34			104.34	104.34	92.88	
3/22/05 1:15	56	123.19	990.17	342.59	62.23	6.39	100.00	123.19	400.07	0.3979	104.23			104.23	104.23	110.41	
3/22/05 2:15	57	122.97	979.86	342.47	62.90	6.42	100.00	122.97	402.78	0.3988	104.45			104.45	104.45	110.07	
3/22/05 6:30	58	121.45	1319.39	341.04	66.58	5.22	100.00	121.45	457.33	0.4097	104.36			104.36	104.36	121.76	
3/22/05 10:10	59	120.91	1284.39	341.29	68.08	3.16	100.00	120.91	447.77	0.4085	104.71			104.71	104.71	124.43	
3/22/05 11:30	60	121.19	1247.39	341.42	69.24	2.82	100.00	121.19	448.94	0.4087	104.74			104.74	104.74	121.79	
3/23/05 17:00	61	128.53	483.62	346.54	42.89	4.16	100.00	128.53	294.82	0.3467	102.81			102.81	102.81	111.17	
3/23/05 18:00	62	128.66	489.42	346.40	40.50	3.99	100.00	128.66	290.28	0.3435	102.33			102.33	102.33	111.96	
3/23/05 20:55	63	130.51	401.33	347.73	28.14	3.70	100.00	130.51	350.72	0.3790	100.65			100.65	100.65	100.77	
3/23/05 21:55	64	130.39	396.28	347.44	29.22	3.62	100.00	130.39	352.42	0.3783	100.01			100.01	100.01	99.91	
3/24/05 3:00	65	133.28	359.59	349.06	30.61	3.40	100.00	133.28	304.58	0.3520	104.68			104.68	104.68	94.05	
3/24/05 4:15	66	133.39	359.44	349.12	27.34	3.40	100.00	133.39	315.69	0.3587	104.81			104.81	104.81	93.56	
3/24/05 7:45	67	128.88	735.21	345.83	49.25	-2.05	100.00	128.88	347.19	0.3755	105.00			105.00	105.00	104.85	
Column Changeout		Column Changeout													Column Changeout		
4/6/05 16:20	68	116.37	1694.08	337.65	77.29	12.01	100.00	116.37	497.40	0.4095	102.55			102.55	102.55	121.88	
4/6/05 17:30	69	116.02	1691.29	337.41	78.79	11.79	100.00	116.02	505.92	0.4091	102.66			102.66	102.66	120.60	
4/7/05 1:00	70	120.73	1281.21	340.56	72.60	11.87	100.00	120.73	453.76	0.4076	104.33			104.33	104.33	124.55	
4/7/05 2:05	71	120.52	1323.89	340.24	72.35	11.68	100.00	120.52	455.81	0.4078	103.98			103.98	103.98	122.55	
4/7/05 5:30	72	124.00	913.62	342.85	61.23	12.26	100.00	124.00	407.03	0.3984	103.57			103.57	103.57	117.70	
4/7/05 6:30	73	123.85	914.59	342.78	61.39	12.34	100.00	123.85	401.34	0.3967	104.09			104.09	104.09	117.68	
4/7/05 10:45	74	129.52	560.44	346.80	55.18	8.46	100.00	129.52	342.52	0.3733	104.75			104.75	104.75	124.97	
4/7/05 11:45	76	128.91	547.44	346.61	55.80	7.83	100.00	128.91	337.37	0.3705	105.01			105.01	105.01	125.36	
4/7/05 17:00	75	127.54	561.43	345.55	65.79	4.55	100.00	127.54	350.56	0.3765	103.78			103.78	103.78	121.37	
4/7/05 18:00	77	128.24	561.74	345.97	65.88	4.42	100.00	128.24	332.89	0.3681	103.75			103.75	103.75	121.51	
4/8/05 2:05	78	130.44	546.91	346.90	66.56	-4.58	100.00	130.44	350.88	0.3774	103.77			103.77	103.77	123.17	
4/8/05 3:10	79	131.63	554.46	347.66	65.06	2.51	100.00	131.63	328.88	0.3660	103.80			103.80	103.80	124.41	
4/8/05 11:00	81	129.80	613.10	346.60	75.62	11.11	100.00	129.80	390.50	0.3940	104.89			104.89	104.89	121.89	
4/8/05 12:00	80	128.10	689.20	334.70	79.65	-2.18	100.00	128.10	393.50	0.3970	104.28			104.28	104.28	121.55	
4/11/05 11:30	82	116.67	1535.06	338.26	71.88	11.35	100.00	116.67	434.23	0.4044	104.17			104.17	104.17	127.74	
4/11/05 12:30	83	117.03	1513.03	338.49	72.17	11.42	100.00	117.03	432.41	0.4040	104.03			104.03	104.03	126.49	
4/11/05 14:30	84	121.89	1091.09	341.78	64.20	9.16	100.00	121.89	369.96	0.3854	104.26			104.26	104.26	122.97	
4/11/05 15:30	85	121.41	1089.63	341.65	64.44	7.79	100.00	121.41	365.07	0.3833	104.64			104.64	104.64	123.63	
4/12/05 1:30	86	124.59	744.40	343.35	94.03	9.25	100.00	124.59	331.47	0.3715	104.20			104.20	104.20	111.16	
4/12/05 2:30	87	124.36	742.20	343.24	94.25	9.40	100.00	124.36	316.11	0.3628	104.23			104.23	104.23	111.51	
4/13/05 10:00	88	117.22	1684.25	338.34	93.67	10.26	100.00	117.22	303.20	0.3511	104.59			104.59	104.59	131.14	
4/13/05 11:00	89	117.16	1679.68	338.32	89.43	9.62	100.00	117.16	315.60	0.3583	104.74			104.74	104.74	130.30	
4/13/05 14:45	90	127.81	712.09	345.65	95.88	5.71	16.00	127.81	197.12	0.2637	104.31			104.31	104.31	112.99	
4/13/05 15:45	91	127.09	749.45	345.17	94.99	3.97	16.00	127.09	167.59	0.2241	104.39			104.39	104.39	112.20	

Date/Time	Sample	STR Feed		CO2 Flow		FTIR		Ambient Temp (F)
		TT2077 (F)	FT216 (SCFM)	CO2 Conc %	FTIR %	CO2 Conc %	FTIR %	
3/15/05 20:10	44	208.07	17.77					48
3/15/05 21:10	45	208.47	12.73					47
3/16/05 2:15	46	208.62	0.00					45
3/16/05 3:15	47	207.50	0.00					45
3/16/05 10:15	50	200.79	42.14					43
3/16/05 11:15	48	203.63	40.29					46
3/18/05 8:35	49	168.25	49.50					55
3/18/05 9:35	51	169.37	48.12					60
3/18/05 16:00	52	183.65	43.47					76
3/18/05 17:00	53	184.00	42.91					75
3/18/05 17:30	54	193.68	40.30					74
3/18/05 18:30	55	193.51	41.96					71
3/22/05 1:15	56	162.24	41.30					62
3/22/05 2:15	57	161.51	39.81					62
3/22/05 6:30	58	161.15	47.65					55
3/22/05 10:10	59	163.28	46.14					64
3/22/05 11:30	60	161.50	39.83					70
3/23/05 17:00	61	193.29	24.36					71
3/23/05 18:00	62	192.45	25.39					69
3/23/05 20:55	63	206.62	24.50					67
3/23/05 21:55	64	206.73	23.90					64
3/24/05 3:00	65	204.31	22.76					55
3/24/05 4:15	66	204.92	22.42					55
3/24/05 7:45	67	171.82	35.13					58
Column Changeout								
4/6/05 16:20	68	156.26	48.61	1.18				76
4/6/05 17:30	69	154.54	45.21	0.918				76
4/7/05 1:00	70	163.17	44.84	1.80				60
4/7/05 2:05	71	161.67	46.14	1.74				60
4/7/05 5:30	72	168.18	37.81	3.14				58
4/7/05 6:30	73	167.80	38.96	3.44				58
4/7/05 10:45	74	184.90	20.66	0.852				73
4/7/05 11:45	76	185.83	20.49	0.974				76
4/7/05 17:00	75	183.13	20.10	2.44				79
4/7/05 18:00	77	183.43	21.21	2.66				78
4/8/05 2:05	78	183.46	20.70	0.726				60
4/8/05 3:10	79	184.39	23.33	0.968				59
4/8/05 11:00	81	178.60	18.15	1.04				74
4/8/05 12:00	80	175.30	20.75	1.13				76
4/11/05 11:30	82	165.14	48.39	0.980				74
4/11/05 12:30	83	165.03	48.40	1.120				75
4/11/05 14:30	84	172.02	43.36	1.64				77
4/11/05 15:30	85	173.15	43.53	1.58				78
4/12/05 1:30	86	175.48	41.03	3.20				55
4/12/05 2:30	87	175.24	40.40	2.90				56
4/13/05 10:00	88	175.43	41.10	0.454				75
4/13/05 11:00	89	175.02	38.83	0.726				81
4/13/05 14:45	90	183.17	27.76	2.74				85
4/13/05 15:45	91	181.23	30.42	2.60				84

Table A2. Mass Balance - CO₂ Capacity for Three Calculation Methods

Sample	Abs Liquid Capacity (g CO ₂ /min)	Stripper CO ₂ flow (g CO ₂ /min)	Abs Gas Capacity (g CO ₂ /min)
44	1041	937	1663
45	996	671	1552
46	870	0	1608
47	810	0	1494
50	2240	2222	2017
48	2236	2124	1777
49	2619	2610	2991
51	2671	2537	3042
52	2399	2292	2709
53	2430	2262	2706
54	2074	2125	2376
55	2096	2212	2320
56	2222	2177	1821
57	2169	2099	1716
58	2360	2512	2151
59	2406	2433	2497
60	2006	2100	2203
61	1495	1284	1256
62	1378	1339	1196
63	1403	1292	1122
64	1268	1260	1108
65	1141	1200	883
66	1186	1182	940
67	1726	1852	1702
Column Changout			
68	2569	2563	2374
69	2439	2383	2170
70	2379	2364	2177
71	2371	2432	2128
72	1987	1993	1709
73	2075	2054	1776
74	1279	1089	1212
76	1303	1080	1210
75	1268	1060	1023
77	1276	1118	1042
78	1254	1092	1118
79	1321	1230	1207
81	1366	957	1191
80	1455	1094	1084
82	2634	2551	2334
83	2691	2552	2395
84	2514	2286	2183
85	2480	2295	2160
86	2203	2163	1754
87	2191	2130	1759
88	1964	2167	1817
89	1871	2047	1770
90	1599	1464	1376
91	1585	1604	1295

Table A3. Heat Balance Comparison of Predicted and Measured Reboiler Duties

Sample	Enthalpy CO2 (BTU/min)	Enthalpy Feed (BTU/min)	Enthalpy Lean (BTU/min)	Cooling Water (BTU/min)	Heat Loss from Stripper (BTU/min)	Heat of CO2 Desorption (BTU/min)	Predicted Reboiler Duty (BTU/min)	Actual Reboiler Duty (BTU/min)
44	-81	-644	647	3160	2150	2065	8585	8538
45	-77	-637	636	3212	2161	1976	8544	8554
46	-68	-439	443	2204	2186	1727	6929	6471
47	-63	-457	454	3022	2186	1606	7662	7281
50	-168	-1192	1198	4283	2206	4426	13138	13674
48	-165	-1118	1103	4377	2173	4326	12932	13418
49	-174	-2659	2691	4415	2075	5187	16854	18836
51	-172	-2627	2652	4691	2020	5167	16985	18623
52	-151	-1633	1660	5960	1851	4654	15606	17325
53	-156	-1624	1640	5667	1863	4655	15294	16646
54	-138	-1169	1181	6637	1874	4166	14889	16101
55	-154	-1152	1189	4506	1908	4274	12875	13327
56	-141	-3988	4005	606	1922	4364	14745	15742
57	-136	-4007	4018	623	1917	4235	14664	15598
58	-152	-5558	5584	648	1962	4833	18433	20759
59	-151	-5397	5364	746	1867	4800	18023	20227
60	-126	-5331	5341	568	1779	4073	16965	19648
61	-100	-1282	1287	839	1870	2757	7935	7814
62	-98	-1294	1303	783	1888	2695	7865	7908
63	-103	-766	752	1020	1915	2673	7023	6498
64	-97	-720	740	1002	1945	2509	6820	6415
65	-90	-685	699	894	2043	2322	6553	5832
66	-91	-682	690	856	2047	2349	6534	5830
67	-122	-2428	2442	662	2010	3550	10972	11825
Column Changout				Column Changout				
68	-155	-8354	8384	597	1800	5091	24070	26691
69	-145	-8575	8615	531	1804	4785	24164	26643
70	-150	-5967	6012	819	1968	4706	19321	20166
71	-152	-6131	6152	755	1970	4766	19623	20808
72	-131	-3639	3670	659	1976	3949	13762	14499
73	-136	-3678	3679	656	1979	4096	13952	14498
74	-82	-2002	2020	781	1806	2349	8876	8908
76	-83	-1950	1974	574	1770	2364	8550	8659
75	-79	-2099	2126	670	1723	2310	8849	8745
77	-82	-2097	2126	468	1736	2375	8721	8748
78	-81	-2176	2207	682	1949	2327	9260	8745
79	-89	-2129	2150	699	1955	2531	9376	8826
81	-78	-2724	2742	55	1786	2304	9532	9417
80	-85	-3120	3141	983	1759	2529	11449	11183
82	-167	-6167	6194	2486	1851	5144	21675	23642
83	-169	-6153	6180	2216	1840	5201	21421	23304
84	-159	-3745	3756	1914	1810	4762	15828	17169
85	-159	-3672	3704	2165	1800	4737	15918	17165
86	-150	-2420	2420	1089	2048	4332	12159	11949
87	-149	-2419	2431	1171	2037	4287	12197	11910
88	-81	-1538	1550	16026	1408	4098	24538	26398
89	-77	-1557	1563	16490	1342	3886	24761	26522
90	-79	-460	467	7033	1275	3038	12194	11655
91	-81	-521	512	7932	1287	3164	13334	12238

Table A4. Mass Transfer Parameters for the Absorber

Sample	Avg CO2 Flow (g CO2/min)	Sat Vaisala CO2 Out (Vapor Frac)	Equilibrium CO2 at top (Vapor Frac)	Sat Vaisala CO2 In (Vapor Frac)	Equilibrium CO2 at bottom (Vapor Frac)	Δy top	Δy bottom	Δy log mean	Driving Factor top	Driving Factor bottom	K_{Ga} (lbmole/ft ² h)
44	1041	0.00082	0.00001	0.11452	0.01503	0.00080	0.09949	0.02048	56	7.6	4.05
45	996	0.00068	0.00001	0.10693	0.01054	0.00066	0.09640	0.019226	52	10.1	4.13
46	870	0.00082	0.00001	0.11609	0.02504	0.00081	0.09105	0.019128	96	4.6	3.62
47	810	0.00058	0.00001	0.10728	0.01313	0.00058	0.09415	0.018355	67	8.2	3.51
50	2231	0.06041	0.00046	0.14261	0.24260	0.05996	-0.09999		133	0.6	error
48	2180	0.05744	0.00046	0.12998	0.24548	0.05697	-0.11549		124	0.5	error
49	2614	0.00651	0.00024	0.11810	0.04996	0.00627	0.06813	0.025938	28	2.4	8.03
51	2604	0.00499	0.00020	0.11944	0.05028	0.00479	0.06916	0.024115	25	2.4	8.60
52	2345	0.01631	0.00029	0.12310	0.07318	0.01602	0.04991	0.029823	56	1.7	6.26
53	2346	0.01682	0.00030	0.12449	0.07546	0.01653	0.04903	0.02989	57	1.6	6.25
54	2099	0.02899	0.00031	0.12553	0.06564	0.02868	0.05989	0.042388	94	1.9	3.95
55	2154	0.03208	0.00027	0.12577	0.06999	0.03181	0.05578	0.042677	118	1.8	4.02
56	2200	0.05100	0.00076	0.12183	0.07739	0.05024	0.04444	0.047278	67	1.6	3.71
57	2134	0.05285	0.00075	0.11911	0.07740	0.05209	0.04171	0.04671	70	1.5	3.64
58	2436	0.02199	0.00063	0.11455	0.09202	0.02135	0.02252	0.021933	35	1.2	8.85
59	2419	0.00912	0.00067	0.12929	0.11368	0.00845	0.01561	0.011665	14	1.1	16.52
60	2053	0.00848	0.00095	0.11728	0.08651	0.00753	0.03077	0.016513	9	1.4	9.90
61	1389	0.00755	0.00022	0.12006	0.07674	0.00733	0.04332	0.02026	35	1.6	5.46
62	1358	0.00657	0.00016	0.11295	0.06284	0.00641	0.05011	0.021254	41	1.8	5.09
63	1347	0.01764	0.00034	0.11810	0.09381	0.01730	0.02429	0.0206	52	1.3	5.21
64	1264	0.01951	0.00033	0.11794	0.09397	0.01918	0.02397	0.021489	60	1.3	4.69
65	1170	0.03891	0.00064	0.11744	0.08903	0.03827	0.02841	0.033096	60	1.3	2.82
66	1184	0.03966	0.00063	0.12334	0.09130	0.03903	0.03204	0.03542	63	1.4	2.66
67	1789	0.01100	0.00041	0.10474	0.06333	0.01059	0.04141	0.022607	27	1.7	6.30
Column Changeout											
68	2566	0.00961	0.00024	0.11796	0.00610	0.00937	0.11185	0.041329	41	19.3	4.95
69	2411	0.00858	0.00022	0.10863	0.00448	0.00836	0.10414	0.037969	38	24.2	5.06
70	2372	0.01768	0.00021	0.11352	0.01313	0.01747	0.10038	0.047422	86	8.6	3.98
71	2402	0.01776	0.00021	0.11029	0.01203	0.01755	0.09826	0.046855	86	9.2	4.08
72	1990	0.03614	0.00033	0.11090	0.02233	0.03580	0.08858	0.058262	108	5.0	2.72
73	2065	0.04013	0.00039	0.11788	0.02585	0.03974	0.09204	0.062268	103	4.6	2.64
74	1184	0.00649	0.00013	0.11463	0.01762	0.00636	0.09701	0.033275	50	6.5	2.83
76	1192	0.00837	0.00014	0.11620	0.01818	0.00823	0.09801	0.036236	59	6.4	2.62
75	1164	0.02777	0.00023	0.11976	0.01314	0.02754	0.10662	0.058419	120	9.1	1.59
77	1197	0.02745	0.00023	0.12076	0.01229	0.02722	0.10847	0.058773	120	9.8	1.62
78	1173	0.00498	0.00014	0.10734	0.01306	0.00484	0.09428	0.030123	37	8.2	3.10
79	1276	0.00733	0.00015	0.11448	0.01745	0.00718	0.09703	0.034507	49	6.6	2.95
81	1161	0.00531	0.00020	0.11757	0.00949	0.00511	0.10808	0.033743	26	12.4	2.74
80	1275	0.00568	0.00019	0.10763	0.00856	0.00548	0.09907	0.032337	30	12.6	3.14
82	2592	0.00790	0.00009	0.11141	0.00557	0.00781	0.10584	0.037611	89	20.0	5.49
83	2621	0.00873	0.00009	0.11525	0.00618	0.00864	0.10907	0.039602	93	18.6	5.27
84	2400	0.01737	0.00029	0.11564	0.01939	0.01708	0.09625	0.045791	60	6.0	4.18
85	2387	0.01634	0.00033	0.11438	0.01817	0.01602	0.09620	0.044725	50	6.3	4.25
86	2183	0.03501	0.00078	0.12007	0.04868	0.03422	0.07139	0.050548	45	2.5	3.44
87	2160	0.03359	0.00086	0.11844	0.05088	0.03273	0.06756	0.048062	39	2.3	3.58
88	2065	0.00667	0.00021	0.11345	0.03225	0.00647	0.08120	0.029538	32	3.5	5.57
89	1959	0.00520	0.00022	0.11021	0.02634	0.00499	0.08387	0.027952	24	4.2	5.58
90	1531	0.03961	0.00179	0.13118	0.12482	0.03782	0.00636	0.017642	22	1.1	6.91
91	1594	0.03858	0.00172	0.12446	0.11645	0.03686	0.00801	0.018898	22	1.1	6.72

Table A5. Pressure Drop Data for the Absorber

Sample	Absorber Packing	ABS LEAN FLOW FT403 (GPM)	GAS Flow FT900 (ACFM)	Pressure Drp PDT450 (in H2O)	Pressure Drp PDT451 (in H2O)	Absorber Loadings Lean (mol/mol)	Rich (mol/mol)	Bed Temp TT4076 (F)	bottom bed $\Delta P/G^2$ (inH2O)/(ACFM) ² (*10 ⁻⁶)	top bed $\Delta P/G^2$ (inH2O)/(ACFM) ² (*10 ⁻⁶)
44	Flexipac 1Y	4.99	250	0.31	0.32	0.19	0.46	173.2	5.0	5.2
45	Flexipac 1Y	4.92	250	0.30	0.29	0.19	0.44	170.8	4.8	4.7
46	Flexipac 1Y	3.47	250	0.21	0.26	0.17	0.49	168.0	3.4	4.1
47	Flexipac 1Y	3.49	249	0.21	0.25	0.17	0.47	165.6	3.4	4.0
50	Flexipac 1Y	7.80	500	2.05	2.43	0.19	0.57	142.4	8.2	9.7
48	Flexipac 1Y	7.76	500	1.94	2.32	0.20	0.57	145.9	7.8	9.3
49	Flexipac 1Y	9.99	500	2.25	2.66	0.19	0.54	165.8	9.0	10.6
51	Flexipac 1Y	9.95	500	2.21	2.59	0.18	0.53	167.6	8.9	10.4
52	Flexipac 1Y	7.80	500	1.67	2.10	0.16	0.58	149.2	6.7	8.4
53	Flexipac 1Y	7.73	500	1.71	2.15	0.16	0.58	148.9	6.8	8.6
54	Flexipac 1Y	6.87	501	1.60	2.00	0.16	0.58	139.4	6.4	8.0
55	Flexipac 1Y	6.80	500	1.59	1.96	0.15	0.59	136.0	6.4	7.9
56	Flexipac 1Y	15.00	450	3.79	5.83	0.35	0.55	157.4	18.8	28.8
57	Flexipac 1Y	15.03	450	3.83	5.96	0.36	0.55	156.5	18.9	29.4
58	Flexipac 1Y	21.19	389	5.58	5.55	0.39	0.53	120.5	36.8	36.6
59	Flexipac 1Y	21.26	360	4.18	16.49	0.39	0.54	110.6	32.3	
60	Flexipac 1Y	21.24	351	3.81	11.10	0.40	0.53	107.7	31.0	
61	Flexipac 1Y	7.51	200	0.64	0.76	0.29	0.55	170.7	15.9	19.1
62	Flexipac 1Y	7.50	200	0.64	0.67	0.30	0.54	170.8	16.0	16.9
63	Flexipac 1Y	6.12	200	0.52	0.17	0.29	0.58	158.0	13.1	4.3
64	Flexipac 1Y	6.07	200	0.51	-0.01	0.30	0.59	155.6	12.8	
65	Flexipac 1Y	5.39	200	0.47	-0.83	0.31	0.60	143.9	11.8	
66	Flexipac 1Y	5.39	200	0.47	-0.83	0.30	0.60	142.9	11.8	
67	Flexipac 1Y	10.43	317	1.54	12.42	0.30	0.55	166.2	15.3	
		Column Changeout		Column Changeout				Column Changeout		
68	IMTP-40	27.54	400	2.49	1.10	0.30	0.42	110.7	15.6	6.9
69	IMTP-40	27.44	400	2.65	1.18	0.30	0.41	109.3	16.5	7.4
70	IMTP-40	21.73	400	2.96	0.84	0.31	0.45	118.0	18.5	5.2
71	IMTP-40	21.64	400	2.84	0.79	0.31	0.45	117.1	17.8	4.9
72	IMTP-40	14.51	400	2.56	1.95	0.31	0.49	154.3	16.0	12.1
73	IMTP-40	14.50	400	2.53	2.03	0.31	0.49	156.0	15.9	12.7
74	IMTP-40	10.72	201	0.45	0.27	0.30	0.46	118.1	11.2	6.7
76	IMTP-40	10.76	200	0.44	0.25	0.30	0.46	122.5	11.1	6.3
75	IMTP-40	11.28	200	0.58	0.37	0.31	0.46	132.7	14.4	9.2
77	IMTP-40	11.23	200	0.58	0.37	0.31	0.45	132.4	14.5	9.1
78	IMTP-40	11.30	203	0.47	0.30	0.30	0.45	112.8	11.6	7.3
79	IMTP-40	11.31	206	0.48	0.32	0.31	0.46	117.5	11.4	7.6
81	IMTP-40	13.00	200	0.34	-0.09	0.31	0.44	117.2	8.5	
80	IMTP-40	14.30	200	0.47	0.28	0.30	0.44	114.9	11.8	7.0
82	IMTP-40	21.99	401	2.46	1.18	0.25	0.40	113.4	15.3	7.4
83	IMTP-40	21.94	400	2.54	1.08	0.25	0.40	114.3	15.9	6.7
84	IMTP-40	14.98	400	2.49	2.00	0.25	0.47	165.7	15.6	12.5
85	IMTP-40	15.02	399	2.50	2.06	0.25	0.47	166.4	15.7	13.0
86	IMTP-40	10.39	400	2.12	2.08	0.25	0.53	156.0	13.3	13.0
87	IMTP-40	10.42	400	2.13	2.07	0.25	0.53	156.8	13.3	12.9
88	IMTP-40	16.10	301	1.27	0.69	0.31	0.47	117.2	14.1	7.6
89	IMTP-40	16.02	300	1.13	0.64	0.31	0.46	115.2	12.6	7.1
90	IMTP-40	7.96	300	1.02	1.01	0.30	0.58	154.9	11.4	11.2
91	IMTP-40	7.96	300	1.06	1.05	0.31	0.58	153.7	11.8	11.7

Figure A1. Computer Schematic of Stripper Area

Figure A2. Computer Schematic of Gas Area

Figure A3. Computer Schematic of Absorber Area

Appendix B

Table B1. Tabulated Values for Sample Times, Temperatures, and Absorber Lean Loadings for Campaign 3 FTIR Analysis

Date	Time	Adjusted Time (min)	Adjusted Time (hr)	Temperature TT4078 (F)	Lean Loading
4/6/2005	4:20:00 PM	0	0.000	100.838	0.302
4/6/2005	5:30:00 PM	70	1.167	100.747	0.298
4/7/2005	1:00:00 AM	520	8.667	96.941	0.308
4/7/2005	2:05:00 AM	585	9.750	96.320	0.311
4/7/2005	5:30:00 AM	790	13.167	105.253	0.309
4/7/2005	6:30:00 AM	850	14.167	108.404	0.307
4/7/2005	10:45:00 AM	1105	18.417	89.720	0.304
4/7/2005	11:45:00 AM	1165	19.417	91.781	0.302
4/7/2005	5:00:00 PM	1480	24.667	98.886	0.307
4/7/2005	6:00:00 PM	1540	25.667	99.055	0.305
4/8/2005	2:05:00 AM	2025	33.750	90.291	0.303
4/8/2005	3:10:00 AM	2090	34.833	91.107	0.308
4/8/2005	11:00:00 AM	2560	42.667	97.100	0.305
4/8/2005	12:00:00 PM	2620	43.667	96.000	0.304
4/11/2005	11:30:00 AM	6950	115.833	95.829	0.247
4/11/2005	12:30:00 PM	6910	115.167	96.565	0.248
4/11/2005	2:30:00 PM	7030	117.167	115.379	0.254
4/11/2005	3:30:00 PM	7090	118.167	118.091	0.252
4/12/2005	1:30:00 AM	7690	128.167	134.959	0.250
4/12/2005	2:30:00 AM	7750	129.167	136.653	0.250
4/13/2005	10:00:00 AM	9640	160.667	96.597	0.309
4/13/2005	11:00:00 AM	9700	161.667	97.253	0.310
4/13/2005	2:45:00 PM	9925	165.417	136.730	0.305
4/13/2005	3:45:00 PM	9985	166.417	134.813	0.309

Table B2. Measured CO₂ Concentrations at the Top of the Absorber Column for FTIR and Vaisola AI404 Analyzers

Date	Time	Adjusted Time (min)	Adjusted Time (hr)	Vaisola AI404 Analyzer (vol% CO ₂)	FTIR 1	FTIR 2	FTIR 3	FTIR 4	FTIR 5	FTIR AVG (vol %)
4/6/2005	4:20:00 PM	0	0.000	0.973	1.3	1.2	1.2	0.88	1.3	1.176
4/6/2005	5:30:00 PM	70	1.167	0.869	0.93	0.76	0.8	1	1.1	0.918
4/7/2005	1:00:00 AM	520	8.667	1.790	1.5	1.9	1.4	2	2.2	1.8
4/7/2005	2:05:00 AM	585	9.750	1.794	1.6	1.8	1.9	1.9	1.5	1.74
4/7/2005	5:30:00 AM	790	13.167	3.657	3.2	2.9	3.1	3.2	3.3	3.14
4/7/2005	6:30:00 AM	850	14.167	4.069	3.3	3.5	3.4	3.3	3.7	3.44
4/7/2005	10:45:00 AM	1105	18.417	0.649	0.84	0.83	0.82	0.84	0.93	0.852
4/7/2005	11:45:00 AM	1165	19.417	0.835	1	1	1	0.98	0.89	0.974
4/7/2005	5:00:00 PM	1480	24.667	2.762	2.5	2.4	2.4	2.5	2.4	2.44
4/7/2005	6:00:00 PM	1540	25.667	2.733	2.7	2.7	2.6	2.6	2.7	2.66
4/8/2005	2:05:00 AM	2025	33.750	0.485	0.69	0.69	0.72	0.75	0.78	0.726
4/8/2005	3:10:00 AM	2090	34.833	0.726	0.84	0.79	0.81	1.3	1.1	0.968
4/8/2005	11:00:00 AM	2560	42.667	0.536	1.2	1.1	1.1	0.88	0.9	1.036
4/8/2005	12:00:00 PM	2620	43.667	0.555	1.5	1.3	1	1	0.84	1.128
4/11/2005	11:30:00 AM	6950	115.833	0.795	0.97	0.95	1.1	0.96	0.92	0.98
4/11/2005	12:30:00 PM	6910	115.167	0.878	1.1	1.2	1.1	1.1	1.1	1.12
4/11/2005	2:30:00 PM	7030	117.167	1.757	1.6	1.6	1.7	1.6	1.7	1.64
4/11/2005	3:30:00 PM	7090	118.167	1.655	1.6	1.5	1.6	1.6	1.6	1.58
4/12/2005	1:30:00 AM	7690	128.167	3.716	3.2	3.1	3.3	3.2	3.2	3.2
4/12/2005	2:30:00 AM	7750	129.167	3.588	3.5	2.9	3	2.5	2.6	2.9
4/13/2005	10:00:00 AM	9640	160.667	0.668	0.55	0.18	0.56	0.3	0.68	0.454
4/13/2005	11:00:00 AM	9700	161.667	0.520	0.92	0.61	0.94	0.83	0.33	0.726
4/13/2005	2:45:00 PM	9925	165.417	4.225	2.8	2.9	2.7	2.6	2.7	2.74
4/13/2005	3:45:00 PM	9985	166.417	4.071	2.4	2.8	2.8	2.5	2.5	2.6

**Table B3. Measured H₂O Concentrations at the Top of the Absorber Column
for FTIR Analysis**

Date	Time	Adjusted Time (min)	Adjusted Time (hr)	FTIR 1	FTIR 2	FTIR 3	FTIR 4	FTIR 5	FTIR AVG (vol %)
4/6/2005	4:20:00 PM	0	0.000	4.4	4.3	4.2	4.5	4.6	4.4
4/6/2005	5:30:00 PM	70	1.167	4.4	4.4	4.4	4.3	4.4	4.38
4/7/2005	1:00:00 AM	520	8.667	3.3	3	3.1	2.7	3	3.02
4/7/2005	2:05:00 AM	585	9.750	3.5	3.5	3.3	3	3.5	3.36
4/7/2005	5:30:00 AM	790	13.167	5.7	5.7	5.4	5.6	5.4	5.56
4/7/2005	6:30:00 AM	850	14.167	6	6.1	6.3	6.1	6.2	6.14
4/7/2005	10:45:00 AM	1105	18.417	3.8	4.3	4.2	4.3	4	4.12
4/7/2005	11:45:00 AM	1165	19.417	4.4	4.3	4.5	4.4	4.4	4.4
4/7/2005	5:00:00 PM	1480	24.667	4.3	4.2	4.3	4.4	4.5	4.34
4/7/2005	6:00:00 PM	1540	25.667	4.3	4.4	4.5	4.5	4.4	4.42
4/8/2005	2:05:00 AM	2025	33.750	3.8	3.9	3.9	3.7	3.8	3.82
4/8/2005	3:10:00 AM	2090	34.833	3.7	3.7	3.6	4	4	3.8
4/8/2005	11:00:00 AM	2560	42.667	4.7	4.7	5	4.4	4.5	4.66
4/8/2005	12:00:00 PM	2620	43.667	4.5	4.7	4.4	4.3	4.4	4.46
4/11/2005	11:30:00 AM	6950	115.833	3.6	3.4	3.5	3.2	3.7	3.48
4/11/2005	12:30:00 PM	6910	115.167	3.6	4	3.7	4.2	4	3.9
4/11/2005	2:30:00 PM	7030	117.167	7.3	7.5	7.7	7.3	7.8	7.52
4/11/2005	3:30:00 PM	7090	118.167	8.1	8.1	7.8	8.1	8.1	8.04
4/12/2005	1:30:00 AM	7690	128.167	11.1	12.5	11.5	11.5	11.4	11.6
4/12/2005	2:30:00 AM	7750	129.167	8.7	8.6	9.4	9.4	9.9	9.2
4/13/2005	10:00:00 AM	9640	160.667	0	0	0	0	0	0
4/13/2005	11:00:00 AM	9700	161.667	3.5	3.9	4.2	4.3	4.4	4.06
4/13/2005	2:45:00 PM	9925	165.417	13.4	13	13.1	13	12.6	13.02
4/13/2005	3:45:00 PM	9985	166.417	12.4	12.6	12.6	12.2	12.5	12.46

**Table B4. Measured NH₃ Concentrations at the Top of the Absorber Column
from FTIR Analysis**

Date	Time	Adjusted Time (min)	Adjusted Time (hr)	FTIR 1	FTIR 2	FTIR 3	FTIR 4	FTIR 5	FTIR AVG (ppm)
4/6/2005	4:20:00 PM	0	0.000	280	278	272	272	283	277
4/6/2005	5:30:00 PM	70	1.167	382	396	405	396	400	395.8
4/7/2005	1:00:00 AM	520	8.667	634	527	517	616	520	562.8
4/7/2005	2:05:00 AM	585	9.750	718	607	678	673	713	677.8
4/7/2005	5:30:00 AM	790	13.167	1294	1305	1273	1294	1276	1288.4
4/7/2005	6:30:00 AM	850	14.167	1328	1368	1345	1361	1356	1351.6
4/7/2005	10:45:00 AM	1105	18.417	861	937	937	941	932	921.6
4/7/2005	11:45:00 AM	1165	19.417	931	931	963	961	955	948.2
4/7/2005	5:00:00 PM	1480	24.667	849	847	864	841	860	852.2
4/7/2005	6:00:00 PM	1540	25.667	873	922	852	857	839	868.6
4/8/2005	2:05:00 AM	2025	33.750	1037	1037	1032	1013	1018	1027.4
4/8/2005	3:10:00 AM	2090	34.833	988	987	969	995	1004	988.6
4/8/2005	11:00:00 AM	2560	42.667	974	971	985	975	973	975.6
4/8/2005	12:00:00 PM	2620	43.667	962	977	961	967	981	969.6
4/11/2005	11:30:00 AM	6950	115.833	72	69	70	71	71	70.6
4/11/2005	12:30:00 PM	6910	115.167	102	105	107	118	110	108.4
4/11/2005	2:30:00 PM	7030	117.167	451	461	458	463	473	461.2
4/11/2005	3:30:00 PM	7090	118.167	469	469	466	465	471	468
4/12/2005	1:30:00 AM	7690	128.167	760	815	780	760	769	776.8
4/12/2005	2:30:00 AM	7750	129.167	533	521	507	523	526	522
4/13/2005	10:00:00 AM	9640	160.667	0	0	0	0	0	0.01
4/13/2005	11:00:00 AM	9700	161.667	7.6	4.2	0	16.4	15.6	8.76
4/13/2005	2:45:00 PM	9925	165.417	51	51	55	52	55	52.8
4/13/2005	3:45:00 PM	9985	166.417	57	58	60	60	64	59.8

**Table B5. Measured MEA Concentrations at the Top of the Absorber Column
from FTIR Analysis**

Date	Time	Adjusted Time (min)	Adjusted Time (hr)	FTIR 1	FTIR 2	FTIR 3	FTIR 4	FTIR 5	FTIR AVG (ppm)
4/6/2005	4:20:00 PM	0	0.000	79	78	72	63	75	73.4
4/6/2005	5:30:00 PM	70	1.167	99	89	91	92	82	90.6
4/7/2005	1:00:00 AM	520	8.667	55	46.6	23.6	22	22.9	34.02
4/7/2005	2:05:00 AM	585	9.750	34.5	22.9	13.8	16.3	24.9	22.48
4/7/2005	5:30:00 AM	790	13.167	45.8	67	59	41.2	40	50.6
4/7/2005	6:30:00 AM	850	14.167	71	46.9	43.9	55	32.3	49.82
4/7/2005	10:45:00 AM	1105	18.417	44.1	19	37.9	49.1	26	35.22
4/7/2005	11:45:00 AM	1165	19.417	26	39.2	42.3	30.2	56	38.74
4/7/2005	5:00:00 PM	1480	24.667	17.7	12.5	12.9	13.2	11.6	13.58
4/7/2005	6:00:00 PM	1540	25.667	24	12.2	22.8	21.4	32	22.48
4/8/2005	2:05:00 AM	2025	33.750	43.5	42	34.5	45.9	34.9	40.16
4/8/2005	3:10:00 AM	2090	34.833	30.1	34.8	33	30.4	41.6	33.98
4/8/2005	11:00:00 AM	2560	42.667	41.7	38.2	80	58	68	57.18
4/8/2005	12:00:00 PM	2620	43.667	54	146	59	80	42.5	76.3
4/11/2005	11:30:00 AM	6950	115.833	144	128	118	102	89	116.2
4/11/2005	12:30:00 PM	6910	115.167	44.7	38.6	42.1	39.9	36.3	40.32
4/11/2005	2:30:00 PM	7030	117.167	135	132	116	160	87	126
4/11/2005	3:30:00 PM	7090	118.167	174	129	112	108	155	135.6
4/12/2005	1:30:00 AM	7690	128.167	208	284	190	205	217	220.8
4/12/2005	2:30:00 AM	7750	129.167	125	183	156	161	147	154.4
4/13/2005	10:00:00 AM	9640	160.667	0	0	0	0	0	0
4/13/2005	11:00:00 AM	9700	161.667	269	421	524	654	690	511.6
4/13/2005	2:45:00 PM	9925	165.417	232	237	233	231	187	224
4/13/2005	3:45:00 PM	9985	166.417	216	229	212	225	221	220.6