MEMBRANE PROCESS TO CAPTURE CO_2 FROM COAL-FIRED POWER PLANT FLUE GAS

Award Number DE-NT0005312
Second Quarterly Progress Report
Report Period: January 1, 2009 – March 31, 2009

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prepared for

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EXECUTIVE SUMMARY

This second quarterly progress report describes work conducted for the Department of Energy (DOE NETL) on development of a membrane process to capture carbon dioxide (CO_2) from power plant flue gas (award number DE-NT0005312). The work was conducted by the project partners from January 1, 2009 through March 31, 2009.

The primary goal of this two-year research program is to demonstrate, in a field test, the potential of a membrane process to capture up to 90% of CO_2 in coal-fired flue gas with less than a 35% increase in the cost of electricity (COE). MTR is conducting this project with Arizona Public Services (APS), who will host the membrane field test at their Cholla 995 MW power plant, and the Electric Power Research Institute (EPRI), who will conduct a comparative cost analysis of the proposed membrane CO_2 capture process. MTR's progress reports for this project include pertinent results of quarterly work performed by APS and EPRI.

Direct CO_2 capture from power plant flue gas has been the subject of many studies, and while amine absorption seems to be the leading candidate technology, membrane processes have also been suggested. The Achilles heel of previous membrane processes has been the enormous membrane area required for separation because of the low partial pressure of carbon dioxide in flue gas. MTR is using a two-fold approach to address this issue:

(1) the development of high-permeance membranes to reduce the required membrane area and capital cost, and
(2) the use of incoming combustion air in a countercurrent/sweep module design to generate separation driving force and reduce the need for vacuum pumps and the associated parasitic energy cost.

In a previous DOE NETL-funded program, MTR developed membranes with CO_2 permeances approximately ten-fold higher than commercial CO_2-selective membranes. These new membranes – designated Polaris™ – also have the highest CO_2/N_2 selectivity for any non-facilitated transport polymeric membrane. Using measured membrane performance values, preliminary process design simulations suggest a promising CO_2 separation and liquefaction cost of \$20–30/ton CO_2. Flow schemes also show that based on the membrane module performance obtained to date, 90% of the CO_2 in flue gas can be separated using about 12% of the plant's energy. If this CO_2 is to be injected underground for geologic sequestration, an additional 4-6% of plant energy is required for compression to supercritical CO_2 and another 4% is needed for transportation, injection, and monitoring.

Process design calculations show that increasing membrane permeance or reducing the installed membrane cost can further improve the economics of CO_2 capture. High membrane CO_2/N_2 selectivity is beneficial; however, selectivity values above 25 produce little additional improvement in system performance due to pressure ratio limitations.

During this second quarter of project work:

- A new fabrication technique that reduces the time and cost of Polaris™ membrane production was developed. This protocol was used to produce a commercial run of Polaris™ CO_2 capture membrane that showed an average CO_2 permeance of 1,300 gpu and a CO_2/N_2 selectivity of 54. This performance exceeds the original project target of 1,000 gpu for CO_2 permeance and indicates that the first project milestone has been met.

- Low-pressure-drop membrane modules were prepared and tested with simulated flue gas mixtures at various temperatures and feed pressures. Test results confirm the effectiveness of these modules for removing CO_2 from flue gas.
- Project results and our overall approach were presented at the March 2009 DOE NETL contractor's review meeting in Pittsburgh, PA. Generally favorable feedback was received.
- A meeting was held with EPRI to set the baseline membrane design configuration for use in EPRI's comparative cost analysis of the membrane process versus other capture technologies.
- Detailed engineering designs for the Cholla membrane test skid were prepared. Final revisions are underway and the fabricator is expected to begin work in June 2009.

Work in the next quarter will focus on finalizing design and beginning assembly of the Cholla test skid. Concurrently, APS will begin modifications to the Cholla plant to accommodate the MTR skid. In addition, fabrication and testing of sweep modules with low-pressure-drop characteristics will continue at MTR, as will aging studies of membrane and module components in a wet, SO_2-containing environment. Finally, on April 29, 2009, we presented our project results and future plans at the DOE NETL peer review meeting in Pittsburgh, PA. Currently, all project tasks are on schedule.

MEMBRANE PROCESS TO CAPTURE
CO_2 FROM COAL-FIRED POWER PLANT FLUE GAS

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BACKGROUND

Carbon dioxide (CO_2) emissions from coal-fired power plants are believed to contribute significantly to global climate change.[1] The direct approach to address this problem is to capture the carbon dioxide in flue gas and sequester it underground.[2-4] However, the high cost of separating and capturing CO_2 with conventional technologies currently prevents the adoption of this approach. This project investigates the technical and economic feasibility of a new membrane process to capture CO_2 from power plant flue gas.

Direct CO_2 capture from power plant flue gas (referred to as simply "flue gas" for the rest of this report) has been the subject of many studies. Currently, CO_2 capture with amine absorption seems to be the leading candidate technology – although membrane processes have been suggested.[5,6] The Achilles heel of previous membrane processes has been the enormous membrane area required for separation, because of the low partial pressure of carbon dioxide in flue gas. To address this problem, MTR has proposed a two-pronged strategy:

1. develop extremely permeable membranes to reduce the membrane area required for CO_2 capture, and
2. design novel countercurrent/sweep modules and use combustion air to generate a driving force for CO_2 transport through these modules.

Membrane permeance directly impacts the capital cost and footprint of a membrane CO_2 capture system. Current commercial membranes have insufficient CO_2 permeances, resulting in membrane areas and capital costs that are not economically competitive with other technologies or the DOE's carbon capture goals. Recently, MTR has developed new membranes with ten times the CO_2 permeance of conventional gas separation membranes. These membranes are part of the solution to achieving an economical carbon capture process.

The second aspect of our membrane solution is to use a countercurrent/sweep module design that utilizes a portion of the incoming combustion air as the sweep gas to generate separation driving force, thereby reducing the need for energy intensive compressors or vacuum pumps.[7] Figure 1 shows a simplified flow scheme illustrating our approach.

- In this design, after electrostatic precipitation and desulfurization treatment (not shown), the flue gas from the boiler (stream ①) is directed to a conventional cross-flow membrane module. Driving force for separation in this module is generated by a permeate-side vacuum pump.
- The CO_2-and-water-enriched permeate (stream ②) undergoes a series of compression-condensation steps that recover greater than 99% of the water in flue gas.
- The dried CO_2 (stream ⑦) is then sent to a final compression-condensation-membrane loop that generates a 96+% liquid CO_2 stream ready for sequestration.
- The CO_2-depleted flue gas that leaves as the residue from the first membrane step (stream ③) is sent to a second membrane step that employs a countercurrent/sweep module. This module uses incoming combustion air (stream ④) as a sweep to generate driving force for CO_2 transport. The air sweep strips most remaining CO_2 from the flue gas and then is sent to the boiler for combustion (stream ⑤).
- The treated flue gas leaves as the residue of the sweep module (stream ⑥) and is directed to the power plant stack.

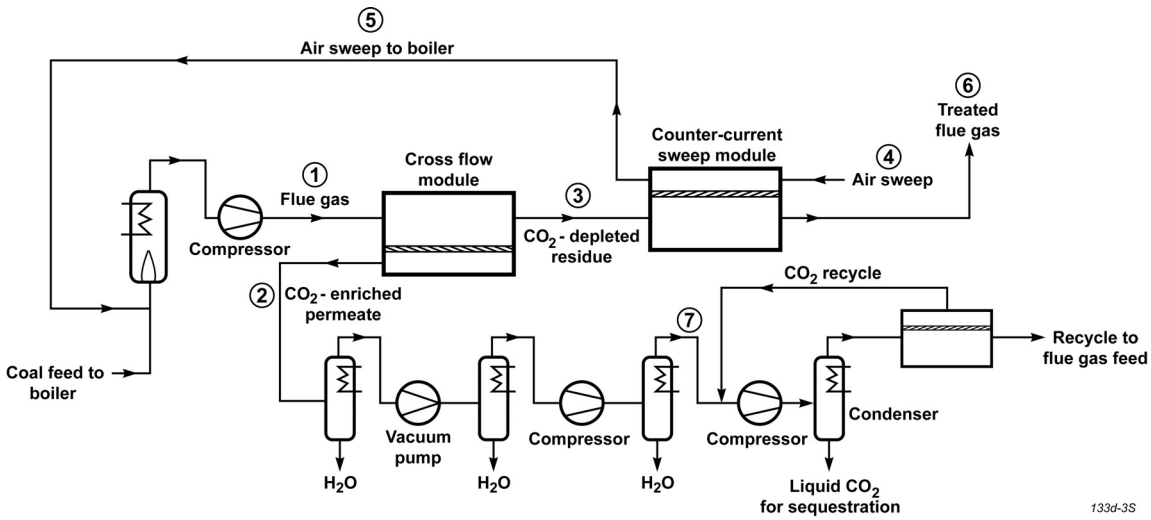

Figure 1. Simplified flow diagram of the proposed membrane process to capture and sequester CO_2 in flue gas from a coal-fired power plant.

This membrane design has a number of advantages over previously proposed membrane processes:

(1) Using an existing air stream to generate a CO_2 partial pressure gradient in the second membrane step reduces the need for compressors or vacuum pumps and the associated energy costs. In this way, the sweep module avoids the energy penalty of compression or vacuum treatment and provides an essentially "free" separation.

(2) By recycling CO_2 to the boiler via the air sweep loop, the CO_2 concentration in the flue gas exiting the boiler increases from about 13% to approximately 18%. This increases the CO_2 partial pressure driving force for transport in the first membrane step. Consequently, the membrane area and system cost is reduced.

Simulations suggest that the Figure 1 process design can capture 90% of the CO_2 in coal-fired flue gas as liquid CO_2 ready for sequestration using about 15% of the plant energy. Improved process flow schemes may be possible and will be a subject of study as this program progresses.

RESULTS AND DISCUSSION

During this second quarter of project work, the following progress was made:

- A new fabrication technique that reduces the time and cost of Polaris™ membrane production was developed. This protocol was used to produce a commercial run of Polaris™ CO_2 capture membrane that showed an average CO_2 permeance of 1,300 gpu and a CO_2/N_2 selectivity of 54. This performance exceeds the original project target of 1,000 gpu for CO_2 permeance and indicates that the first project milestone has been met.
- Low-pressure drop membrane modules were prepared and tested with simulated flue gas mixtures at various temperatures and feed pressures. Test results confirm the effectiveness of these modules for removing CO_2 from flue gas.
- Project results and our overall approach were presented at the March 2009 DOE NETL contractor's review meeting in Pittsburgh, PA. Generally favorable feedback was received.

- A meeting was held with EPRI to set the baseline membrane design configuration for use in their comparative cost analysis of the membrane process versus other capture technologies.
- Detailed engineering designs for the Cholla membrane test skid were prepared. Final revisions are underway and the fabricator is expected to begin work in June 2009.

Specific details of these activities are reported below, organized by task number as described in the project statement of work.

Task 1. Make High CO_2 Permeance Membrane Rolls

During this period, a roll of MTR's Polaris™ membrane was prepared on our commercial coating machine. This membrane roll was fabricated using a new procedure that reduces the time and cost of making the membrane. The pure-gas permeance of membrane stamps was measured at different locations along the roll. The results of these measurements, shown below in Table 1, indicate that the membrane roll is very uniform. The average CO_2 permeance is 1,300 gpu and the average CO_2/N_2 selectivity is 54. These values are the best produced to date, and exceed our project milestone performance target of 1,000 gpu for CO_2 in a defect-free membrane.

Table 1. Pure-Gas Permeances for Polaris™ Production Run 030209

Sample Position Along Roll Length	Sample Position Along Roll Width	Permeance (gpu)				Selectivity		
		N_2	CH_4	H_2	CO_2	CO_2/CH_4	CO_2/H_2	CO_2/N_2
50 ft	left	25	83	108	1,330	16	12	54
	middle	23	78	104	1,310	17	13	57
	right	24	77	105	1,240	16	12	52
120 ft	left	26	86	116	1,370	16	12	52
	middle	26	84	114	1,290	15	11	49
	right	21	71	94	1,270	18	14	60
Average		24	80	107	1,300	16	12	54

The membrane described in Table 1 was used to prepare several Polaris modules which are currently undergoing testing. A portion of this membrane run was also set aside for aging and exposure tests. These studies can help us understand the effect of different operating conditions and flue gas contaminant levels on membrane performance. Preliminary aging tests from an earlier membrane run (SC030609) are reported below.

Figures 2 and 3 show membrane CO_2 permeance and CO_2/N_2 selectivity, respectively, as a function of aging time. In these studies, membrane stamps were stored in three different environments between permeation measurements. The three aging environments at ambient pressure were:

1. air at room temperature (25°C),
2. air at 50°C,
3. CO_2 at 50°C.

These conditions were chosen as baseline environments to study the aging characteristics of the Polaris™ membrane.

The data in Figures 2 and 3 show both CO_2 permeance and CO_2/N_2 selectivity decreased over time initially, and then began to level off for the membrane samples stored in air. A slightly faster aging rate and larger overall decrease in the CO_2 permeance and selectivity were observed at 50°C in air compared to ambient air conditions. The reason for the decline in performance for the samples aged in air is not

entirely clear, although composite membranes often show an initial decrease in performance associated with residual solvent removal and polymer structural relaxation.

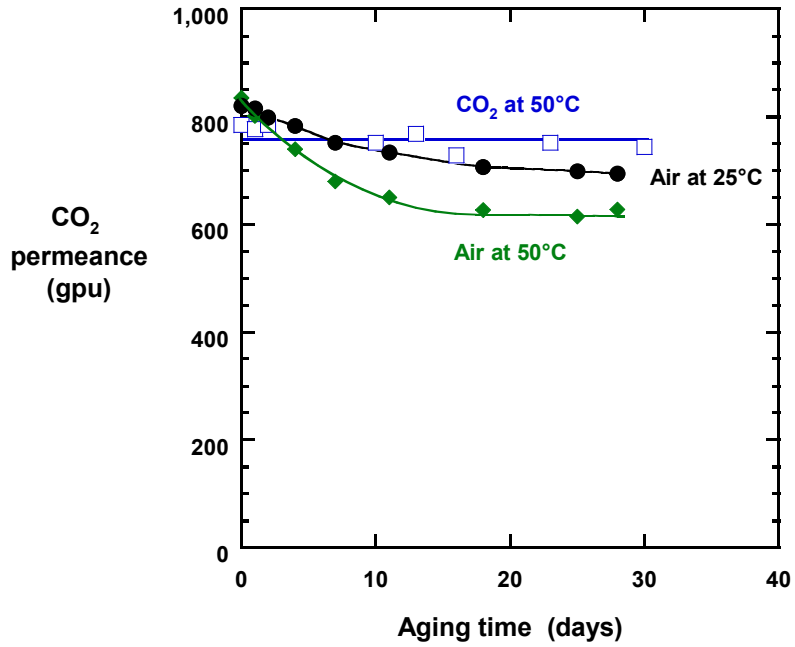

Figure 2. Pure-gas CO_2 permeance of Polaris™ membranes as a function of aging time in various environments. Gas permeances were measured at 50 psig feed pressure.

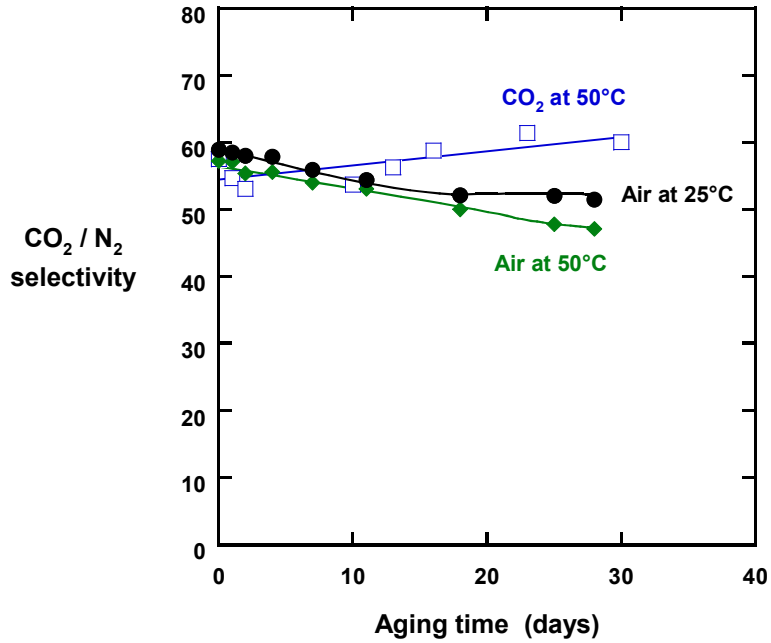

Figure 3. Pure-gas CO_2/N_2 selectivity of Polaris™ membranes as a function of aging time in various environments. Gas permeances were measured at 50 psig feed pressure.

In contrast to the samples aged in air, the membrane sample stored in CO_2 at 50°C shows very stable CO_2 permeance and even slightly increasing CO_2/N_2 selectivity over four weeks. The reason for this difference in behavior could be related to the fact that CO_2 often causes swelling in polymeric membranes. It is possible that swelling of the Polaris™ membrane induced by CO_2 exposure compensates for any polymer relaxation and associated aging. Regardless of the exact reason, these results indicate that Polaris™ membranes are quite durable in a CO_2 environment.

Additional exposure tests are now underway with a gas mixture containing 1,000 ppm SO_2 and 18% CO_2 balanced with N_2 at 50°C, and this same mixture saturated with water; results will be reported in the next quarter. These exposure tests will give some indication of the stability of Polaris™ membranes in a flue gas environment prior to the Cholla field test. In addition bomb tests of module components and continuous module testing with a simulated flue gas mixture are also scheduled for summer 2009.

% Task 1 completed: 25%.

Task 2. Optimize Designs and Manufacture Modules

During this reporting period, two new modules (5414 and 5549) were prepared and tested for separation performance and pressure drop characteristics. These 4-inch diameter, 40-inch long (commercial length) modules each contain about 1 m^2 of membrane area. As shown in Table 2, the newest module (5549) has the highest pure-gas permeances produced to date, due to the use of a new membrane formulation.

Table 2. Comparison of Pure-Gas Permeances and CO_2/N_2 Selectivity in Modules 4488, 5414 and 5549. The feed pressure is 25 psia and permeate pressure is 15 psia.

Module	Membrane Formulation	Module Design	Pure-Gas Permeance (gpu)		Pure-Gas CO_2/N_2 Selectivity
			N_2	CO_2	
4488	Regular	Generation 1	15	650	43
5414	Regular	Generation 2	9	450	50
5549	New	Generation 2	17	890	54

We also changed the module design to achieve a lower feed-to-residue pressure drop. Figure 4 compares the feed-to-residue pressure drops of Modules 4488 and 5414; the new generation module (5414) clearly shows lower pressure drops compared to Module 4488. This improvement is important to minimize the energy penalty associated with pumping flue gas through the CO_2 capture membrane system.

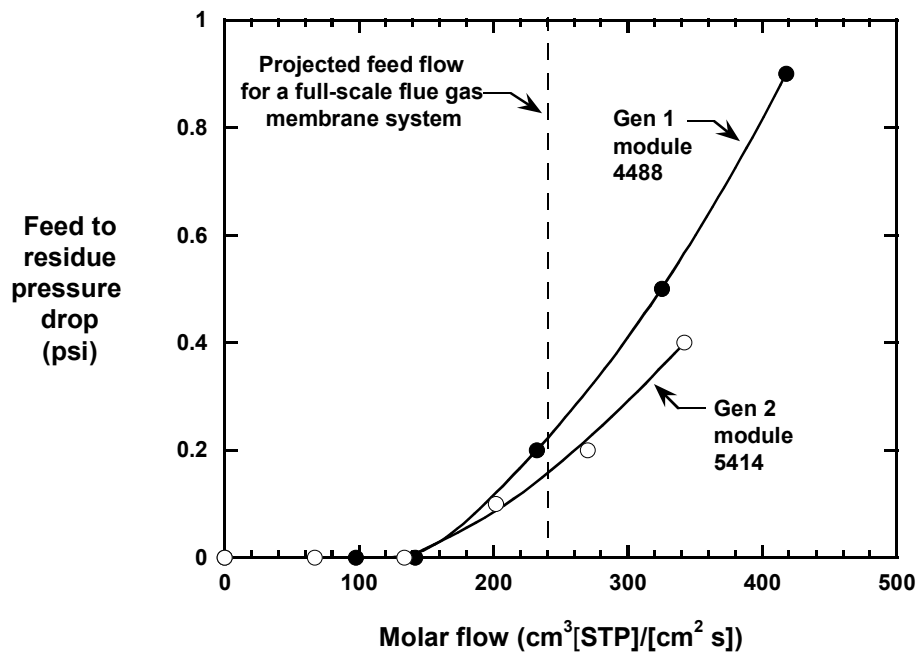

Figure 4. Feed-to-residue pressure drop for Modules 4488 and 5414 as a function of feed side molar flow (superficial velocity). Feed gas is nitrogen at 40 psia. The vertical dashed line is the projected feed flow for a full-scale flue gas plant where the feed gas is split and fed to multiple 4-element housings in parallel.

The data in Figure 4 indicate that the feed-to-residue pressure drop is relatively low for the generation 1 module (<1 psi), and even lower for the generation 2 modules (<0.5 psi), over the range of flow rates examined. The vertical dashed line in Figure 4 corresponds to the projected feed flow rate to a full-scale (600 MW) flue gas CO_2 capture system. For this system, it is assumed that the first step membrane array contains 90 mega-bundle skids, each containing four pressure housings; in turn, each pressure housing holds 28 12-inch elements. The feed gas is split and delivered as a center feed to each of the pressure housings. In this configuration, the feed gas will flow through two elements in series and approximately 5,000 in parallel. The pressure drop data in Figure 4 are for flow through one 40-inch element, whereas the configuration described above would involve flow through two 40-inch elements (a total path length of 80 inches). Consequently, the actual pressure drop in a large system will be higher than that shown in Figure 4 (approximately double), although still quite low – less than 0.5 psi for the generation 2 module design.

% Task 2 completed: 25%.

Task 3. Test Modules on Bench System

During this reporting period, cross-flow Modules 5414 and 5549 were tested with pure gases and a mixture of N_2 and CO_2. Figure 5 compares the pure-gas and mixed-gas CO_2 permeances and CO_2/N_2 selectivities of Module 5549 at different CO_2 partial pressures in the feed. These figures show that the higher the CO_2 partial pressure in the feed, the higher the CO_2 permeance and the selectivity. For example, for Module 5549 at 27°C, increasing CO_2 partial pressure in the feed from 3.0 to 8.4 psia increased the mixed-gas CO_2 permeance from 470 gpu to 760 gpu and the selectivity from 19 to 29. These results are typical of polymeric membrane systems where condensable permeants such as CO_2 often show pressure dependent permeability.

For the base case flue gas CO_2 capture membrane design, the expected CO_2 partial pressure at the feed inlet to the membrane system will be about 7 psia. This CO_2 partial pressure will drop over the length of a module as CO_2 permeates the membrane. Nevertheless, design calculations indicate that these membranes maintain sufficient performance over the range of CO_2 partial pressures expected in the field to effectively capture CO_2 from flue gas.

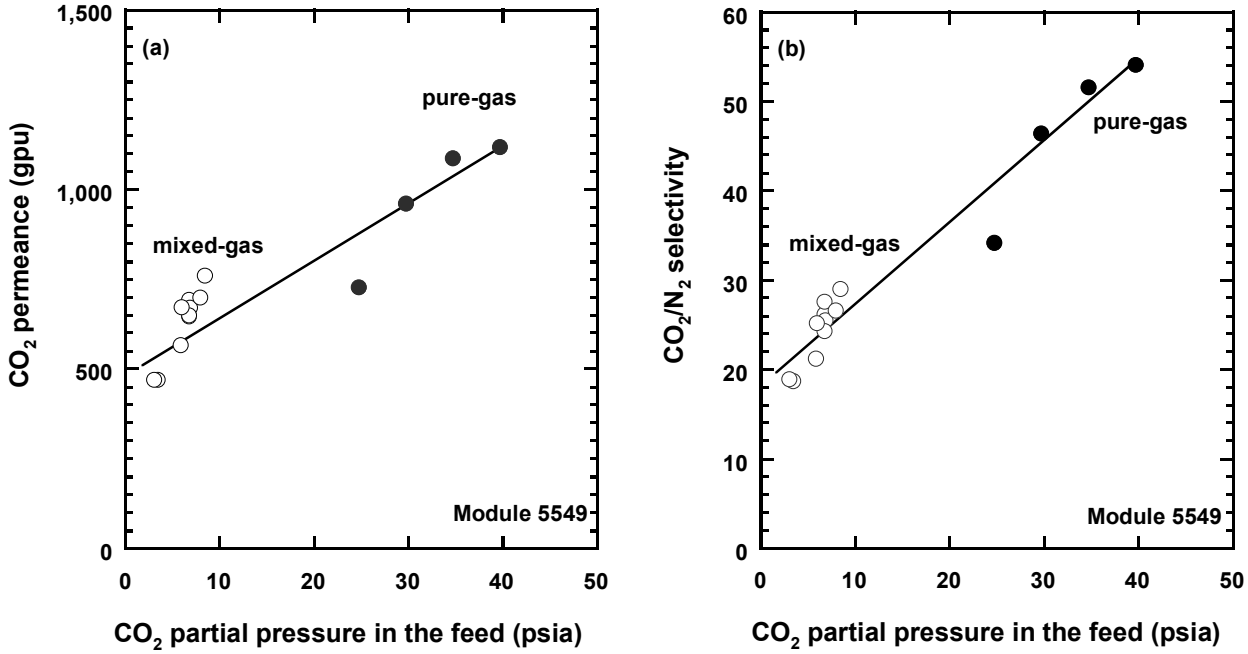

Figure 5. Mixed-gas (open symbols) and pure-gas (closed symbols) (a) CO_2 permeance and (b) CO_2/N_2 selectivity of Module 5549 at 27°C as a function of CO_2 partial pressure in the feed.

After evaluating module performance at different CO_2 partial pressures in the feed, we ran the modules at the proposed CO_2 feed inlet partial pressure of 7.2 psia at temperatures ranging from 27°C to 50°C. Figure 6 shows the mixed-gas performance of Module 5414 as a function of feed temperature. As expected for a solubility-selective polymer membrane, mixed-gas CO_2/N_2 selectivity decreases with increasing temperature because N_2 permeance increases faster with temperature than that of CO_2.

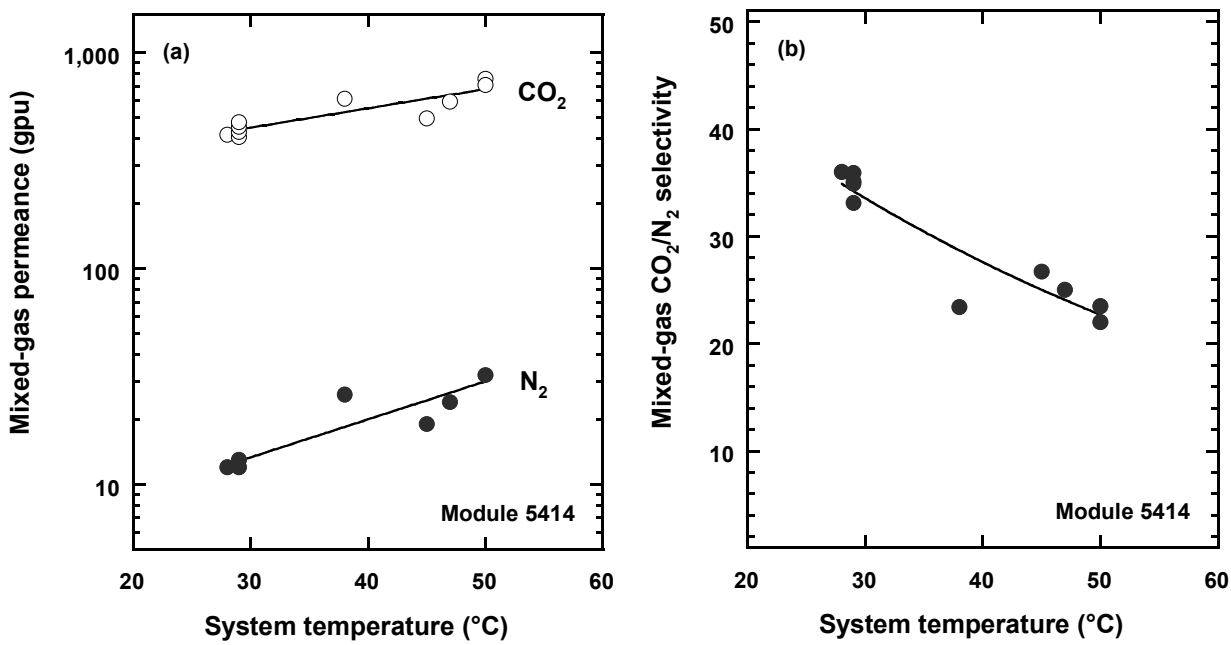

Figure 6. Mixed-gas (a) permeances and (b) CO_2/N_2 selectivity of Module 5414 as a function of system temperature. Feed CO_2 partial pressure was about 7 psia in these experiments.

Because of low CO_2 partial pressure and temperature effects, the mixed-gas CO_2/N_2 selectivity of Module 5414 at 50°C is considerably lower than pure-gas values for membrane stamps at room temperature (typically CO_2/N_2 >50). Nevertheless, module selectivity under these realistic operating conditions is still greater than 20, and based on design calculations, sufficient for cost- effective CO_2 capture from flue gas.

Figure 7 compares the mixed-gas CO_2 permeance and CO_2/N_2 selectivity of Modules 5414 and 5549 as a function of operating temperature. Both modules use the same design; the only difference between them is that Module 5549 uses a new Polaris™ membrane formulation that shows higher permeances. For example, at 50°C, the CO_2 permeance of Module 5549 is 1,600 gpu compared to 750 gpu for Module 5414. However, Module 5549 shows consistently lower mixed-gas CO_2/N_2 selectivities than module 5414 over the temperature range examined. The reason for the lower mixture selectivities of Module 5549 is not clear at this time. Both modules have similar pure-gas selectivities (see Table 2), and their performance was unchanged in tests conducted after the mixture temperature dependence study. It is possible that the higher permeance of Module 5549 is resulting in pressure ratio limitations in our experimental setup that limit module performance. We will conduct additional testing in the next quarter to clarify this issue.

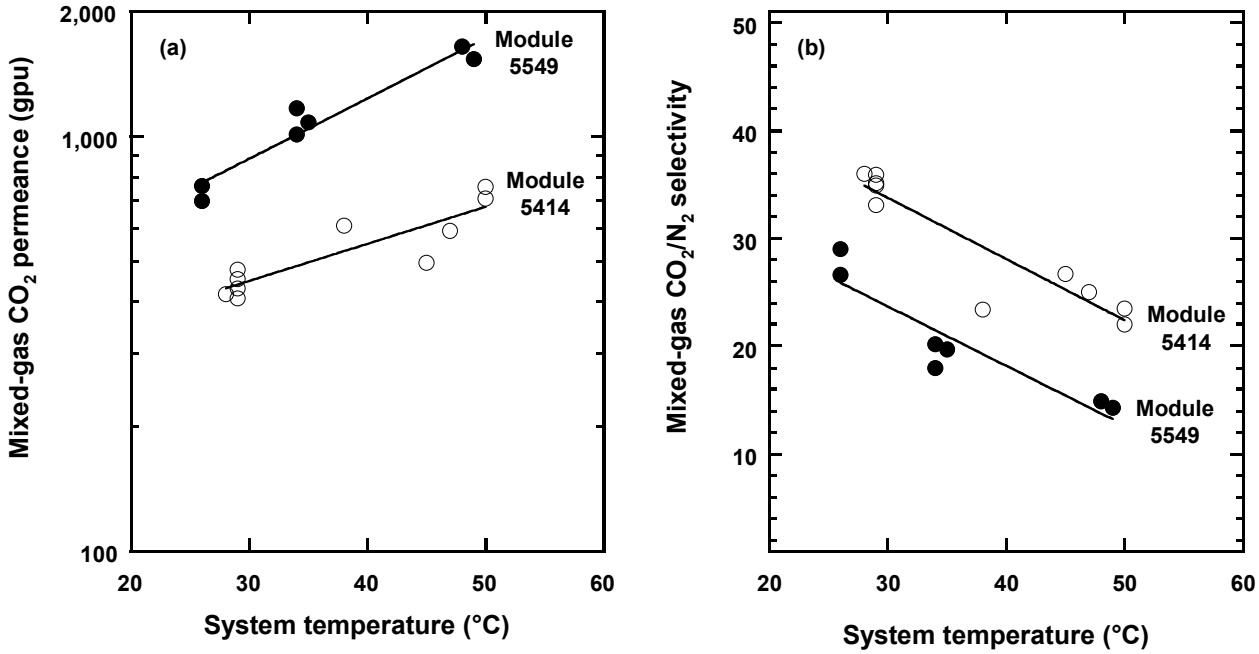

Figure 7. Mixed-gas (a) CO_2 permeance and (b) CO_2/N_2 selectivity of Modules 5414 and 5549 as a function of system temperature.

After completing temperature cycling tests, both modules were re-tested with pure gases to see if their properties had changed over the test period. For both modules, pure-gas tests results before and after mixed-gas experiments were very similar, suggesting that the modules were stable.

% Task 3 completed: 25%.

Task 4. Design and Fabricate the Membrane Test Skid for Use at the APS Cholla Plant

An initial design for the Cholla test skid has been completed. Engineering drawings have been reviewed, final revisions are in progress, and the skid design is expected to go to the fabricator in June 2009. Figure 8 shows a preliminary general arrangement drawing of the test skid. There are four module housings in total, each with a capacity to hold four 8-inch-diameter, commercial-scale membrane modules. The two lower housings will hold standard cross-flow modules where driving force for CO_2 capture will be provided by a vacuum pump. The two upper housings are designed to hold countercurrent/sweep modules, where driving force for CO_2 capture will be provided by an air sweep on the permeate side of the modules. The skid will be thoroughly instrumented with flow, temperature, pressure, and gas concentration measurement equipment. The skid footprint is approximately 24 feet by 7 feet.

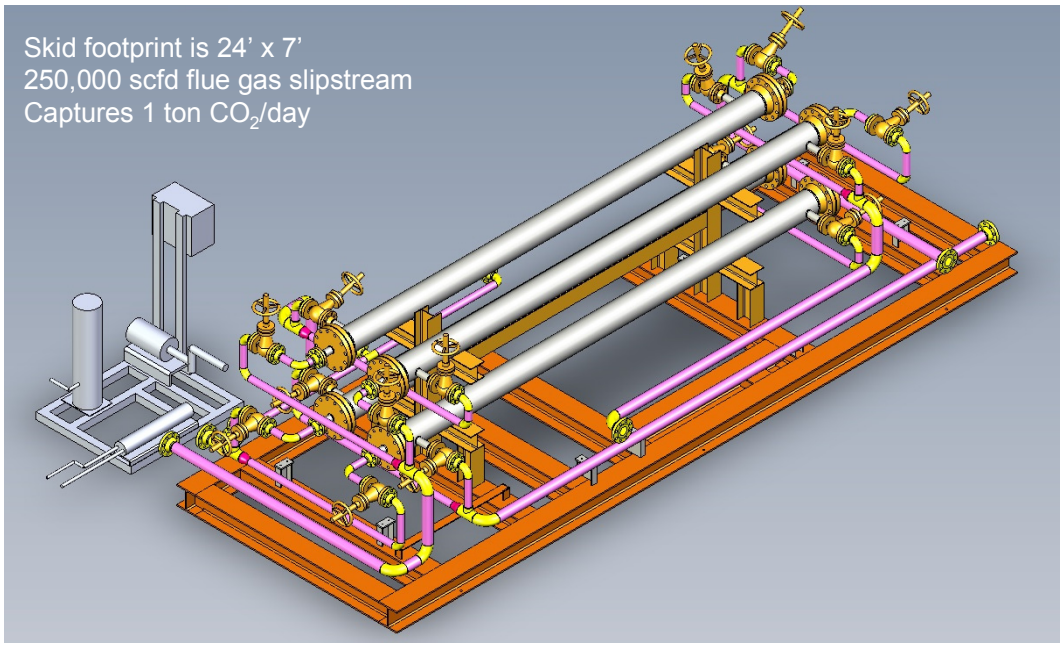

Figure 8. Preliminary general arrangement drawing of the Cholla test skid. The two lower housings will hold the first step cross-flow modules and the upper housings will hold the second step countercurrent/sweep modules.

% Task 4 completed: 25%.

Task 5. Modify the Cholla Plant to Accommodate the MTR Test Skid

During the reporting period, the location of the membrane skid testing site at the Cholla Plant was determined. The flue gas will be withdrawn from Unit #3, after the gas has passed through the newly installed FGD (Flue Gas Desulfurization) system and newly upgraded baghouse (coal-side fabric filter). The test site will be located about 500 feet away from the flue gas sampling point. Exhaust from the membrane skid will travel about 300 ft to return to the stack.

A purchase order was issued to Worley Parsons to engineer the process for the membrane skid testing. The work scope covers Task 5.1 and Task 5.2, repeated here for convenience.

Task 5.1. Conduct Process Design

Process design activities will consist of the following:

- Develop the process configuration that will deliver treated flue gas at desired temperature and pressure to the membrane skid (MS).
- Determine gas requirements for the MS including gas velocity and pressure, particulate parameters, temperature, moisture content, sulfur content and other membrane requirements.
- Develop the pretreatment necessary to create a gas flow that meets the stated membrane requirements.
- Design the process flow and layout to meet the MS gas needs.
- Highlight redundancy and gas movement characteristics of the process.

Task 5.2. Prepare Equipment Parameters and Specifications

Based on Task 5.1, a bill of materials with specifications for each piece of equipment including flow rates, temperatures, capacity, etc will be created. The listing will indicate where back up or multiple pieces of equipment will be required. Each piece of equipment will be specified at an order level.

By October, Worley Parsons will deliver process flow sheets, engineering documents for construction, and a bill of materials with specifications for each piece of equipment to APS. In the meantime, APS will begin other site modifications to prepare for the MTR membrane test skid.

% Task 5 completed: 20%.

Task 6. Conduct a Comparative Economic Analysis of the Proposed Membrane Process

During this quarter, a meeting was held at EPRI to discuss the key aspects of the proposed membrane CO_2 capture process. A baseline membrane process design was selected, and the overall mass and energy balances for this process were provided to EPRI. This process will be the membrane design that EPRI uses to conduct the comparative economic analysis between membranes and other CO_2 separation processes.

% Task 6 completed: 10%.

CONCLUSIONS AND FUTURE PLANS

Key accomplishments for the second quarter of project work are summarized in the following list.

- A new fabrication technique that reduces the time and cost of Polaris™ membrane production was developed. This protocol was used to produce a commercial run of Polaris™ CO_2 capture membrane that showed an average pure-gas CO_2 permeance of 1,300 gpu and a CO_2/N_2 selectivity of 54. The performance exceeds the original project target of 1,000 gpu for CO_2 permeance and indicates that the first project milestone has been met.
- Low-pressure-drop membrane modules were prepared and tested with simulated flue gas mixtures at various temperatures and feed pressures. Test results confirm the effectiveness of these modules for removing CO_2 from flue gas.
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Work in the next quarter will focus on finalizing design and beginning assembly of the Cholla test skid. Concurrently, APS will begin site modifications to the Cholla plant to accommodate the MTR skid. In addition, fabrication and testing of sweep modules with low-pressure-drop characteristics will continue at MTR, as will aging studies of membrane and module components in a wet, SO_2-containing environment. Finally, on April 29, 2009, we presented our project results and future plans at the DOE NETL peer review meeting in Pittsburgh, PA.

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Appendix A. Cost Plan and Status Report

Baseline Reporting Quarter	YEAR 1, Start: 10-1-08 End: 9-30-09				YEAR 2, Start: 10-1-09 End: 9-30-10			
	Q1	Q2	Q3	Q4	Q5	Q6	Q7	Q8
Baseline Cost Plan (from SF424A)								
Federal Share	$ 348,543	$ 348,544	$ 348,544	$ 348,544	tbd	tbd	tbd	tbd
Non-Federal Share	$ 106,824	$ 106,823	$ 106,824	$ 106,823	tbd	tbd	tbd	tbd
Total Planned (Federal and non-Federal)	$ 455,367	$ 455,367	$ 455,368	$ 455,367	tbd	tbd	tbd	tbd
Cumulative Baseline Cost	$ 455,367	$ 910,734	$ 1,366,102	$ 1,821,469	tbd	tbd	tbd	$ 2,573,280
Actual Incurred Costs								
Federal Share	$ 116,810	$ 307,424						
Non-Federal Share	$ -	$ 39,431						
Total Planned (Federal and non-Federal)	$ 116,810	$ 346,855						
Cumulative Baseline Cost	$ 116,810	$ 463,665						
Variance								
Federal Share	$ 231,733	$ 41,120						
Non-Federal Share	$ 106,824	$ 67,392						
Total Planned (Federal and non-Federal)	$ 338,557	$ 108,512						
Cumulative Baseline Cost	$ 338,557	$ 447,069						

After a slow start in first quarter spending due to previously discussed issues (time needed to shift MTR manpower from other activities after the official award notification was received and a NEPA hold through Jan 2009 limiting the number of tasks on which work could be started), costs approached anticipated levels in the second quarter. We anticipate that costs, including the non-federal share, will soon return to the baseline plan.

Appendix B. Critical Path Project Milestones

Task #	Project Milestone Description	Project Duration - 24 months Start: 10/1/08 End: 9/31/10								Planned Start Date	Planned End Date	Actual Start Date	Actual End Date	Comments (notes, explanation of deviation from baseline plan)
		Project Year 1				Project Year 2								
		Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4					
1-3	Confirm that membranes give CO_2 permeances of at least 1,000 gpu in bench-scale tests and that modules made from these membranes can operate effectively to achieve 90% CO_2 capture.	xxx	xxx	xxx	xxX					1QFY09	4QFY09	12/01/08		This milestone was achieved ahead of schedule in Q2.
4-5	Complete fabrication of the Cholla membrane test skid with all necessary instrumentation and controls.	xxx	xxx	xxx	xxX					1QFY09	4QFY09	1/1/09		Task initiation slightly delayed. However, we still anticipate achieving this milestone as scheduled.
9-10	Complete the six-month field test of the membrane skid at the Cholla power plant. Finish the data analysis and optimization studies.					xxx	xxx	xxx	xxX	1QFY10	4QFY10			
11-12	Confirm that low-cost components can be used for membrane-based CO2 capture and begin planning for larger proof-of-concept system							xxx	xxX	3QFY10	4QFY10			
6, 13	Complete a technical and economic analysis, based on experimental and field test data, that describes the potential of the membrane CO_2 capture technology to be retrofitted to existing coal-fired power plants and meet the program objective of >90% CO_2 capture with < 35% increase in the cost of electricity.					xxx	xxx	xxx	xxX	1QFY10	4QFY10			

x Duration of effort directed toward the milestone; X Milestone evaluation and decision point