CARBON DIOXIDE CAPTURE FROM FLUE GAS USING DRY REGENERABLE SORBENTS

QUARTERLY TECHNICAL PROGRESS REPORT

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ABSTRACT

This report describes research conducted between April 1, 2005 and June 30, 2005 on the use of dry regenerable sorbents for removal of carbon dioxide from flue gas from coal combustion and synthesis gas from coal gasification. Supported sodium carbonate sorbents removed up to 76% of the carbon dioxide from simulated flue gas in a downflow cocurrent flow reactor system, with an approximate 15 second gas-solid contact time. This reaction proceeds at temperatures as low as 25°C. Lithium silicate sorbents remove carbon dioxide from high temperature simulated flue gas and simulated synthesis gas. Both sorbent types can be thermally regenerated and reused. The lithium silicate sorbent was tested in a thermogravimetric analyzer and in a 1-in quartz reactor at atmospheric pressure; tests were also conducted at elevated pressure in a 2-in diameter high temperature high pressure reactor system. The lithium sorbent reacts rapidly with carbon dioxide in flue gas at 350-500°C to absorb about 10% of the sorbent weight, then continues to react at a lower rate. The sorbent can be essentially completely regenerated at temperatures above 600°C and reused. In atmospheric pressure tests with synthesis gas of 10% initial carbon dioxide content, the sorbent removed over 90% of the carbon dioxide. An economic analysis of a downflow absorption process for removal of carbon dioxide from flue gas with a supported sodium carbonate sorbent suggests that a 90% efficient carbon dioxide capture system installed at a 500 MW_e generating plant would have an incremental capital cost of \$35 million (\$91/kW_e, assuming 20 percent for contingencies) and an operating cost of \$0.0046/kWh. Assuming capital costs of \$1,000/kW for a 500 MW_e plant the capital cost of the down flow absorption process represents a less than 10% increase, thus meeting DOE goals as set forth in its Carbon Sequestration Technology Roadmap and Program Plan.

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1.0 EXECUTIVE SUMMARY

The objective of this project is to develop a simple and inexpensive process to separate CO₂ as an essentially pure stream from a fossil fuel combustion system using a regenerable sorbent. The sorbents being investigated in this project are alkali carbonates (particularly sodium carbonate) and lithium silicate. Sodium carbonate is converted to bicarbonate or to an intermediate salt through reaction with carbon dioxide and water vapor. The sorbent is regenerated to carbonate when heated, producing a nearly pure CO₂ stream after condensation of water vapor. Lithium ortho-silicate reacts with carbon dioxide to produce lithium carbonate and lithium meta-silicate. Upon heating, the carbon dioxide is released and the sorbent is regenerated.

A novel contacting scheme has been developed to employ supported sodium carbonate sorbents for removal of CO₂ from flue gas. A bench scale reactor system has been constructed and used to test a 15% supported sodium carbonate sorbent to determine the extent of carbon dioxide removal from a simulated flue gas stream achievable in a gas-solid contact time of approximately 15 seconds. At near ambient temperatures, 76% removal was achieved. In longer residence time reactors, the extent of removal is expected to improve. An economic analysis of a process based on this reaction was conducted. A downflow reactor system coupled to a sorbent regenerator composed of a steam heated hollow screw conveyor was sized. Preliminary capital and operating costs for such a system, installed at a 500 MW_e generating plant, were estimated at \$35 million (\$76/kW_e) and \$0.0046/kWh respectively.

Lithium silicate sorbents were tested for use in removal of CO₂ from high temperature flue gas in a TGA, an atmospheric pressure 1-in diameter reactor and a high temperature high pressure reactor. Very rapid capture of CO₂ was observed up to about 10% of sorbent weight. The reaction continued at a slower rate. The sorbent was regenerated, releasing CO₂, upon heating to 700°C.

The same lithium silicate sorbents were also tested for use in removal of CO₂ from high temperature synthesis gas. The sorbents capture CO₂ at temperatures as low as 300°C, however the reaction rate improves with increasing temperature up to about 550°C. Similar reactivity was observed in testing with sulfur free syngas and syngas containing 1% H₂S.

2.0 INTRODUCTION

Fossil fuels used for power generation, transportation, and by non-utility sectors are the primary sources of anthropogenic CO₂ emissions. While there are many potential approaches to limiting greenhouse gas emissions, including increased energy efficiency and use of carbon-free fuels, it is becoming increasingly clear that CO₂ capture and sequestration will play an important role in mitigating the progress of global warming. In the near future, CO₂ capture efforts will likely focus on large stationary sources, such as fossil fueled power plants, since they will offer the benefits of economy of scale and the greatest benefits of carbon dioxide reduction from any one industry. It is for this reason that the United States Department of Energy's Carbon Sequestration Program administered by the Office of Fossil Energy and managed by the

National Energy Technology Laboratory conducts and funds research to develop CO₂ capture and sequestration technologies.

The focus of this project is to develop a simple and inexpensive process to remove CO₂ from the flue gas of existing power plants using a dry, regenerable sorbent. This capture technology is based on the reversible reactions between carbon dioxide and supported sorbents. Using a thermal swing cyclic process, an essentially pure carbon dioxide stream can be removed from flue gas for subsequent sequestration or reuse. The carbonate based process is suitable for coal-fired power plants incorporating wet flue gas desulfurization and natural gas-fired power plants, and can be retrofitted to existing plants. The silicate based process is suitable for high temperature flue gas as well as synthesis gas produced for use in integrated gasification combined cycle (IGCC) power generation systems.

Capture of CO₂ from low temperature flue gas using sodium carbonate (Na₂CO₃) sorbents results in the reversible formation of sodium bicarbonate (NaHCO₃) and/or Wegscheider's salt (Na₂CO₃•3NaHCO₃):

Reaction 1

Reaction 2

Both forward reactions (CO₂ absorptions) are exothermic. The equivalent reverse reactions (sorbent regeneration) are endothermic and produce equal molar quantities of CO₂ and H₂O. Condensation of H₂O from the regeneration product results in a pure CO₂ stream suitable for sequestration or reuse.

Capture of CO₂ from high temperature flue gas, or synthesis gas using lithium silicate results in the conversion of lithium ortho-silicate to lithium meta-silicate, in accordance with Reaction (3):

Reaction 3

The reverse reaction which takes place, when the sorbent is heated, produces a pure stream of CO₂ for sequestration or reuse. The incorporation of promoters in the sorbent formulation can greatly increase the reactivity of the sorbent.

This report describes activities conducted between April 1, 2005 and June 30, 2005 by RTI. Activities conducted this quarter include bench-scale downflow testing of sodium carbonate based sorbents in low temperature simulated flue gas, thermogravimetric analysis and bench-

scale fluidized bed testing on lithium silicate sorbents and an economic analysis of a sodium carbonate-based CO₂ capture process for low temperature flue gas.

3.0 EXPERIMENTAL

3.1 Downflow Reactor Testing of Supported Sodium Carbonate

RTI designed and constructed a 3-in diameter atmospheric pressure cocurrent downflow reactor system, and conducted a series of tests to determine the rate of reaction of the sodium carbonate-based supported sorbent with carbon dioxide and water vapor. The reactor system is shown in Figures 1 and 2. The center section of the reactor is enclosed by a 3-ft clamshell furnace with a single zone furnace. The gas feed system for this reactor system begins with a pair of mass flow controllers (MFCs) for metering in carbon dioxide and nitrogen. The gas from the MFCs flows into the lower inlet of the liquid vaporizer system which is heated externally with heat tapes and internally with a small heating rod. Liquid water is fed into the vaporizer with a positive displacement pump. As the liquid vaporizes, the vapor is swept up and out of the vaporizer with the gas flow. The preheated feed gas/vapor mixture enters the upper section of the reactor below the sorbent entrance point. Sorbent is fed from a hopper at the top of the reactor, through a valve by gravity. Sorbent flow is started after the flows of CO₂ and N₂ are established. Sorbent is collected in a bucket at the bottom of the reactor. The sorbent flow rate is calculated by weighing the collected sorbent at the end of each test. The temperature of the collected sorbent is monitored with a thermocouple. The gas exiting the reactor passes through a condenser to a nondispersive infrared CO₂ analyzer. The sorbent is regenerated between tests and reused.

Figure 1. Bench scale downflow reactor system

Figure 2. Schematic of downflow reactor system

Initially, the reactor was operated with sand to establish the conditions necessary for good solids flow and the test the gas delivery and gas analysis systems. One test was conducted with calcined trona (grade T-50) which absorbed little or no CO₂ in the short reactor residence time. Seven tests were then conducted with SCI-0123105-1 sorbent, composed of 15% sodium carbonate on an inert support. Results of fluidized bed and entrained bed testing of this sorbent were reported previously (Green, et al. 2005b).

3.2 Testing of Lithium Silicate Based Sorbent

3.2.1 CO₂ Removal from High Temperature Flue Gas

Lithium silicate based sorbent evaluations were conducted in the thermogravimetric analyzer, the 1-in atmospheric pressure quartz fixed-bed reactor system and the 2-in high pressure fixed bed reactor system.

3.2.1.1 Thermogravimetric analyzer studies

Tests were conducted to compare the capacity of the baseline alumina-supported lithium silicate sorbent with formulations incorporating two different promoters. A moisture-free gas mixture containing 20% CO₂/balance N₂ was used for testing at 550°C.

3.2.1.2 Low Pressure Quartz Microreactor Testing

Six tests were conducted in the 1-in quartz microreactor system. This system was described previously (Green, et al. 2005a). These tests were conducted in fixed-bed mode at varying concentrations of CO₂ and H₂O, temperature and space velocities. CO₂ capacities were determined by integration of the inlet and outlet CO₂ analyzer signals up to the time of CO₂ breakthrough.

3.2.1.3 High Pressure Reactor Testing

One test was conducted in the 2-in diameter high pressure high temperature reactor. This system is shown in Figure 3. The test was conducted at approximately 550°C, at a pressure of 280 psig, with a space velocity of 2000 hr⁻¹(at STP), with a gas composed of 2% CO₂/balance N₂ (no water vapor).

Figure 3. High Temperature high pressure reactor system used for testing of lithium silicate sorbent

3.2.2 CO₂ Removal from High Temperature Synthesis Gas

3.2.2.1 Thermogravimetric analyzer studies

A series of TGA tests were conducted in simulated sulfur-free syngas at temperatures between 300 and 550°C to determine the range of temperatures at which the lithium silicate sorbent would absorb CO₂. Additional multi-cycle testing was conducted at 550°C in both simulated sulfur-free and simulated sulfur containing syngas. The sorbent regeneration potential was evaluated isothermally in CO₂-free gas.

3.2.2.2. Low Pressure Quartz Microreactor Testing

One test was conducted in the 1-in quartz microreactor system, at 500°C, with a simulated clean syngas. The CO₂ concentration was continuously monitored. The test was conducted at atmospheric pressure.

4.0 RESULTS AND DISCUSSION

4.1 Downflow Reactor Testing of Supported Sodium Carbonate

Following a downflow reactor test with using calcined T-50 trona in which essentially no CO₂ was absorbed, a series of 7 tests were conducted with SCI-012705-1 sorbent, composed of

15% sodium carbonate supported on an inert ceramic material. The properties of this sorbent are shown in Table 1.

Table 1. Properties of SCI-012705-1 Sorbent

Compact Bulk Density (g/cc)	0.96
Average Particle Size (μm)	76.38
BET Surface Area (m^2/g)	96.5
Attrition-resistance (DI) ^a	DI = 12.3

^aRTI sorbents were measured by Davison method (DI). Lower DI values indicate physically strong catalysts and sorbents. A typical DI value range for Fluid Catalytic Cracking (FCC) Catalysts is DI = 10 - 20.

Seven tests were conducted this quarter at varying sorbent flow rates and temperatures. Gas flow rates were established prior to starting sorbent flow. CO₂ concentration was monitored before, during and after the period of sorbent flow. Test conditions and CO₂ removals (based on steady-state monitored concentration differences before and during sorbent flow) are shown in Table 2.

Table 2. Downflow Reactor Test Conditions

Test	1	2	3	4	5	6	7
Gas Flow Rate (SLPM)	33	33	33	33	33	33	33
CO ₂ Concentration (%)	3	3	3	3	3	2	1.5
H ₂ O Concentration (%)	3	3	3	3	3	3	3
Sorbent Flow Rate (g/min)	33	33	53	139	162	225	92
Temperature (°C)	60	62	56	60	34	25	27
CO ₂ Removal (%)	19	16	29	35	52	76	67 ^a
^a maximum removal observed during the course of the test							

Carbon dioxide concentrations measured during these tests are shown in Figures 4 through 10.

The results of these tests indicate that significant CO₂ removals are possible in a 15 second gas residence time. Lower gas temperatures improve CO₂ removals, as previously confirmed in other reactor systems. One factor that may limit the rate of absorption is localized heating of the sorbent particle surface. While bulk sorbent temperatures are well within the temperature window for the bicarbonate reaction product, the particle surface may be warmer due to the exothermic reaction.

Higher sorbent flow rates (higher solids-to-gas ratios) clearly improve CO₂ removal; however, the sorbent does not reach capacity in a single pass through the system. The maximum fractional CO₂ removal observed in the seven tests was 76% in test 6. This corresponded to the test with the lowest temperature as well as the highest sorbent flow rate (solids-to-gas ratio). Test 5 was conducted at a higher inlet CO₂ concentration, a slightly higher temperature and a significantly lower sorbent flow rate than Test 6. Test 5 produced the greatest rate of removal of CO₂ on a mass basis (as opposed to a percent reduction basis). The greatest sorbent loading was also observed in Test 5.

Figure 4. Carbon dioxide removal downflow absorption test #1 (3% CO₂)

Figure 5. Carbon dioxide removal downflow adsorption test #2 (3% CO₂)

Figure 6. Carbon dioxide removal: downflow absorption test #3 (3% CO₂)

Figure 7. Carbon dioxide removal: downflow absorption test #4 (3% CO₂)

Figure 8. Carbon dioxide removal: downflow absorption test # 5 (3% CO₂)

Figure 9. Carbon dioxide removal: downflow absorption test #6 (2% CO₂)

Figure 10. Carbon dioxide removal: downflow absorption test #7 (1.5% CO₂)

Full-scale downflow equipment would have a longer gas-solid contact time which could lead to much greater CO₂ removals (and a greater extent of reaction) if the progress of the reaction is not limited by increased surface temperature of the sorbent. Full scale operation would also involve treatment of flue gas with much greater carbon dioxide concentrations.

4.2 Lithium Silicate Sorbent Testing in High Temperature Flue Gas

4.2.1 Thermogravimetric Analyzer Studies

The feasibility of using lithium silicate based sorbents for removal of CO₂ from high temperature flue gas was evaluated by preliminary testing in the TGA. Figure 11 shows the results of three cycles of CO₂ absorption conducted at 600°C in an atmosphere of 20% CO₂/80% N₂. The sorbent displayed a rapid initial weight gain of about 10% due to reaction with CO₂. The reaction proceeded more slowly until the absorption cycle was arbitrarily terminated after approximately 60 minutes. Regeneration at 700°C (two cycles shown) was rapid and essentially complete.

The original lithium silicate sorbent material and two other improved formulations, incorporating different promoters, were tested at 550°C in 20% CO₂/80% N₂. Results are shown in Figure 12. The reactivity of the improved formulations, as characterized by their 10-minute weight gains was greatly increased over the original sorbent. The reactivity of the sorbent incorporating promoter B increased over 150%.

Figure 11. Multicycle CO₂ absorption by lithium silicate sorbent at 600°C; regeneration at 700°C

Figure 12. CO₂ absorption curves of the original and improved lithium silicate sorbents

4.2.2 Low pressure quartz microreactor testing

Six fixed-bed absorption tests were conducted in the 1-in quartz reactor with the lithium silicate sorbent under various conditions. The test conditions and results are shown in Table 3. Capacities are reported based on the mass of CO₂ absorbed in a 10-minute absorption period, as determined by integrating the continuous CO₂ monitor data. These tests conducted with mixtures of CO₂ and N₂ (and H₂O in test 6) demonstrated that the reaction will not be inhibited by the presence of water vapor in flue gas. In addition, the reaction appears to be much faster

at 600°C than at 550°C. Further doubling the gas-solid contact time makes only a small improvement in the capacity of the sorbent, so it may be possible to achieve even faster rates at higher space velocities.

4.2.3 High pressure Reactor Testing

The lithium silicate material was also tested in the high pressure bench-scale reactor in fixed bed mode. A simulated flue gas of 2% CO₂/98% N₂ was used. The CO₂ concentration was limited in this initial test because of concern that, if a higher CO₂ concentration were used, the sorbent temperature might increase (due to the exothermic reaction) to an extent that would limit the reaction. The test was conducted at 280 psig at approximately 550°C. Test data, shown in Figure 13 show almost complete removal of CO₂ in the early stages of the reaction. A slight temperature rise in the sorbent bed was observed, consistent with the exothermic absorption reaction. The CO₂ removal efficiency for the early stages of the test is shown in Figure 14.

Table 3. Summary of Low Pressure High Temperature CO₂ Capture Tests with Lithium Silicate Sorbent

Run ID	CO ₂ Concentration (%)	H ₂ O Concentration (%)	Space Velocity (hr-1)	Temperature (°C)	CO ₂ capacity (wt%)	Comment
1	5	---	1000	550	5.4	low CO ₂ concentration
2	12	---	1000	550	7.0	standard run
3	12	---	500	550	7.1	low Space Velocity
4	24	---	1000	550	8.5	high CO ₂ concentration
5	12	---	1000	600	11.4	high reaction temperature
6	12	18	1000	550	14.6	with H ₂ O

Figure 13. High pressure low concentration CO₂ removal with lithium silicate sorbent

Figure 14. CO₂ Removal efficiency: early stages of high pressure, low concentration test

4.3 Lithium Silicate Sorbent Testing in IGCC Synthesis Gas

4.3.1 Thermogravimetric Analyzer Studies

The feasibility of using lithium silicate based sorbents for removal of CO₂ from high temperature IGCC synthesis gas was evaluated by preliminary testing in the TGA. Testing was conducted in a simulated sulfur free gas mixture containing 12% CO₂ /35% H₂/ 48% CO/ 5% H₂O, at temperatures ranging from 300 to 550°C. Sorbent weight gain data are shown in Figure 15. These data demonstrate that the reaction takes place at temperatures as low as 300°C, but that the rate and extent of weight gain increases with increasing temperature. Because of the presence of CO and H₂O in the simulated syngas, some part of this weight gain may reflect absorption of CO₂ produced by the water gas shift reaction.

Reaction 4

At 550°C, the weight gain approaches 30% of sorbent weight within 3 minutes reaction time. Similar reactivity was observed at a temperature of 550°C in a simulated "raw" syngas mixture containing 12% CO₂ /34% H₂/ 48% CO/ 5% H₂O/ 1% H₂S.

Figure 15. Effect of temperature reactivity of lithium silicate sorbent in clean syngas

4.3.2 Low pressure quartz microreactor testing

A fixed-bed absorption test was conducted in the 1-in quartz reactor with the lithium silicate sorbent at 500°C and atmospheric pressure. The simulated clean syngas contained 10% CO₂/ 42% CO/ 30% H₂/ 18% H₂O. CO₂ removal data are shown in Figure 16. More than 90% CO₂ removal was obtained for the first 9 minutes of the test, after which the outlet CO₂ concentration increased rapidly.

4.4 Economic Analysis of Thermal Swing Co-current Downflow Process for Capture of Carbon Dioxide from Flue Gas

4.4.1 Background

The only currently available process for capturing CO₂ from flue gas that is also capable of being retrofitted to existing plants is based on amine scrubbing. The Econamine FG Plus process (Reddy et al., 2003), which uses a solvent of monoethanolamine (MEA) with an oxidation inhibitor, has been used commercially for CO₂ recovery. Amine-based scrubbing processes are costly and energy intensive because of the presence of contaminants that may be detrimental to the solvent and the energy demand associated with solvent regeneration. The total cost of capturing CO₂ from coal-fired power plant exhaust gas using amine-based systems has been estimated at \$40/ton of CO₂ (Rao and Rubin, 2002). Nonetheless, advanced MEA

Figure 16. CO₂ removal efficiency of lithium silicate sorbent at 500°C and atmospheric pressure: microreactor testing

scrubbing systems are still considered the transition technology. They will be used for many carbon dioxide point sources until emerging capture and separation technologies are demonstrated and operational and technology risks are reduced as required for wide-scale utility application.

All separation processes based on sorbents or solvents involve energy consumption (typically in the form of heat for regeneration of the sorptive media and recovery of the product). Desirable features of these processes include relatively low energy requirements for regeneration/recovery, high working capacity, and the ability to produce a byproduct CO₂ stream of sufficient purity. Additionally, long sorbent life (and low sorbent replacement cost) as well as easy disposability of spent or used sorbent at the end of its useful life contribute to economic attractiveness.

Energy requirements for regeneration/recovery are important, however, in addition to the heat required (desorption, distillation, stripping, heat of reverse reaction), the ultimate energy penalty of the process is dependent to a large extent on the temperature at which this heat is required (or steam pressure). Thus the ability to use heat at a lower temperature or steam at a lower pressure represents a process advantage in that the same amount of heat can be provided at a lower output penalty or less derating of the power plant.

4.4.2 Novel Downflow Reactor Concept

Recognizing these problems with the riser configuration, RTI developed a novel reactor configuration (shown schematically in Figure 17). This design uses a downward flow entrained reactor to reduce the fan horsepower that would be needed to lift the sorbent particles by entrainment in flue gas, but maintains the short residence time and efficient heat transfer mechanism inherent in an entrained-bed reactor. This design employs a hollow screw conveyor to lift and regenerate the sorbent using the latent heat of low-pressure (35 psia) steam to be condensed on the inside of the screw. Based on this design, the proposed CO₂ capture process can be retrofitted between a wet flue gas desulfurization (WFGD) system and exhaust stack with minimal modifications to existing equipment or processes. This makes power plants with WFGD systems the most promising candidates for early adoption of this technology. Figure 18 shows how the proposed process would fit into an existing power plant without any additional equipment requirements.

4.4.3 Economic Evaluation

To evaluate the commercialization potential of the proposed process, cost estimates were developed on the basis of 90 percent removal of the CO₂ produced by a coal fired boiler with a capacity of 500 MWe. With the equipment and utility streams sized accordingly, a preliminary estimate of the capital and operating costs were made. Capital costs were estimated at \$34.7 million. These estimates represent an incremental capital cost of \$76/kWe. Assuming 20 percent for contingencies, the increase in capital cost of \$91/kWe meets DOE goals of limiting CO₂ capture technology capital costs to <10 percent (assuming capital costs of \$1000/kW) for a coal-fired power plant. Annual operating costs were estimated to be approximately \$18.4 million (\$0.0046/kwh).

Figure 17. Conceptual downflow CO₂ capture reaction with heated screw conveyor regenerator

The basis of these estimates was a flue gas rate of 160,000 SCFH per MWe capacity and a desulfurized flue gas concentration of 11.5 percent CO₂ at the outlet of a WFGD. The CO₂ capture process for a 500 MWe power plant would be required to treat 80 million SCFH and collect about 4.9 million tons of CO₂ annually. Dividing this flow into two parallel towers of 14-ft diameter and 80-ft height meets the residence time requirement for the sorbent. A third parallel process train (to serve as a back up during periods of down time for maintenance) was included in the cost estimate.

The scope of the estimate includes the downflow reactor, solids bin, stack fan, two pumps, regenerator off-gas condenser, regeneration and cooling screw conveyors, and the screw motors. CO₂ compression costs were omitted because of the uncertainty regarding site specific requirements and sequestration methods. Sequestration costs are expected to be unaffected by the choice of capture technology.

Figure 18. Retrofit of downflow CO₂ capture process into exiting coal fired power plant

Using the scaled up material/energy balance along with the equipment sizing, all equipment costs were estimated using a module costing technique based on size to provide an overall capital investment. Direct operating costs were calculated while indirect costs were determined by factors taken from Turton et al. based on direct and capital costs (Turton, 2003). Table 4 outlines the results obtained from the cost estimation, exclusive of parasitic power costs.

Operating expenses listed in Table 4 do not include the impact of withdrawal of 35 psia steam (which is used to heat and regenerate the reacted sorbent) from the power generation process. This steam condenses on the inside of the hollow screw conveyor to supply the heat for regenerating the sorbent. If optimal heat integration is assumed for the proposed process, the steam withdrawn for regeneration would lower the useful power production of the plant by about 15 percent. Therefore, the actual annual operating costs for this process should include the power losses from the steam withdrawal in addition to the annual operating cost of the facility.

These power losses were calculated based on steam requirements for electricity generation. According to the Theoretical Steam Rate Tables (ASME, 1969), 5.91 lb of 1500 psia steam superheated to 1000°F would generate 1 kWh of electricity when it is reduced to saturation at 2"Hg (abs). When the same steam is reduced to 35 psia saturation, it requires 8.83 lbs to generate 1 kWh of electricity. Estimating an 80 percent thermal efficiency, 0.044 kWh of electricity is lost for every pound of steam withdrawn to regenerate the sorbent. Figure 19 illustrates how the power cycle is affected by removing the steam for sorbent regeneration.

Table 4. Estimation of Cost to Retrofit CO₂ Capture Process to 500 MWe Plant

Equipment	Bare Module Cost (2001 \$)
Downflow Contactor	\$874,088
Solids Bin	\$319,234
Stack Fan	\$4,246,289
Regenerator Screw	\$1,400,857
Cooling Screw	\$1,400,857
Condenser	\$1,125,310
Screw Motors	\$240,185
Cooling Water Pump	\$34,606
Condensate Pump	\$34,606
Total Bare Module Cost	\$29,028,102

Annual Operating Expenses			
Type	quantity	cost	total
Labor (Col)	12	\$50,000/yr	\$600,000
Replacement Sorbent	4.5x10^6 lb/yr	\$2.00/lb	\$9,055,002
Supervisory and Clerical Labor	0.18*Col		\$108,000
Maintenance	0.06*TCI		\$2,267,375
Operating Supplies	0.009*TCI		\$340,106
Depreciation	0.1*TCI		\$3,778,958
Taxes and Insurance	0.032*TCI		\$1,209,267
Overhead	0.708*Col+0.036*TCI		\$1,785,225
Total Annual Operating Cost			\$18,401,908

Total Capital Investment (TCI)*	
*Estimated as an addition to existing plant and adjusted to 2005 dollars	\$34,658,677

As shown in Figure 19, a 500 MWe power plant would reduce about 3.7 million pounds per hour of 1500 psia superheated steam to 2" Hg (abs) for electricity generation. To regenerate the sorbent, approximately 2 million pounds per hour of 35 psia steam would be withdrawn from the plant (and thus unavailable for power generation). With a power loss of 0.044 kWh/lb of steam withdrawn, the plant would lose about 89 MW, not accounting for any heat integration or efficiency factors. This results in a 17.8 percent de-rating for a 500 MWe plant, but optimum heat integration might reduce this to a realistic value of around 15 percent. These losses in combination with the annual operating expenses would fulfil the criteria set by DOE limit increases in the cost of electricity for post-combustion CO₂ control technology to <20 percent.

Figure 19. Impact on plant output of steam withdrawal

5.0 OTHER PROJECT ACTIVITIES

Two papers were presented in May 2005 at the Fourth Annual Conference on Carbon Capture and Sequestration, in Alexandria, VA.

6.0 CONCLUSIONS

Laboratory studies indicate that the 15% supported sodium carbonate sorbent (SCI-012705-1) will absorb significant quantities of CO_2 from simulated flue gas in a downflow cocurrent reactor system with a gas-solids contact time of approximately 15 seconds. The reaction occurs at temperatures between 25 and 62°C, and is favored by low temperatures and high sorbent to gas ratios. An economic analysis of a system which incorporates a downflow reactor and a upflow heated hollow screw conveyor/regenerator suggested that a system of this design, installed at a wet flue gas desulfurization equipped coal-fired power plant would have an incremental capital cost of \$35 million and operating costs of \$0.0046/kWh.

Lithium silicate sorbents are effective for removal of CO_2 from both flue gas and synthesis gas. The optimal temperature appears to be 550 to 600°C; however the reaction proceeds at temperatures as low as 300°C. The sorbent can be rapidly and essentially completely regenerated by heating to 700°C. The reactivity of the sorbent can be improved by incorporation of promoters. In atmospheric pressure microreactor testing at a space velocity of

1000 hr⁻¹, the sorbent was exposed to synthetic flue gas containing 12% CO₂, and was found to absorb up to 11.4% of its weight of CO₂ in a 10-minute reaction time. In testing, in clean synthesis gas containing 12% CO₂, a weight gain of 28% was observed in the course of 2 minutes. Some part of this weight gain may be CO₂ which was produced by conversion of CO through the water gas shift reaction.

7.0 FUTURE WORK

Additional downflow reactor tests will be conducted to optimize the absorption process for the sodium carbonate based sorbent. Additional design work will be directed toward a bench-scale heated hollow screw regenerator/ conveyor system to evaluate the heat transfer rates achievable for regeneration of the sodium carbonate sorbent and the necessary reaction time.

Additional testing of the lithium silicate sorbent material for removal of CO₂ from flue gas at higher space velocities will be conducted in the 1-in diameter microreactor system. TGA tests will be conducted to determine the effect or the presence of sulfur-containing gases on the reactivity and regenerability of the lithium silicate sorbent.

8.0 REFERENCES

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