CARBON DIOXIDE CAPTURE FROM FLUE GAS USING DRY REGENERABLE SORBENTS

QUARTERLY TECHNICAL PROGRESS REPORT

Reporting Period: January 1, 2001 to March 31, 2001

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DOE Cooperative Agreement No.: DE-FC26-00NT40923

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May 2001

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ABSTRACT

Electrobalance studies of calcination and carbonation of sodium bicarbonate materials were conducted at Louisiana State University. Calcination in an inert atmosphere was rapid and complete at 120°C. Carbonation was temperature dependent, and both the initial rate and the extent of reaction were found to decrease as temperature was increased between 60 and 80°C. A fluidization test apparatus was constructed at RTI and two sodium bicarbonate materials were fluidized in dry nitrogen at 22°C. The bed was completely fluidized at between 9 and 11 in. of water pressure drop. Kinetic rate expression derivations and thermodynamic calculations were conducted at RTI. Based on literature data, a simple reaction rate expression, which is zero order in carbon dioxide and water, was found to provide the best fit against reciprocal temperature. Simulations based on process thermodynamics suggested that approximately 26 percent of the carbon dioxide in flue gas could be recovered using waste heat available at 240°C.

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1.0 EXECUTIVE SUMMARY

The objective of this project is to develop a simple, inexpensive process to separate CO_2 as an essentially pure stream from a fossil fuel combustion system using a regenerable, sodium-based sorbent. The sorbent being used in this project is sodium bicarbonate or "baking soda."

Sodium bicarbonate sorbents were calcined in an inert gas atmosphere in an electrobalance apparatus. Calcination to a final mass consistent with stoichiometric loss of carbon dioxide was rapid and essentially complete at 120°C . Calcined materials were then exposed to a simulated, natural-gas-combustion flue gas of 8 percent carbon dioxide and 16 percent water vapor at 60, 70, and 80°C . Both the initial rate of reaction and the final weight increased with decreasing temperature. The reaction rate approached zero after about 200 min. The temperature dependence of the final weight is consistent with a reversible reaction model.

A fluidization test apparatus was constructed and used to determine pressure drop versus flow rate relationships for two of the sodium bicarbonate materials. Dry nitrogen was used to fluidize the materials at 22°C . Pressure drop data were erratic until absorbed moisture had been removed from the materials. Under cold flow conditions, the bed could be completely fluidized at 9 to 11 in. of water pressure drop, corresponding to a superficial velocity of 5 to 10 ft/min.

Kinetic rates of carbonation of sodium carbonate were derived from the literature and fitted to various reaction rate models. A reaction rate expression that was zero order in both carbon dioxide and water vapor provided the best fit against reciprocal temperature, and an equation representing this relationship is presented.

The thermodynamics of a cyclic calcination/carbonation process was investigated. The availability of waste heat in the flue gas for use in regeneration of the sorbent limits the extent of carbon dioxide recovery possible. Using heat available in flue gas at 240°C , approximately 26 percent of the carbon dioxide present in the flue gas could be recovered with essentially no efficiency penalty to the power plant.

2.0 INTRODUCTION

Increasing amounts of anthropogenic CO₂ emitted into the atmosphere are believed to be a significant factor in global climate change. The Department of Energy's (DOE's) carbon sequestration roadmap makes large point sources of CO₂ emissions (e.g., conventional, pulverized-coal, steam power plants; natural gas-fired combined cycle plants; and advanced power-generation systems) primary targets for carbon sequestration. Development of technologies to implement carbon sequestration at these large point sources is expected to have a rapid and significant impact on anthropogenic CO₂ emissions. This technology development will provide an opportunity for the United States to take the lead in mitigating global greenhouse gas emissions.

Sodium bicarbonate (NaHCO₃) or trona (Na₂CO₃ • NaHCO₃ • 2H₂O) may be used as the basis for a dry, regenerable sorbent technology to economically capture CO₂ from dilute flue gas streams. Sodium bicarbonate, or "baking soda," is commonly used to capture HCl and SO₂ from the flue gas but not to capture CO₂. Note that NaHCO₃ decomposes upon heating according to the reaction

which releases CO₂. Conversely, NaHCO₃ is formed by

In this reaction, CO₂ is absorbed from a flue gas stream by NaHCO₃. Several patents (Krieg, et al., 1984; Sarapata et al., 1987; and Falotico, 1993) describe processes and process improvements to optimize Reaction (2).

The NaHCO₃ can be subsequently regenerated by heating via Reaction (1). In effect, this chemistry enables CO₂ to be separated from a low-pressure flue gas stream and converted into a pure CO₂ stream for subsequent use or sequestration.

HCl and SO₂ in the flue gas are also absorbed by NaHCO₃ according to the following reactions:

In fact, Reactions (3) and (4) are used industrially for removing acidic compounds from incinerator and furnace stack gases (Maziuk, 1996). Commercial-grade NaHCO₃ has also been used as an in-duct injection sorbent for removal of SO₂ and HCl from hydrogen chloride flue gas streams generated in coal-fired power plants. Despite significantly better performance of NaHCO₃ over limestone, its use for SO₂ removal has gained limited commercial acceptance in the electric utility industry primarily because of its high cost when considered for one-time use (not regenerated).

Trona may also be used as a regenerable sorbent for CO₂ according to the following reactions:

Trona is initially calcined according to

Subsequent carbonation and calcination reactions proceed according to

This report describes activities conducted between January 1, 2001 and March 31, 2001 by Research Triangle Institute (RTI) and subcontractors Louisiana State University (LSU) and Church and Dwight (C&D). Activities conducted this quarter include electrobalance (thermogravimetric analysis [TGA]) studies at LSU, sorbent characterization at C&D the assembly of a cold-flow fluidization test apparatus at RTI, fluidization testing at RTI, kinetic rate investigations based on literature data at RTI, and process optimization at RTI.

3.0 EXPERIMENTAL

3.1 Electrobalance (Thermogravimetric Analysis) Testing

Six sodium-based sorbents were forwarded to LSU from RTI—four grades of sodium bicarbonate (SBC) from C&D and two grades of trona from Solvay (natural sodium sesquicarbonate, Na₂CO₃•NaHCO₃•2H₂O). Selected properties of these materials, both as-received and following calcination was reported in the initial RTI quarterly report (Green et al., 2001).

Table 1 describes the six sorbents and Table 2 summarizes the reaction conditions studied to date at LSU. All SBC samples from C&D were effectively 100% pure; the primary difference was the particle size. The trona samples differed both in purity and particle size.

Table 1. Sorbent Precursor Descriptions

Sorbent Precursor		Manufacturer	Description
Grade #1	SBC	C&D	USP Powdered
Grade #2	SBC	C&D	USP Fine Granular
Grade #3	SBC	C&D	USP Fine Powdered
Grade #5	SBC	C&D	USP Coarse Granular
T-50	Trona	Solvay	93.5% Purity
T-200	Trona	Solvay	97.5% Purity

Pressure during calcination and carbonation was limited to 1 atm for application to flue gases, while the calcination temperature and range of carbonation temperatures studied were based on prior thermodynamic analysis. The CO₂ and H₂O contents of the carbonation gas provide a reasonable approximation of actual contents resulting from the combustion of CH₄ using 10 percent excess air.

An electrobalance has been used during the initial experimental phase. All tests to date have used the same calcination conditions and the same carbonation gas composition. The sole reaction parameter studied to date has been carbonation temperature. An initial charge of approximately 75 mg of sorbent precursor was heated from room temperature to 100°C at a rate of 5°C/min and from 100°C to the final calcination temperature of 120°C at a rate of 1°C/min under flowing He.

After calcination was complete (as indicated by constant weight), the temperature was decreased at a rate of 1°C/min—still under He—until the desired carbonation temperature (60°C to 80°C) was reached. The gas composition was then changed to 8-mol% CO₂, 16-mol% H₂O, balance He at 300 sccm, and carbonation was continued until the reaction rate approached zero.

Table 3 indicates the matrix of single-cycle experimental tests completed to date. An ‘x’ in the matrix indicates that a run has been completed using the indicated sorbent and carbonation temperature. Duplicate runs have been completed using SBC Grade #1 at 70°C. As will be discussed, not all results are consistent at this time and selected runs will be repeated in the future.

Table 2. Sorbent Reaction Conditions

Calcination	
Temperature	120°C
Pressure	1 atm
Gas Composition	100% He
Carbonation	
Temperature	60°C, 70°C, or 80°C
Pressure	1 atm
Gas Composition	8 mol% CO ₂ 16 mol% H ₂ O 76 mol% He
Gas Flow Rate	300 sccm

Table 3. Matrix of Completed Single-Cycle Tests

Carbonation Temperature, °C	Sorbent					
	#1	#2	#3	#5	T-50	T-200
60	x		x		x	
70	x, x	x	x	x	x	x
80	x		x		x	

3.2 Fluidization Testing

A cold flow fluidization test unit was designed and constructed at RTI in order to obtain data for designing a fluid-bed reactor. The test unit is constructed of 4-in. transparent polyvinyl chloride (PVC) pipe, fitted with a porous quartz frit to support the bed of sorbent material. A Brooks 5851-E mass flow controller, with a range of 0 to 50 slpm, is used to meter dry nitrogen to a plenum below the frit. Differential pressure is measured with a Capsuhelic model W32FNS129 gauge, connected to pressure taps below the frit and at the exit from the PVC pipe. The gas outlet tube is equipped with a fabric filter to control nuisance dust. The unit is shown in Figure 1.

Figure 1. Fluid-bed Cold-flow Test Unit

RTI conducted fluidization tests to determine pressure drops as a function of gas velocity on two sodium bicarbonate materials.

4.0 RESULTS AND DISCUSSION

4.1 Electrobalance (TGA) Testing at LSU

4.1.1 Typical Electrobalance Response Curve

A typical, single-cycle, electrobalance response curve is shown in Figure 2, where dimensionless sample weight and temperature are shown as a function of time. SBC Grade #3 sorbent was used in this test at a carbonation temperature of 60°C, following calcination of the sorbent. Decomposition of NaHCO_3 to Na_2CO_3 began at about 100°C and was complete soon

after the final calcination temperature of 120°C was reached. The final dimensionless weight, m_f , is quite near the theoretical value of 0.631 that is indicated by the horizontal dashed line.

Figure 2. Typical Electrobalance Response During a Single Calcination-Carbonation Cycle

The temperature was then decreased to the 60°C carbonation temperature. CO₂ and H₂O were added after 150 min to produce the desired carbonation gas composition at a total flow rate of 300 sccm. The dimensionless weight increase corresponded to removal of CO₂ from the gas phase via the conversion of Na₂CO₃ to 2NaHCO₃. The global reaction rate, which is related to the slope of the dimensionless weight-time curve, begins at a high value, decreases with time, and approaches zero after about 300 min. Complete carbonation would produce a final dimensionless weight of 1.0 and fractional carbonation as a function of time, $f(t)$, can be calculated from

$$f(t) = \frac{m(t) - 0.631}{1.0 - 0.631} = \frac{m(t) - 0.631}{0.369} \quad (7)$$

$m(t)$ is the dimensionless weight at time t after the beginning of carbonation. In this example test $f(200)$ (measured between 150 and 350 min), is approximately 0.67. The results shown in Figure 2 are typical of all tests completed to date.

4.1.2 Reproducibility

Figure 3 shows the dimensionless weight as a function of time during the carbonation phase of the two tests at 70°C using SBC sorbent Grade #1. Electrobalance noise shown in Figure 2 has been removed by smoothing the data so that the individual test results may be clearly distinguished. There is considerable difference in early results from the two tests, but little difference after about 130 minutes.

Figure 3. Duplicate Carbonation Tests Using SBC Grade #1 at 70°C.

Note that one of the tests shows a maximum dimensionless weight after about 200 min. While there is no readily apparent reason why this maximum should exist, possible causes are currently being investigated. Possibilities include an anomaly associated with the data smoothing routine and/or temperature fluctuations during the experiment.

4.1.3 Calcination

As indicated in the previous section, the theoretical value of the final dimensionless weight corresponding to complete calcination of NaHCO_3 is 0.631. Final experimental values, which ranged from 0.622 to 0.637, were all consistent with complete calcination.

The theoretical dimensionless weights corresponding to complete calcination of the trona samples are different because of the different initial composition and presence of impurities. The following values for final dimensionless weight were calculated based on the assumption that the impurities are nonvolatile. For T-200 containing 2.5% impurities, $m_f = 0.711$, and for T-50 with 6.5% impurities, $m_f = 0.723$. Experimental values for the three tests using T-50 were consistent with the theoretical value and ranged from 0.717 to 0.727. However, in the single test using T-200, the experimental value of $m_f = 0.760$ was significantly above the theoretical value.

4.2 Carbonation

Figure 4 compares the smoothed results for the three tests using SBC Grade #3 at temperatures of 60°C, 70°C, and 80°C. Only the carbonation portion of the cycle is shown, and

$t = 0$ corresponds to the introduction of reactive CO₂ and H₂O. Both the initial rate of reaction, as measured by the initial slope of the dimensionless weight-time curve, and the final dimensionless weight increased with decreasing temperature. In addition, the reaction rate approached zero after about 200 min of carbonation at both 60°C and 70°C, while the reaction rate was small, but finite, after 200 min at 80°C. An additional run at lower temperature, say 50°C, is impossible with this feed gas composition because the dew point of the gas is above 50°C.

Figure 4. The Effect of Carbonation Temperature Using SBC Grade #3

The decreasing rate with increasing temperature is attributed to reaction reversibility. The carbonation reaction is exothermic and equilibrium fractional CO₂ removal decreases with increasing temperature. It is reasonable to speculate that the reaction rate is proportional to the difference between the CO₂ concentration in the bulk gas and the equilibrium CO₂ concentration at that temperature. The "HSC Chemistry" program was used to calculate the equilibrium mole fraction of CO₂ as a function of temperature, and the difference between bulk and equilibrium concentrations was calculated from the following equation:

$$C_{Ao} - C_{Ae} = \frac{(y_{Ao} - y_{Ae})P}{RT} \quad (8)$$

C_{Ao} and C_{Ae} are the bulk and equilibrium concentrations of CO₂, y_{Ao} and y_{Ae} are the bulk and equilibrium mole fractions of CO₂, P is the pressure, R is the gas constant, and T is the absolute temperature. The results are:

$$T = 60^{\circ}\text{C} \quad C_{Ao} - C_{Ae} = 0.0028 \text{ mol/L}$$

$$T = 70^{\circ}\text{C} \quad C_{Ao} - C_{Ae} = 0.0025 \text{ mol/L}$$

$$T = 80^{\circ}\text{C} \quad C_{A0} - C_{Ae} = 0.0016 \text{ mol/L.}$$

Thus, the CO_2 reaction-driving force is reduced by more than 40 percent at 80°C compared to 60°C .

Figure 5 compares the dimensionless weight-versus-time response during the carbonation cycle for three samples—SBC Grades #1 and #3 and trona T-50—for a reaction temperature of 60°C . The initial dimensionless weights are again very close to the theoretical values of 0.631 for SBC and 0.723 for trona T-50. The initial reaction rates, as measured by the slopes of the curves between $t=0$ and $t=25$ min, are approximately equal. Similarly, the final dimensionless weights for the two SBC samples are reasonably close. Note that the larger final value of dimensionless weight for trona T-50 does not necessarily correspond to increased fractional carbonation since the final dimensionless weight corresponding to complete carbonation of that sample would be about 1.12.

Figure 5. Comparison of the Carbonation Results of Three Sorbents at 60°C

The previous figures indicate that the dimensionless weight-time curves are approximately linear during the early stages of the reaction and that carbonation is essentially complete after 200 min at both 60°C and 70°C . As a result, fractional carbonation after 25 min was arbitrarily selected to represent the initial reaction rate and fractional carbonation after 200 min to represent the realistically achievable sorbent capacity. Fractional conversions $f(25)$ and $f(200)$ were calculated according to Equation 7 for the SBC sorbents and according to Equations 9 and 10 for the trona sorbents.

$$f(t) = \frac{m(t) - 0.723}{1.12 - 0.723} = \frac{m(t) - 0.723}{0.397} \quad \text{Trona T-50} \quad (9)$$

$$f(t) = \frac{m(t) - 0.711}{1.12 - 0.711} = \frac{m(t) - 0.711}{0.409} \quad \text{Trona T-200} \quad (10)$$

$f(25)$ and $f(200)$ results are summarized in matrix form in Tables 4 and 5, respectively.

Table 4. Initial Reaction Rates as Represented by Values of $f(25)$

Carbonation Temperature, °C	Sorbent					
	SBC #1	SBC #2	SBC #3	SBC #5	T-50	T-200
60	0.25		0.24		0.22	
70	0.16, 0.08	0.14	0.16	0.15	0.13	0.24
80	0.02		0.02		0.19	

Table 5. Achievable Sorbent Capacity as Represented by Values of $f(200)$

Carbonation Temperature, °C	Sorbent					
	SBC #1	SBC #2	SBC #3	SBC #5	T-50	T-200
60	.067		0.67		0.67	
70	0.59, 0.62	0.59	0.60	0.61	0.53	0.59
80	0.29		0.23		0.49	

Table 4 shows, in general, that the initial reaction rate decreases with increasing temperature. This is certainly true for SBC Grades 1# and #3, but not necessarily true for trona T-50. Achievable capacity, $f(200)$, also appears to decrease with increasing temperature. All sorbents tested at all three temperatures show this effect, but the decrease observed with trona T-50 is smaller than with either of the SBC sorbents.

There appears to be relatively little difference in either the initial reaction rate or the achievable capacity among the different sorbents. At 60°C, both the initial rate and achievable capacity are effectively equal for SBC Grade #1, SBC Grade #3, and trona T-50. Similarly, five of the seven tests at 70°C produced similar initial rates, and the achievable conversion was reasonably close for all seven tests. Both NaHCO₃ sorbents tested at 80°C gave similar initial rates and achievable conversion, but results using trona T-50 were quite different.

Identification of the ‘outlying’ results from Tables 4 and 5 provides guidance for selecting tests that should be repeated. The candidates for repeat tests are SBC Grade #1 at 70°C, trona T-200 at 70°C, and trona T-50 at 80°C.

4.3 Fluidization Test Data

Fluidization tests were conducted on SBC Grade #3 and SBC Grade #5 in the cold-flow test apparatus to obtain pressure drops and minimum fluidization velocities for design of the fluidized-bed reactor system. Both materials were tested at 22°C with sorbent masses of 2.5 kg. Initial attempts to test these materials led to erratic pressure drop data, which probably resulted from small amounts of moisture in the sorbent. Because the fluidizing gas used was dry nitrogen from a compressed gas cylinder, the pressure drop data stabilized after the fluidizing gas passed through the bed for a few hours. The data presented in Figures 6 and 7 represent test data

obtained on fresh SBC Grade #3 and SBC Grade #5 sorbents after they had been dried in the fluidization apparatus.

The data suggest that the bed can be completely fluidized at a pressure drop of 9 to 11 in. of water, corresponding to a superficial velocity of 5 to 10 ft/min. The mass of the bed, 2.5 kg (5.5 lb) divided by the cross-sectional area of the test apparatus, 81.3 cm² (12.6 in²), corresponds to a pressure of about 12 in. of water. Additional tests on other sorbents, as well as calcined sorbents are planned for the next quarter.

4.4 Kinetic Rate Derivations

RTI derived kinetic rate constants for use in reactor design from the examples given by Sarapata, et al. (1987). The data, which included eight usable measurements, were tested against five different reaction rate expressions. Equations 11 through 15 represent the models tested:

$$-\ln(1-X) = k_1 t \quad (11)$$

$$-\ln(1-X) = k_2 P_{CO_2} t \quad (12)$$

$$-\ln(1-X) = k_3 P_{CO_2} P_{H_2O} t \quad (13)$$

$$-\ln(1-X) = k_4 (P_{CO_2} P_{H_2O} - K_{eq}) t \quad (14)$$

$$-\ln(1-X) = k_5 P_{H_2O} t \quad (15)$$

where,

X = the extent of Reaction (2)

P_{CO₂} = the partial pressure of CO₂, atm

P_{H₂O} = the partial pressure of H₂O, atm

t = reaction time, min

Figure 6. Fluidization of SBC Grade #3

Figure 7. Fluidization of SBC Grade #5

K_{eq} = the temperature-specific equilibrium constant for Reaction (1),
calculated as,

$$\ln (K_{eq}) = 40.23 - (15445/T) \quad (16)$$

where,

T = the temperature, K

and k_1 through k_5 are the relevant kinetic constants.

Sarapata's data and the corresponding kinetic constants are given in Table 6.

When the derived rate constants were tested for linearity against the inverse absolute reaction temperature, the best fit was obtained with the constants derived from Reaction (11). Based on Sarapata's data,

$$k_1 = 1.572 \times 10^3 e^{(-3550/T)} \quad (17)$$

This value of rate constant will be compared with the TGA results of LSU and bench-scale testing to be conducted at RTI.

4.5 Process Simulation and Optimization

The most significant limitation on the use of the sorbents investigated is the availability of process energy to regenerate the sorbent and release a concentrated carbon dioxide stream. The exothermic reaction of carbon dioxide with sodium carbonate occurs rapidly at temperatures below 70°C. Energy available at this temperature has a low value. Regeneration of the sodium bicarbonate takes place readily at temperatures greater than 110°C. Waste heat in flue gas is generally used to preheat combustion air and boiler feed water. Following recovery of heat for these purposes, flue gas is often available for discharge at 175 to 250°C. Following sorbent regeneration, the flue gas would still require a temperature sufficient to rise through the

Table 6. Reaction Data for Carbonation of Sodium Carbonate and Kinetic Rate Constants.

		Inlet Gas					Initial Solids		Reaction Rate Constants				
Example*	Temp (°F)	PCO ₂ (atm)	PH ₂ O (atm)	Keq (atm ²)	X _{Na2CO3}	t (min)	Na ₂ CO ₃ (g)	NaHCO ₃ (g)	K1 (min ⁻¹)	K2 (min ⁻¹ atm ⁻¹)	K3 (min ⁻¹ atm ⁻²)	K4 (min ⁻¹ atm ⁻²)	K5 (min ⁻¹ atm ⁻¹)
II	194	0.300	0.700	0.1024	0.8085	20	500	0	8.26 × 10 ⁻²	2.75 × 10 ⁻¹	3.94 × 10 ⁻¹	7.68 × 10 ⁻¹	1.18 × 10 ⁻¹
III	158	0.135	0.307	8.605 × 10 ⁻³	0.9113	45	306.6	306.6	5.38 × 10 ⁻²	3.99 × 10 ⁻¹	1.3	1.64	1.75 × 10 ⁻¹
IV	122	0.107	0.123	5.324 × 10 ⁻⁴	0.6614	40	211	422	2.71 × 10 ⁻²	2.53 × 10 ⁻¹	2.06	2.14	2.20 × 10 ⁻¹
IV	122	0.107	0.123	5.324 × 10 ⁻⁴	0.9117	50	211	422	4.85 × 10 ⁻²	4.54 × 10 ⁻¹	3.69	3.84	3.95 × 10 ⁻¹
V	122	0.062	0.123	5.324 × 10 ⁻⁴	0.8744	70	306.6	306.6	2.96 × 10 ⁻²	4.78 × 10 ⁻¹	3.89	4.18	2.41 × 10 ⁻¹
VI	87.8	0.113	0.0459	2.698 × 10 ⁻⁵	0.8645	260	500	0	7.69 × 10 ⁻³	6.80 × 10 ⁻²	1.48	1.49	1.67 × 10 ⁻¹
VII	87.8	0.143	0.0459	2.698 × 10 ⁻⁵	0.8362	160	500	0	1.13 × 10 ⁻²	7.91 × 10 ⁻²	1.72	1.73	2.46 × 10 ⁻¹
VII	87.8	0.143	0.0459	2.698 × 10 ⁻⁵	0.923	180	500	0	1.42 × 10 ⁻²	9.96 × 10 ⁻²	2.17	2.18	3.10 × 10 ⁻¹

*Example numbers are based on Sarapata (1987).

LSU will continue electrobalance testing of carbonation and regeneration reactions, and repeat tests where precision appears questionable. C&D will undertake additional materials characterization determination, particularly focusing on additional surface areas measurements, and will also advise RTI on various engineering issues involved with injection of H₂O during carbonation and regeneration of sorbent to monohydrate phase.

5.0 CONCLUSIONS

1. Electrobalance studies indicated that sodium bicarbonate materials could be rapidly calcined in an inert atmosphere at 120°C.
2. The reaction of sodium carbonate and carbon dioxide, in gas representative of flue gas from natural gas combustion, was temperature dependent, both with regard to initial rate and extent of reaction, in the range of 60 to 80°C.
3. Two sodium bicarbonate sorbent materials were fluidized in dry nitrogen in RTI's fluidization test apparatus at superficial velocities of 5 to 10 ft/min. The fluidization characteristics of these sorbents matched with standard catalysts used in petroleum refineries.
4. Based on literature data, the rate of reaction of sodium carbonate to sodium bicarbonate can be represented by
- $\ln(1-X) = k_1 t$, where
 $k_1 = 1.572 \times 10^3 e^{(-3550/T)}$
5. Using waste heat available in natural gas combustion gas, process simulations indicated that approximately 26 percent of the carbon dioxide produced can be captured in a cyclic calcination/carbonation scheme.

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