ADVANCED IN-DUCT SORBENT INJECTION FOR SO₂ CONTROL

TOPICAL REPORT NO. 3 SUBTASK 2.3: SORBENT OPTIMIZATION

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ABSTRACT

The objective of this research project is to develop second-generation duct injection technology as a cost-effective compliance option for the 1990 Clean Air Act Amendments. Specific process performance goals are to achieve 90% SO₂ removal and 60% sorbent utilization efficiency. Research is focused on the Advanced Coolside process, which has shown the potential of achieving these targets. The objective of Subtask 2.3, Sorbent Optimization, was to explore means of improving performance and economics of the Advanced Coolside process through optimizing the sorbent system. Pilot plant tests of commercial and specially prepared hydrated limes showed that the process is relatively insensitive to sorbent source. This can be an important economic advantage, allowing the use of the lowest cost sorbent available at a site. A pilot plant hydration study conducted in cooperation with Dravo Lime Company further indicated the relative insensitivity of process performance to lime source and to lime physical properties. Pilot plant tests indicated that the use of very small amounts of additives in the Advanced Coolside process can improve performance under some circumstances; however, additives are not necessary to exceed process performance targets.

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BACKGROUND AND INTRODUCTION

In-duct dry sorbent injection technology has been actively developed in the U.S. since the early 1980s. The performance of these processes has been well-established through the development of the Coolside process (CONSOL)¹⁻⁶ and the HALT process (Dravo)^{7,8} and through the DOE duct injection technology development program.⁹⁻¹¹ These development efforts have included pilot-scale tests, proof-of-concept tests, and a full-scale utility demonstration. Established performance is in the range of 40-50% SO₂ removal at 2.0/1 Ca/S molar ratio and 20-25°F approach to adiabatic saturation temperature using hydrated lime as the sorbent. Additionally, the 105 MWe demonstration of the Coolside process at the Ohio Edison Edgewater Station⁴⁻⁶ showed that an SO₂ removal of 70% can be attained by improving calcium hydroxide sorbent activity with sodium-based additive injection at a 0.2 Na/Ca molar ratio (~32% sorbent utilization).

Process performance data and economic analyses support the potential attractiveness of duct sorbent injection for a range of retrofit applications.¹² However, the applicability as a compliance option for the Clean Air Act or other regulations can be expanded by increasing SO₂ removal and sorbent utilization. Higher SO₂ removal became more important for retrofit technologies with the passage of the 1990 Clean Air Act Amendments, which limit SO₂ emissions to 1.2 lb/MMBtu by the year 2000 and establish an emission cap thereafter. Higher sorbent utilization is an important area for improvement because of the large impact of sorbent cost on total cost of SO₂ removal.

The objectives of the project entitled "Advanced In-Duct Sorbent Injection for SO₂ Control" (DOE Contract DE-AC22-91PC90360) are to improve the applicability of in-duct sorbent injection technology as a compliance option for the 1990 Clean Air Act Amendments and to reduce total SO₂ control costs. Specific desulfurization performance targets were established for realizing these objectives. These are to achieve 90% SO₂ removal and 60% sorbent utilization, while retaining the low capital cost and retrofit advantages inherent to in-duct technology.

These targets represent a substantial improvement over existing sorbent injection technologies.

In Subtask 2.1 of this project, Evaluation of Advanced Concepts, pilot plant tests indicated that a process concept, referred to as the Advanced Coolside process, had the potential to achieve the process performance targets (Reference 13: Topical Report 1). SO₂ removal over 90% and sorbent utilization efficiency over 60% was achieved. Other concepts for advanced sorbent injection were evaluated in Subtask 2.1; however, none showed the potential to meet process performance objectives. As recommended in the first Topical Report,¹³ all further testing has focused on optimizing the Advanced Coolside process.

The Advanced Coolside process involves flue gas humidification to near the adiabatic saturation point using a contacting device which simultaneously removes most of the fly ash from the flue gas. The sorbent (hydrated lime) is injected into the highly humid flue gas downstream of the contactor, where it captures SO₂ before being removed in the existing particulate collector. The very high humidity allows high SO₂ removal. High sorbent utilization is achieved by sorbent recycle. Greater recycle is possible than for other duct sorbent injection processes because the fly ash is removed by the contactor prior to sorbent injection. Furthermore, previous testing¹³ indicated that addition of some moisture to the recycle sorbent prior to reinjection can significantly improve process performance.

Subtask 2.1 of this project indicated several approaches for improving the Advanced Coolside process, including optimization of sorbent recycle, optimization of process equipment to reduce capital cost, and optimization of the sorbent. Recycle optimization and process design optimization were evaluated through pilot plant tests in Subtask 2.2 and are reported in Topical Report 2. This report discusses the results of the Sorbent Optimization program.

The objectives of Sorbent Optimization (Subtask 2.3) were to improve process SO₂ removal performance and to improve process economics by increasing sorbent utilization efficiency and/or by reducing sorbent cost. The approach was to develop an understanding of the impacts of sorbent properties on process performance. Previous testing of the Advanced Coolside process used a single

commercial hydrated lime. The sorbent optimization test program included work in the following areas:

- Pilot plant testing of different commercially available sorbents with a range of chemical/physical properties and from a range of geographical regions.
- Pilot plant testing of alternative sorbents such as specially prepared high surface area hydrated limes.
- A test program to investigate the effects of hydration process variables on resulting hydrated lime properties and to investigate the effects of these hydrated lime properties on desulfurization performance. This program was conducted in cooperation with Dravo Lime Company using their lime hydration pilot plant test facility.
- Tests to determine the effects of additives for improving sorbent performance.

CONCLUSIONS

Following are the major conclusions of Subtask 2.3, the Sorbent Optimization program:

1. Pilot plant tests of five different commercial calcitic hydrated limes showed that the Advanced Coolside process is relatively insensitive to the lime source. In conventional sorbent injection processes, such as the Coolside process, sorbent source has a more substantial impact on performance.⁴ The relative insensitivity of the Advanced Coolside process to sorbent source can be an economic advantage, allowing the use of the lowest cost sorbent available. The limes tested represented different geographical regions and were selected from the largest hydration plants in the U.S. The surface areas of the limes ranged from 14 to 24 m²/g. Limes tested in steady-state recycle tests gave SO₂ removals ranging from 86 to 90% at 1.2 Ca/S.
2. Tests did not indicate a substantial advantage to the use of specially prepared high surface area (35-40 m²/g) hydrated limes. One of these sorbents showed marginally better performance than commercial lime; another showed poorer performance.
3. The lime hydration study showed that there is a weak correlation of desulfurization performance with hydration process variables and with lime physical properties. One variable which had a statistically significant positive effect on lime activity was residual moisture content. Hydrated limes produced from two different quicklimes gave similar desulfurization performance, further confirming the insensitivity to sorbent source.
4. Hydrated limes produced in the Dravo pilot plant hydrator consistently had lower surface areas and exhibited lower desulfurization activity than commercially hydrated limes from the same quicklime. Because of the inability of the pilot hydrator to closely simulate commercial hydration, only a limited number of tests were conducted to produce advanced sorbents such as additive-promoted limes.

5. Pilot plant tests showed that the addition of small amounts of additives to the recycle sorbent during the water addition step can improve overall system (duct + baghouse) desulfurization performance. With addition of NaCl or CaCl_2 at a ratio of 0.03 mol/mol fresh Ca, SO_2 removals of 97 to >99% were achieved at Ca/S ratios as low as 1.2. Sorbent utilization efficiencies up to 80% were observed with these additives. The additive addition rates employed were quite small, about 1/15 of that used in the conventional Coolside process. The effect of additive addition was primarily to increase removal across the baghouse. Therefore, these results are primarily applicable for achieving very high SO_2 removal efficiency in a retrofit or new plant with a baghouse. In all the pilot tests the additive was added within the Advanced Coolside process during recycle wetting; this is an advantage in that a commercial hydrated lime from any hydration plant can be used as the sorbent.

DESCRIPTION OF ADVANCED COOLSIDE PROCESS

Figure 1 shows a schematic of the Advanced Coolside process. The process achieves greater SO_2 removal and sorbent utilization than previous duct sorbent injection processes by operating at a higher flue gas humidity and by more fully exploiting the potential of sorbent recycle. The key to the process is a gas/liquid contacting device downstream of the air preheater. The contactor serves two purposes: to nearly saturate the flue gas with water, and to remove most of the coal fly ash from the flue gas. The sorbent is injected downstream of the contactor into the highly humid flue gas. Hydrated lime is very active for SO_2 capture near the saturation point, even in the absence of liquid water droplets. Because the flue gas is humidified prior to sorbent injection, there is no residence time requirement for droplet evaporation. SO_2 is removed in the duct and by the sorbent collected in the existing electrostatic precipitator (ESP) or baghouse. The heat of reaction between SO_2 and hydrated lime raises the temperature of the flue gas by roughly 8-10 °F for each 1000 ppm of SO_2 removed. Therefore, the particulate collector can be operated at an elevated approach to saturation without flue gas reheat. However, because hydrated lime activity is highly sensitive to the approach to saturation, this reaction heat effect also acts as a limiting mechanism for SO_2 capture.

The spent sorbent is captured by the existing particulate collector as a dry powder. Sorbent recycle is an integral component of the Advanced Coolside process. Laboratory and pilot plant tests have shown that recycle sorbent is quite active for SO_2 capture at high humidity. The potential for recycle is increased because fly ash is removed separately before sorbent injection. Furthermore, process performance can be improved by adding small amounts of water to the recycle sorbent prior to re-injection. Water can be added to the recycle sorbent or to the combined recycle and fresh sorbents. The water acts to maintain a close approach to saturation, by evaporating and counteracting the heat of reaction.

Design optimization has been focused on the flue gas/water contactor. For the initial pilot plant testing the contacting device was a Waterloo scrubber.^{14,15} This is a commercially available device, marketed by Turbotak Technologies Inc. (Turbotak), and used primarily for removal of submicron particles from gas

streams. Design and testing of improved contactor designs, substantially simpler than the Waterloo scrubber, were conducted as part of Subtask 2.2 (Design Optimization) and are reported in Topical Report 2.¹⁶

EXPERIMENTAL

ADVANCED COOLSIDE PILOT PLANT DESCRIPTION

Figure 2 is a schematic of the Advanced Coolside desulfurization pilot plant. It is designed to simulate integrated Advanced Coolside operation with combined flue gas saturation and fly ash removal using a contactor, and sorbent injection downstream of the contactor into the saturated flue gas. The plant consists of a flue gas generation system, a flue gas/water contactor, a spent slurry handling system, sorbent injection systems, a recycle sorbent moisture addition system, the test duct section/reactor, a baghouse, and a flue gas analysis system.

Flue Gas Generation System

A simulated flue gas stream is produced by mixing the combustion products of a natural gas combustor, bottled gases (SO_2 and CO_2), steam, plant N_2 , and fly ash with a recycle gas stream within the pilot plant. Gas flow rates of 150 to 350 scfm are generated in this manner. The gas combustor serves to generate make-up flue gas and to raise the flue gas temperature to the desired level. The inlet SO_2 content can be varied from 500 to 2500 ppm by SO_2 injection. The fly ash loading can be varied from 0 to 5 gr/scf. The flue gas adiabatic saturation temperature at the baghouse exit is controlled by the rate of steam injection upstream of the contactor.

Gas recycle provides over 80% of the simulated flue gas flow. After particulate removal, the flue gas is cooled by a heat exchanger, and condensed water is removed by an impaction separator. The gas then is recycled by means of a blower.

Contactor

Most of the sorbent optimization testing was conducted using a second-generation contactor, which consists of a spray chamber followed by a mist eliminator (Figure 3). Some testing was conducted using the third-generation contactor, which consists of a low pressure drop venturi and a centrifugal separator (Figure 4). Both contactors were designed to remove fly ash and saturate flue gas to near saturation. The contactor designs and performance are detailed in Topical Report No. 2.

Spent Slurry Handling

Solids are removed as a slurry from the contactor. The spent slurry is pumped to a gravity separator. Solids are removed as a sludge (approximately 50/50 fly ash/water by weight). The clarified liquor is recycled to the Waterloo scrubber. Make-up fresh water is added as needed.

Flue Gas Ductwork

The saturated flue gas exiting the contactor passes through 53 ft of 5-inch pipe, then 24 ft of 8-inch pipe and then 7 ft of 4-inch pipe before entering the baghouse. This simulates the ductwork in the Advanced Coolside process, providing contact between sorbent particles and the humid flue gas. Sorbent was injected at the contactor exit into the 5-inch pipe.

Recycle Sorbent Moisture Addition

A batch mixer manufactured by Littleford Bros., Inc. (Model FM-130) is used for tests with water addition to recycle sorbent. The mixer is equipped with low-speed plow mixers and a high-speed chopper. Water is added to recycle sorbent using a hydraulic nozzle while the mixer is operating. The water addition/mixing procedure takes about 3-4 minutes for each 60-70 lb batch of recycle sorbent. The mixer used for moisture addition was not optimized for these tests.

Baghouse

A baghouse is used to remove particulate from the duct effluent flue gas. It is a pulse-jet type baghouse with nine bags, giving a total cloth area of 144 ft². Solids are collected in a 55-gal drum under the baghouse hopper. The hopper is sealed by a butterfly valve. The baghouse is heat traced to maintain adiabatic operation.

The flue gas can be reheated before the baghouse to control the approach to saturation at the baghouse exit. Reheat is accomplished by injecting hot air between the duct exit and the baghouse. The approach to saturation at the baghouse exit can be varied from 10 to 25 °F. As mentioned above, a 10 °F approach can be maintained without reheat, due to the reaction heat effect.

Flue Gas Analysis

The flue gas composition is measured continuously by on-line analyzers at four locations: the contactor inlet, the contactor exit (duct inlet), the duct outlet, and the baghouse exit. This allows calculation of SO₂ removals in the contactor, in the ductwork, and in the baghouse. SO₂ and O₂ contents are measured at all locations. The O₂ content is used to correct for air in-leakage. Gas sampling systems are designed to prevent further reaction of SO₂ with the sorbent particles. The sample probe is designed to pull a gas sample at a low velocity (<2 ft/sec) countercurrent to the high-velocity (>40 ft/sec) flue gas flow; this minimizes sorbent entrainment in the gas sample. The sample then is filtered using a heated (>300 °F) filter to minimize reactions between SO₂ and any sorbent particles.

LABORATORY DESULFURIZATION UNIT DESCRIPTION

Some sorbents were screened prior to testing in the pilot plant using a fixed-bed laboratory reactor (Figure 5). The sorbent particles are dispersed in a quartz wool matrix for efficient gas-solid contact. The matrix is contained in a glass tube reactor immersed in a constant temperature bath. The sorbent particles are contacted with a feed gas consisting of 1000 ppm SO₂ in N₂ at set conditions of temperature, contact time and relative humidity. A known portion of the N₂ inlet gas is passed through an electrically heated gas saturator prior to the reactor. The temperature of the saturator determines the relative humidity in the reactor. The utilization of the sorbent is determined by the S/Ca molar ratio of the recovered material.

DRAVO PILOT HYDRATION PLANT DESCRIPTION

The hydration test program was conducted in a continuous horizontal hydrator which has a production capacity of up to 3 tons per day. Quicklime raw feed is stored in 55-gallon drums. The lime is delivered through a hopper onto a variable speed conveyor. The lime size can be varied. Feed rates can be varied from 60 to 240 lb/hr. The conveyor delivers the lime into a mixing chamber equipped with interlocking sectional screw flights, counter-rotating to provide intimate mixing with the hydration water. The hydration water is delivered to the mixing chamber with or without a nozzle. Additives, if used, are combined with the hydration water. Adjustable water temperatures and variable water

addition rates along with the variable lime feed rates permit controlled production of specially formulated hydrates.

Steam produced from the heat of hydration is vented. The hydrating lime is impelled into a seasoner. The mixture moves along a continuous screw conveyor which is equipped with thermocouples to monitor temperatures. An adjustable dam at the end of the seasoner helps control residence time. The hydrated particles overflow the dam and are discharged into 55 gallon drums. The hydrate is not air classified. (Some commercial processes routinely perform air classification to remove the coarser, heavier particles.) Feeding and discharging occur continuously. The unit is designed for scale up to commercial size.

SORBENT CHARACTERIZATION EQUIPMENT

Surface Area, Pore Volume and Porosity

These properties were measured using a Micromeritics DigiSorb 2600 nitrogen adsorption apparatus. This instrument measures the surface area and pore size of materials based upon the physical adsorption of pure nitrogen gas at 77 K and pressures ranging from 2% to 99.8% of the saturation pressure (0.02 to 0.998 P/P₀). Surface areas using the Brunauer, Emmett and Teller (BET) equation were calculated from the volume of gas adsorbed at five relative pressures between 0.05 and 0.21 P/P₀ (five-point BET method). Pore volumes were calculated from the total volume adsorbed at P/P₀ = 0.985. Porosity was calculated using the following equation:

$$\text{Porosity} = \frac{PV}{\frac{1}{D} + PV}$$

where PV is the pore volume in cm³/g and D is the density; a density of 2.24 g/cm³ was assumed for all of the samples. Sample size was typically 1 g. The samples were vacuum degassed at 125 °C for 60 minutes prior to analysis. The weight lost during degas was assumed to be free moisture. Surface area, pore volume, and porosity data are given on a degassed weight basis.

Particle Size

Particle size distribution and average particle size were measured using a Malvern Instruments 2600C EASY Particle Sizer M5.4, which determines particle size distribution in the range 1.9 to 188 μm using a laser light scattering/diffraction technique. The samples were dispersed in acetone immediately prior to analysis.

In addition, particle size analyses were conducted by Dravo Lime Co. on hydrates produced in the hydration pilot plant.

Thermogravimetric Analysis (TGA)

The weight loss vs. temperature data were collected using a Perkin Elmer 7-Series Thermogravimetric Analyzer. These data were used to determine the degree of hydration. Samples were heated from 30 °C to 1000 °C at a rate of 25 °C/min under a continuous flow of dry nitrogen gas. The sample weight was typically 10 to 20 mg. The free moisture, calcium hydroxide, and calcium carbonate contents were determined based on the weight loss in three temperature ranges: 30 °C to 105 °C (free moisture), 350 °C to 525 °C (Ca(OH)_2 decomposition), 525 °C to 750 °C (CaCO_3 decomposition). The degree of hydration was determined by comparing the Ca(OH)_2 content with the total calcium content.

Other Analyses

The moisture was determined by the weight loss after drying to constant weight at 115 °C. The total calcium content was determined by acid digestion followed by titration at a pH of 10 with ethylene diamine tetracetic acid (EDTA) to a calcine indicator endpoint. Carbonate content was calculated from the total carbon content determined using a LECO CHN-1000 analyzer.

TEST SORBENTS

Commercial hydrated limes tested in this study were supplied from Mississippi Lime Co., Ste. Genevieve, Mo.; Centre Lime & Stone Co., Pleasant Gap, PA.; Dravo Lime Co., Black River Division, KY.; Mercer Lime & Stone Co., Butler, PA.; and Wimpey Minerals, Millard Quarry, Annville, PA. A pulverized (-325 mesh) limestone sample from Dravo's Black River operation was also tested. Analyses of these sorbents are given in Table 1.

Specially prepared sorbents included three high surface area hydrates. Two of these samples were supplied by the Illinois State Geological Survey (ISGS), and the other (Wuelfrasorp) was obtained from Rheinische Kalksteinwerke GmbH, Wulfrath, Germany. Samples with additives incorporated during hydration were prepared by Dravo Lime Co. in their pilot hydrator. The additives included sugar, Na_2CO_3 , and NaCl . Analyses of these sorbents are given in Table 2.

Hydrated lime samples used in the hydration optimization tests were prepared from Mississippi and from Black River quicklime by Dravo Lime Co. using the Dravo pilot hydrator. Analyses of these samples are given in Tables 3 and 4.

PILOT PLANT TEST PROCEDURES

Sorbent Injection

In the recycle and once-through tests, the sorbent was injected into the humidified flue gas at the contactor exit duct. Between the sorbent injection point and the baghouse there was 84 ft of ductwork, giving an in-duct gas residence time for each test of 2.5 to 2.7 sec.

Moisture Addition

In the recycle tests, moisture was added to a blend of the recycle and fresh sorbents using the high intensity mixer described above and using the following procedure. The fresh and recycle sorbents were blended for one minute. A set amount of water was added to the blend over a two- to three-minute period, followed by one additional minute of blending. The blend of fresh and recycle sorbents was injected into the duct using a single feeder.

Steady-State Recycle

The Advanced Coolside pilot plant can be operated with steady-state sorbent recycle. Spent sorbent from the baghouse is removed periodically during operation. A portion is returned to the recycle feeder hopper with or without moisture addition, and a portion is discarded. The recycle then is fed continuously back into the flue gas simultaneously with fresh hydrated lime. A recycle test is initiated using baghouse solids from previous once-through or recycle tests as the beginning recycle sorbent.

In some of the previously reported recycle tests, the conditions for steady-state continuous recycle were approached, but not fully established.¹³ The sorbent utilizations based on analyses of baghouse solids were somewhat lower than the calculated utilizations based on gas analyzer and sorbent feed rate data. In the test program reported here, steady-state conditions were more closely approached by extending the duration of the tests and by reducing the inventory of sorbent in the system. Each test was continued until on-the-spot solid analyses confirmed that steady-state recycle conditions had been established, or closely approached.

Baghouse Operation

In the recycle tests reported here, two modes of baghouse operation were employed. In some tests, the baghouse was operated at a relatively high approach to adiabatic saturation (>20 °F) by reheating the flue gas with hot air at the baghouse inlet. Also, the baghouse was pulsed on a more frequent basis. The objective of these tests was to roughly simulate the SO_2 removal expected in an ESP. In other tests, no reheat was used and the baghouse exit was operated at a lower approach (10-13 °F), depending on the heat of reaction. The baghouse was pulsed less frequently. The objective of these latter tests was to simulate higher removal possible in a baghouse. In all the once-through (no recycle) tests, no gas reheat was used.

Performance Measurement

The SO_2 removals reported here were based on the readings of the continuous gas analyzers located at the contactor exit (prior to sorbent injection), the duct exit and the baghouse exit. The data represent an average of data during periods when the process conditions were lined out. For the recycle tests, the removals reported were measured near the end of the test period, when steady-state recycle conditions had been closely approached. The system SO_2 removals were confirmed in each test by analysis of the baghouse solids.

Contactor Operation

In all the sorbent optimization tests, the contactor was operated to achieve near-saturation conditions. As discussed above, two different contactors were used; operating conditions for achieving saturation are given in Topical Report 2.

Flue gas temperature at the contactor inlet was controlled at ca. 300 °F by controlling the firing rate of the gas combustor. The flue gas adiabatic saturation temperature was controlled at ca. 125 °F at the baghouse exit by controlling the rate of steam injection upstream of the contactor. The saturation temperature at the baghouse exit was lower than at the contactor exit or at the duct exit due to dilution by sorbent transport air and by flue gas reheat air. Compared to the control point, the saturation temperature was roughly 3 °F higher at the contactor exit and roughly 1 °F higher at the reactor/duct exit.

No fly ash was injected into the contactor inlet flue gas for the sorbent optimization tests. This was done for test simplicity. As discussed in Topical Report No. 2, previous tests confirmed that the contactors removed over 95% of the inlet fly ash and that the presence of fly ash in the inlet gas did not affect downstream desulfurization performance.

Additive Addition

In tests in which an additive was evaluated, the additive was incorporated either during hydration or during the recycle wetting step. The former was done in the Dravo Lime Co. pilot hydrator. In the latter case, the additive was dissolved in the water used to wet the recycle sorbent and added to the sorbent during the normal water addition step in the Advanced Coolside pilot plant.

HYDRATION TEST PROCEDURES

For the CONSOL test program, Dravo Lime Co. produced hydrates by varying the lime source, lime feed size, lime feed rates, additives, additive concentrations, hydration water temperature, hydration water addition rates, the method of hydration water delivery (with and without a nozzle) and by varying the moisture content in the product. Moisture was determined on site and adjustments were made to the hydrator to control the moisture in the product.

DISCUSSION OF ALTERNATE SORBENT TESTING

PERFORMANCE OF DIFFERENT COMMERCIAL HYDRATED LIMES

Pilot plant testing was conducted with five different commercial hydrated limes, including Mississippi lime, which was the test lime in most of the previous Advanced Coalside studies and in much of the development work for the conventional Coalside process. The commercial hydrates tested had a wide range of BET surface areas, from 14 to 24 m²/g (Table 1). The desulfurization results showed a relatively small variation among the limes tested; the variation was much less than previously observed for the conventional Coalside process⁴. The relative insensitivity of the process to lime source can be advantageous from an economic standpoint. It implies that the lowest cost lime available can be used while maintaining the desired desulfurization performance.

Detailed test conditions and results for the once-through (no recycle) tests with the commercial hydrated limes are given in Table 5. In-duct SO₂ removals at a 1.5 Ca/S mol ratio with the five limes tested ranged from 51 to 54% (Figure 6). The system (duct + baghouse) removals were slightly higher with Mississippi lime, indicating a somewhat higher activity in the baghouse. At 1.5 Ca/S the system removals were 80% for Mississippi lime and 72-76% with the other limes. At a 2.0 Ca/S ratio (Figure 7), the in-duct SO₂ removals ranged from 58 to 69% among the five limes. The system removal was 96% with Mississippi lime, compared to 82 to 88% with the other limes. Figure 8 shows a positive effect of surface area on system SO₂ removals; there does not appear to be a strong correlation between surface area and the in-duct SO₂ removals.

Recycle tests were conducted with three of the commercial hydrated limes (Table 6). The hydrated limes tested, Dravo Lime Co. Black River, Wimpey Minerals Millard lime, and Mississippi hydrated lime, had a wide variation in surface area, from 14 and 24 m²/g. At a 1.2-1.3 Ca/S mol ratio, a 6.8 recycle ratio (1b recycle/1b lime) and 0.12 lb water/lb recycle sorbent, the in-duct SO₂ removals with Black River and Millard limes were 80 and 76%, respectively, somewhat less than the 87% obtained at these conditions with Mississippi lime. The system (duct + baghouse) removals however, were very similar with all three limes (86 to 90%). Sorbent utilizations, based on analyses of baghouse solids, were near 70% for the three limes. These results indicate that the process

performance goals of 90% SO₂ removal and 60% sorbent utilization can be achieved through sorbent recycle using a variety of commercial hydrated limes.

PERFORMANCE OF LIMESTONE

Once-through tests were conducted with a finely pulverized limestone from the Dravo Black River operation. Limestone was of interest because of its low cost, relative to hydrated lime. The results indicate that limestone is not a sufficiently effective sorbent for commercial use in the Advanced Coalside process. However, the results show that CaCO₃ does have significant desulfurization activity. This may be an important observation, since recycle tests¹³ have indicated that a substantial degree of carbonation occurs at high recycle ratios and high SO₂ removals.

Table 7 shows that the in-duct SO₂ removal with limestone at a 1.4 Ca/S mol ratio was 19%, compared to 51% removal with Mississippi hydrated lime at a 1.5 Ca/S ratio. The system removals with limestone and hydrate were 26 and 80 %, respectively. At ca. 2 Ca/S, in-duct and system SO₂ removals with limestone were 23 and 31%, respectively, compared to 64 and 96% with hydrated lime.

PERFORMANCE OF HIGH SURFACE AREA SORBENTS

Three high surface area hydrated limes were tested in the pilot plant. One was obtained from Rheinische Kalksteinwerke in Germany (Wuelfrasorp) and had a BET surface area of 39 m²/g, and two samples were obtained from the Illinois State Geological Survey (ISGS) and had surface areas of 35 and 41 m²/g. The results showed some of these samples to be marginally more active than commercial hydrated lime in once-through tests. However, the performance was not significantly better in recycle testing. Thus, their use in the Advanced Coalside process does not appear to be warranted.

Detailed test conditions and results for once-through tests with high surface area limes and Mississippi lime are shown in Table 8. The results (Figures 9 and 10) show that the performance of Wuelfrasorp was inferior to that of Mississippi lime both in the duct and for the system. The ISGS samples showed somewhat better performance than Mississippi lime at 1.5 Ca/S. The in-duct SO₂ removals were 58-60%, compared to 51% with Mississippi lime. The system removals with the ISGS limes were 83-86%, versus 80% with Mississippi lime. At a 2.0 Ca/S

ratio (Figure 10), the in-duct SO_2 removals with the ISGS samples (67-71%) were slightly better than those with the Mississippi lime (64%). System removals with the ISGS samples (88-94%), however, were somewhat less than those with Mississippi lime (96%).

As a follow up to the once-through tests, a recycle test was made with one of the ISGS high surface area ($41 \text{ m}^2/\text{g}$) samples. The detailed test conditions and results are shown in Table 9 along with previous results with Mississippi hydrated lime. The desulfurization performance with the high surface area lime in recycle tests was very similar to that observed with Mississippi hydrated lime. At a 1.2 fresh Ca/S mol ratio and a recycle ratio of 6.9, the in-duct SO_2 removal was somewhat less with the ISGS sample (80 vs. 87%). The system removals with the two limes were essentially the same (ca. 90%). The sorbent utilizations, based on solids analyses, were also very close, 74% with the ISGS lime vs. 70% with Mississippi hydrate.

DISCUSSION OF HYDRATION OPTIMIZATION TESTS

HYDRATION TESTS

A two-level factorial experimental program was conducted using the Dravo Lime Company hydration pilot plant. The pilot plant and operating procedures are described above. The goal was to determine the effects of hydration variables on hydrated lime properties and the associated effects on desulfurization performance. The hydration process variables studied were: feed lime particle size, water temperature, lime feed rate and target final product moisture content. The target product moisture is the projected moisture content of the product hydrate calculated from the stoichiometric water feed and the water temperature. Process conditions were controlled at two levels of each of these variables and at an overall center-point. The center-point value was the average of the extremes. Table 10 lists the values selected for each variable. In addition two different quicklimes, Mississippi Lime Co. quicklime and Dravo Lime Co. Black River quicklime, were tested.

With four control variables, 17 sets of experimental conditions were required - sixteen corner points plus one center point. There was no replication of any point except the center point. Mississippi quicklime was hydrated once at each of the seventeen sets of conditions. The test at the center point condition was conducted in triplicate. Based on initial evaluations of the hydrates produced in these runs, the quicklime feed rate was eliminated as a process variable for the test program with Black River quicklime. The three-variable, two-level factorial test included nine sets of process conditions. One additional center point was repeated for a total of four tests to improve the sensitivity of the statistical evaluation.

Tables 11 and 12 list the pilot plant hydration test conditions for the Mississippi and Black River quicklimes, respectively.

After hydration, the products were analyzed for various physical properties. Porosity, BET surface area, particle size and moisture content were measured for each hydrate. Reactivity of the hydrates to sulfur dioxide was determined by two different techniques: a bench-scale utilization test and Advanced Coolside pilot plant once-through testing.

SORBENT CHARACTERIZATION

Surface Area, Pore Volume, and Porosity

The surface areas, pore volumes and porosities tended to be slightly higher for the Mississippi hydrate than for the Black River hydrate. The surface areas of the sorbents made by hydration of Mississippi quicklime ranged from 14.1 to 17.5 m²/g and the porosities ranged from 14.5% to 19% (Table 3). The surface areas of the sorbents made by hydration of Black River quicklime ranged from 11.8 to 15.3 m²/g and the porosities ranged from 10.6% to 14% (Table 4).

The surface areas of the hydrates produced in the Dravo pilot plant were generally lower than those of the commercial hydrates produced from the same quicklime. Typical surface areas for commercial Mississippi hydrated lime are 22 to 24 m²/g; typical surface areas for commercial Dravo Black River hydrated lime are 14 to 15 m²/g. These results along with desulfurization results presented below suggest that the pilot hydrator does not closely simulate commercial hydration conditions.

The surface area was affected by hydration process variables; however, the effects differed for the two different quicklimes. The BET surface area of the Mississippi hydrate correlated with the water temperature and quicklime feed rate. For the Black River hydrate, the BET surface area correlated with the target product moisture and quicklime size.

Sorbent porosity was generally higher with higher BET surface area as shown in Figure 11. However, the Mississippi hydrates tended to have higher porosities than the Black River hydrates at similar surface areas. This suggests that the average pore in the Mississippi hydrate was larger than in the Black River hydrate. Porosity was a greater function of the lime source than any other controlled process variable.

The surface area and porosity analyses were duplicated for four of the Black River hydrate samples to determine the reproducibility of the analysis method. The results are shown in Table 4. The results show that the reproducibility was ± 1.6 m²/g for surface area measurements and $\pm 0.3\%$ for porosity measurements at 95% confidence level. This is typical for surface area and porosity using this instrument.

Particle Size

The average particle sizes of the hydrated limes are shown in Tables 3 and 4. These data were supplied by Dravo. For Mississippi hydrates, the particle size was a function of the size of the feed quicklime. The particle size of hydrate from the Black River quicklime was smaller than that of hydrate from Mississippi quicklime. The size of the Black River hydrate was less influenced by the process variables. There was no correlation with quicklime size. There was a weak dependence on the water temperature and the target final product moisture.

Degree of Hydration

The degree of hydration determined using TGA ranged from 84 to 98% for the Mississippi lime hydrate and 86 to 93% for the Black River hydrate as shown in Tables 3 and 4. For both limes the degree of hydration correlated with the target product moisture.

Other Analyses

The calcium carbonate contents for the samples are shown in Tables 3 and 4.

DESULFURIZATION RESULTS

The desulfurization results of both laboratory and pilot plant tests are summarized in Tables 13 and 14. Detailed results of the pilot plant tests are given in Tables 15 and 16.

Laboratory Sorbent Utilization Tests

Laboratory tests in a fixed-bed reactor were conducted to estimate the maximum sorbent utilization. The behavior of Mississippi hydrate in these tests was not significantly dependent on any hydration process variable or sorbent property. For the Black River hydrate, the utilization correlated with the quicklime particle size and target product moisture content.

Pilot Plant SO₂ Removal

The SO₂ removals with limes hydrated in the Dravo pilot plant were generally lower than with commercially hydrated limes from the same quicklime. With Mississippi lime hydrated in the pilot plant, system removals at 1.5 Ca/S ranged from 62 to 78% with an average of 68% (Table 13). In-duct removals ranged from 30 to 60% with an average of 36%. The higher removals were obtained with a

higher residual water contents than typical for commercial hydration. The desulfurization performance with commercially hydrated Mississippi lime at 1.5 Ca/S was 51% in-duct and 80% for the system. At 2.0 Ca/S Mississippi lime produced in the Dravo pilot plant yielded SO₂ removals of 43% in-duct and 71% for the system. This compares with 64% in-duct removal and 96% system removal for commercially hydrated Mississippi lime. These results indicate that the Dravo pilot hydrator does not closely simulate commercial hydration conditions.

As expected based on previous investigations in the Advanced Coolside pilot plant, SO₂ removals increased with increasing residual moisture for hydrates from both quicklimes. Desulfurization performance was also a weak function of quicklime particle size for the two limes. The effect of feed lime size to the hydrator on SO₂ pickup was the opposite for the two sorbents: with increasing lime size, duct removals generally increased for the Mississippi lime hydrate, but decreased for the Black River lime hydrate.

There was no significant effect of quicklime source on the SO₂ removal. This observation is consistent with observations with different commercial hydrated limes.

STATISTICAL ANALYSIS OF TEST DATA

The results of the hydration tests were examined statistically using standard two- and three-level factorial evaluation methods. These methods eliminated variables that were not statistically significant. The results of this evaluation are discussed fully in Topical Report 5, Data Analysis And Computer Modeling. Interrelationships among the measured physical properties and the hydrate reactivity are discussed in Topical Report 5.

The primary conclusions of the statistical analysis are as follows:

- There was a statistically significant difference in the BET surface areas of the hydrates from two different quicklimes (99% confidence level). Lime source was the most important variable in determining hydrate BET surface area.

- Porosity was a greater function of the lime source than any controlled process variable. The difference in the mean porosity values for the lime source was significant at the 99% confidence level.
- There was no statistically significant effect of quicklime source on the duct or system SO_2 removals observed in the pilot plant.
- Variables with statistically significant effects on desulfurization performance were residual moisture content in the hydrate product and quicklime particle size.

DISCUSSION OF ADDITIVE PROMOTION TEST RESULTS

ADDITIVE ADDITION TO RECYCLE

Recycle tests were conducted with small amounts of additives incorporated in the combined recycle and fresh sorbent during the moisture addition step. This is an attractive means of additive incorporation because it uses existing equipment and allows the use of commercial available hydrated lime. The results indicate a moderate enhancing effect of inorganic chloride compounds (NaCl , CaCl_2) on sorbent performance in the baghouse. However, no positive effect was observed in the duct. Based on the results, use of small amounts of these additives may be attractive means of achieving high SO_2 removal efficiencies (90 to >99%) in a plant with a baghouse. Sodium carbonate (Na_2CO_3) showed no positive effect in the duct or baghouse. The detailed test conditions and results of the additive tests are given in Table 17. A summary of the results is given in Table 18.

In Test 13C with 0.03 mol NaCl /mol lime and a baghouse approach temperature of 9 °F, the system SO_2 removal was over 99% at a fresh Ca/S of 1.24. This result demonstrates the capability of the Advanced Coolside process to achieve very high SO_2 removal efficiency and high sorbent utilization using NaCl as an additive in a plant with a baghouse. As shown in Table 17, solids analysis indicated a utilization of 75-77%, which is somewhat less than the expected value at steady state (81%). This indicates that a slightly higher Ca/S ratio would be required to maintain this level of removal; a Ca/S ratio of 1.3 would give the same level of total available Ca as indicated by the solids analyses.

In Test 13A, conducted with NaCl addition at a Na/fresh Ca mol ratio of 0.025, the system (duct+baghouse) SO_2 removal was 84% at a fresh Ca/S ratio of 1.0. The sorbent utilization, based on recovered solids analysis was 78%, higher than seen in previous recycle tests with non-promoted sorbent. The in-duct SO_2 removal for Test 13A was 65%. In Test 13B, also made with NaCl addition, the baghouse approach to saturation was increased from 22 °F to 43 °F in an attempt to increase the in-duct removal. A higher approach in the baghouse reduces baghouse SO_2 removal, increasing the available calcium in the recycle sorbent. The in-duct and system removals in Test 13B were 59 and 75%, respectively.

Test 16 was conducted with CaCl_2 added, at a 0.03 CaCl_2 /fresh Ca mol ratio. At a fresh Ca/S mol ratio of 1.3 and a recycle ratio of 6.8 (dry), the in-duct SO_2 removal with CaCl_2 was 65%, less than the 84% obtained with un-promoted sorbent (Test 17B). The system SO_2 removal with CaCl_2 was 97%, higher than the 92% obtained with unpromoted sorbent. The sorbent utilization with CaCl_2 , based on recovered solids analysis, was 79%, compared to 73% with un-promoted sorbent.

Test 17 showed no enhancing effect of Na_2CO_3 additive. This additive had been effective in the conventional Coolside process. In-duct and system SO_2 removals with Na_2CO_3 were 79 and 93%, respectively, compared to 84 and 92% with un-promoted sorbent.

ADDITIVE ADDITION DURING HYDRATION

A limited program was conducted in which additives were incorporated with lime during hydration using the Dravo Lime Company pilot hydrator; these sorbents were then tested for desulfurization activity in once-through tests in the Advanced Coolside pilot plant. Process performance with additives introduced in this manner could not be accurately determined in this study due to the inability of the pilot hydrator to closely simulate commercial hydration. The unpromoted hydrates from the pilot hydrator had lower surface areas and lower activities than the commercial hydrated limes produced from the same quicklime (Table 19). The tests did indicate that NaCl has an enhancing effect on sorbent activity, primarily in the baghouse. The tests also indicated that Na_2CO_3 and sugar have little or no positive effect.

The detailed test conditions and results with the additive-promoted sorbents, along with those from pilot-produced and commercial un-promoted hydrates are given in Table 19. The NaCl- and Na_2CO_3 -promoted sorbents were made with Mississippi quicklime; the sugar-promoted sorbent was made with Black River quicklime. Additive concentrations were 0.14 Na/Ca mol ratio for NaCl and Na_2CO_3 and 2.3 wt.% for sugar.

The results at a 1.4-1.5 Ca/S mol ratio (Figure 12) show that NaCl had an in-duct SO_2 removal of 53%, compared to 51% with un-promoted commercial hydrated lime and 37% for un-promoted, pilot-hydrated lime. The system SO_2 removal with NaCl

promotion was 97%, substantially higher than the 80% and 60% with un-promoted commercial and un-promoted pilot-hydrated limes, respectively.

Na_2CO_3 addition had little or no enhancing effect. In-duct and system SO_2 removals were 41 and 63%, respectively. The poor results with Na_2CO_3 may be due to the extremely low BET surface area ($6.5 \text{ m}^2/\text{g}$) of the additive-promoted sorbent (Table 19).

Sugar had a detrimental effect on activity. In-duct and system SO_2 removals were 38 and 47%, compared to 53 and 72% with commercial hydrate (Black River) and 44 and 64% with un-promoted, pilot-produced hydrate. Again, the surface area of the sugar-promoted sorbent was low ($6.2 \text{ m}^2/\text{g}$).

The results with the three additives were similar at a 1.8-2.0 Ca/S mol ratio (Figure 13).

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TABLE 1
ANALYSES OF COMMERCIAL SORBENTS

Hydrate	Mississippi	Centre	Black River	Mercer	Millard	Dravo (a)
BET Surface Area, m ² /g	24.4	20.2	14.2	18.2	20.3	-
Lime Index	93.9	94.0	92.2	91.6	91.6	-
<u>As Received Lime, wt %</u>						
Moisture	0.5	0.9	0.5	1.2	0.4	0.1
Ash (925 °C)	75.1	75.9	76.8	75.2	76.4	-
Carbonate (CO ₃)	2.2	1.0	0.8	2.5	1.6	55.3
Ca(OH) ₂ (TGA)	90.9	91.9	89.2	89.2	88.6	-
<u>Ash Elementals, wt % of As-Received Lime</u>						
SiO ₂	0.8	0.7	1.5	0.6	1.2	-
Al ₂ O ₃	0.1	0.2	0.4	0.1	0.5	-
TiO ₂	<0.1	<0.1	<0.1	<0.1	<0.1	-
Fe ₂ O ₃	0.1	0.1	0.2	0.2	0.2	-
CaO	74.7	74.6	72.4	71.7	74.1	49.8
MgO	0.6	0.7	1.9	0.9	0.9	-
Na ₂ O	<0.1	<0.1	<0.1	<0.1	<0.1	-
K ₂ O	<0.1	<0.1	0.1	<0.1	0.1	-
P ₂ O ₅	<0.1	<0.1	<0.1	<0.1	<0.1	-
SO ₃	0.2	<0.1	<0.1	0.1	<0.1	-
<u>Malvern Particle Size, wt %</u>						
+66.9 µm	0	0	0	0	0	-
66.9 x 42.9	1.1	0	0	0	0	-
42.9 x 20.5	6.3	4.1	1.1	0.3	7.0	-
20.5 x 11.4	9.3	15.8	17.2	12.5	14.4	-
11.4 x 5.4	31.3	30.2	38.6	40.3	29.2	-
5.4 x 1.9	40.9	33.3	35.0	38.8	38.8	-
-1.9	11.1	16.6	8.1	8.1	10.6	-
<u>Mean Particle Dia., µm</u>	5.3	5.4	6.1	5.7	5.5	-

(a) -325 mesh limestone from Dravo's Black River operation.

TABLE 2
ANALYSES OF SPECIALLY PREPARED SORBENTS

Hydrate	R.K. (a)	ISGS (b)	ISGS (b)	Mississippi (c)	Mississippi (c)	Mississippi (c)	Black River (c)
Additive	None	None	None	None	Na ₂ CO ₃	NaCl	Sugar
BET Surface Area, m ² /g	39.2	35.0	40.6	15.1	6.5	11.7	6.2
Lime Index	88.0	94.0	92.8	97.0	86.0	89.0	
As-Received Lime, wt %							
Moisture	0.5	0.7	0.7	0.2	0.8	0.2	—
Ash (925 °C)	74.9	75.0	73.5	77.3	75.9	72.9	—
Carbonate (CO ₃)	4.9 (d)	0.9 (d)	6.8 (d)	0.8	6.1	0.7	—
Ca(OH) ₂ (TGA)	83.9	83.5	83.0	88.0	83.6	76.2	86.1
Ash Elementals, wt % of As-Received Lime							
SiO ₂	2.1	0.5	0.5	0.9	0.9	0.9	—
Al ₂ O ₃	0.1	0.2	0.1	0.2	0.2	0.1	—
TiO ₂	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	—
Fe ₂ O ₃	0.2	0.1	0.1	0.1	0.1	0.1	—
CaO	75.5	70.9	73.6	72.7	69.5	67.5	69.1
MgO	0.8	2.0	0.4	1.1	0.9	0.9	—
Na ₂ O	<0.1	0.1	<0.1	<0.1	5.4	5.1	—
K ₂ O	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	—
P ₂ O ₅	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	—
SO ₃	0.1	0.1	0.1	0.1	0.1	0.1	—
Malvern Particle Size, wt %							
+68.9 μm	0	0	0	0	0.3	0.1	—
68.9 x 42.9	0	0	0	0.4	1.8	0.9	—
42.9 x 20.5	0	0	0	10.4	16.4	12.1	—
20.5 x 11.4	2.0	0.8	0	18.5	20.3	17.1	—
11.4 x 5.4	19.2	16.6	0.2	29.0	26.6	27.2	—
5.4 x 1.9	57.3	48.2	14.7	32.6	26.5	32.4	—
-1.9	21.5	34.4	85.1	9.1	8.1	10.2	—
Mean Particle dia., μm	3.6	2.6	1.2	6.5	8.5	6.5	5.7

(a) Rheinische Kalksteinwerke GmbH

(b) Illinois State Geological Survey

(c) Produced in Dravo's pilot hydrator.

(d) Includes alcohol-calcium (methoxy) compounds formed during hydration with alcohol.

TABLE 3
CHARACTERIZATION OF SORBENTS MADE BY HYDRATION OF MISSISSIPPI QUICKLIME
IN THE DRAVO PILOT HYDRATOR.

Dravo Test No.	Degas Weight Loss, wt %	Surface Area, m ² /g	Pore Volume, cm ³ /g	Porosity, %	Average Particle Size, μm	CaCO ₃ wt %	Degree of Hydration, %	Ca(OH) ₂ wt %	Total Ca wt %
19	2.3	14.1	0.078	14.9	13.0	3.1	90	87.8	53.0
20	2.4	14.4	0.076	14.5	5.6	3.3	84	82.8	53.1
21	2.1	14.5	0.077	14.6	13.9	4.6	90	87.7	52.7
22	3.0	16.4	0.095	17.6	15.3	0.8	94	92.3	53.1
23	2.0	15.3	0.080	15.3	18.1	2.5	90	88.0	52.8
24	4.7	17.5	0.103	18.8	5.9	4.4	98	93.6	51.6
25	3.1	16.5	0.094	17.4	-	3.9	94	90.5	52.2
26	2.5	17.3	0.089	16.6	-	2.6	91	89.7	53.2
27	2.0	16.3	0.089	16.7	-	1.7	95	92.5	52.7
28	2.8	15.2	0.090	16.8	5.2	2.0	96	92.4	52.2
29	3.2	14.3	0.086	16.2	5.3	3.6	94	91.5	52.8
30	3.3	14.2	0.086	16.1	3.8	3.6	95	91.9	52.2
31	3.5	16.1	0.102	18.5	4.4	3.2	96	91.9	51.7
33	1.9	16.0	0.085	16.0	3.8	2.5	95	92.8	52.9
34	3.0	15.2	0.083	15.7	3.6	4.4	92	90.1	52.9
35	2.4	16.8	0.088	16.4	6.6	3.1	92	90.3	53.3
36	2.3	14.1	0.081	15.4	6.4	3.4	95	92.3	52.3
37	2.7	16.5	0.091	16.9	4.2	2.9	94	92.5	53.0

TABLE 4

**CHARACTERIZATION OF SORBENTS MADE BY HYDRATION OF BLACK RIVER QUICKLIME
IN THE DRAVO PILOT HYDRATOR**

Dravo Test No.	Degas Weight Loss, wt %	Surface Area, m ² /g	Pore Volume, cm ³ /g	Porosity, %	Average Particle Size, μm	CaCO ₃ wt %	Degree of Hydration, %	Ca(OH) ₂ wt %	Total Ca wt %
39	2.6	14.4/ 13.7	0.068	13.2/ 13.2	4.8	2.1	91	86.4	51.5
40	0.4	13.1	0.060	11.8	4.1	2.0	91	87.4	51.7
41	1.1	11.8	0.057	11.2	5.6	1.7	90	86.6	52.0
42	1.1	14.3	0.067	13.0	5.7	2.3	88	84.3	51.5
43	2.1	13.0/ 12.9	0.065	12.8/ 13.3	4.4	1.5	91	85.7	50.9
44	4.2	14.4	0.071	13.8	4.5	1.9	94	88.2	50.9
45	0.1	12.3	0.053	10.6	5.8	2.2	86	82.2	51.8
46	2.8	15.2/ 15.1	0.071	13.8/ 13.7	5.2	2.3	92	88.2	51.9
47	2.8	13.3	0.063	12.4	5.7	1.1	90	86.2	52.0
48	1.3	14.4	0.069	13.3	4.5	2.5	93	87.5	50.7
49	3.0	12.7	0.065	12.6	5.0	2.1	92	87.2	51.4
50	2.6	15.3/ 13.9	0.069	13.3/ 13.4	5.6	1.6	92	87.9	51.7

TABLE 5

**TEST CONDITIONS AND RESULTS, ONCE-THROUGH (NO RECYCLE) TESTS
WITH COMMERCIAL HYDRATED LIMES**

Test SO—	3	3A	7	7A	9	9A	10A	10B	12A	12B
Run Time, hr	3.4	1.2	2.2	1.8	1.8	1.7	2.3	1.4	2.8	2.8
Sorbent	Mississippi	Mississippi	Centre	Centre	Black River	Black River	Mercer	Mercer	Millard	Millard
BET Surface Area, m ² /g	24.4	24.4	20.2	20.2	14.2	14.2	18.2	18.2	20.3	20.3
SORBENT DATA										
Fresh Ca/S Mole Ratio	1.49	2.05	1.48	2.00	1.50	2.02	1.51	1.97	1.50	2.01
Fresh Feedrate, lb/hr	8.14	11.05	8.12	10.95	8.39	11.20	8.36	11.15	8.25	11.04
DUCT FLUE GAS CONDITIONS										
In-Duct Residence Time, s	2.6	2.6	2.6	2.6	2.6	2.6	2.6	2.6	2.6	2.6
Duct Inlet SO ₂ Content, ppmv—dry	1489	1474	1508	1500	1488	1475	1461	1493	1499	1501
APPROACH TO SATURATION, °F										
Duct Exit	11	11	10	12	12	14	9	11	9	10
Baghouse Exit	18	17	19	21	18	20	15	17	14	15
Contactor Inlet Temp, °F	281	280	280	280	282	280	280	281	280	280
Contactor Exit Temp, °F	129	128	128	127	129	130	129	129	129	129
Duct Exit Temp, °F	138	138	137	139	139	141	136	138	137	138
Baghouse Exit Temp, °F	144	143	145	147	144	146	141	143	141	142
Baghouse Exit Wet Bulb, °F	126	126	126	126	126	126	126	126	127	127
Reactor Inlet Flue Gas Flow, scfm	360	360	360	360	360	360	360	360	360	360
SO₂ REMOVAL, %										
In-Duct	51	64	54	66	53	58	53	59	54	69
System (Duct + Baghouse)	80	96	76	88	72	82	74	85	75	87
SORBENT UTILIZATION, %										
Flue Gas Analyzers	53	47	52	44	48	40	49	43	50	43
Ash Analysis	—	—	—	—	41	40	43	40	—	—
TGA	—	—	—	—	44	44	45	42	45	45

TABLE 6
TEST CONDITIONS AND RESULTS, RECYCLE SIMULATION TESTS
WITH COMMERCIAL HYDRATED LIMES

Test	13	14	19
Run Time, hr	115	72	64
Fresh Sorbent	Mississippi	Black River	Millard
SORBENT DATA			
Fresh Ca/S Mole Ratio (a)	1.21	1.25	1.24
Fresh Feedrate, lb/hr	6.29	6.56	6.43
Recycle Feedrate, lb/hr	52.92	54.08	53.18
Recycle Ratio, lb recycle/lb fresh lime	8.41	8.24	8.27
Recycle Ratio, dry basis	6.89	6.75	6.77
Recycle Available Ca/S, Mol Ratio (a)	1.71	1.63	1.91
Total Available Ca/S, Mol Ratio (a)	2.92	2.88	3.15
Water Addition, lb/hr	5.89	6.02	5.92
lb Water/lb Recycle Sorbent	0.12	0.12	0.12
DUCT FLUE GAS CONDITIONS			
In-Duct Residence Time, sec	2.7	2.7	2.7
Duct Inlet SO ₂ Content, ppmv—dry	1501	1494	1494
Solids Loading, gr/scf	20.3	20.8	20.5
Approach to Saturation, °F			
Duct Exit	4	5	3
Baghouse Exit	23	22	23
Contactor Inlet Temp, °F	281	280	280
Contactor Exit Temp, °F	130	127	128
Duct Exit Temp, °F	131	133	130
Baghouse Exit Temp, °F	149	149	149
Baghouse Exit Wet Bulb, °F	126	127	126
Duct Inlet Flue Gas Flow, scfm	340	340	340
SO₂ REMOVAL, %			
In-Duct	87	80	76
System	90	86	86
SORBENT UTILIZATION, %			
Steady State (b)	75	69	70
Flue Gas Analyzers (c)	69	69	66
Ash Analysis (d)	69	67	65
TGA Analysis (e)	71	71	67

(a) Includes all calcium in fresh and recycle sorbent not tied up with sulfur (e.g., Ca(OH)₂ and CaCO₃).

(b) Based on flue gas analysis and fresh sorbent feed rate/composition, assuming steady state.

(c) Based on flue gas analysis, and recycle and fresh sorbent feed rates/compositions.

(d) Based on baghouse solids analysis (S,Ca).

(e) Based on baghouse solids analysis (TGA).

TABLE 7
TEST CONDITIONS AND RESULTS,
ONCE-THROUGH (NO RECYCLE) TESTS WITH LIMESTONE

Test SO— Run Time, hr Sorbent	3 3.4 Mississippi Hydrate	36 1.0 Limestone	3A 1.2 Mississippi Hydrate	36A 1.1 Limestone
SORBENT DATA				
Fresh Ca/S Mole Ratio	1.49	1.41	2.05	1.83
Fresh Feedrate, lb/hr	8.14	11.49	11.05	14.96
DUCT FLUE GAS CONDITIONS				
In-Duct Residence Time, sec	2.6	2.6	2.6	2.6
Duct Inlet SO ₂ Content, ppmv—dry	1489	1496	1474	1497
Approach to Saturation, °F				
Duct Exit	11	6	11	6
Baghouse Exit	18	9	17	9
Contactactor Inlet Temp, °F	281	280	280	279
Contactactor Exit Temp, °F	129	129	128	129
Duct Exit Temp, °F	138	134	138	134
Baghouse Exit Temp, °F	144	136	143	136
Baghouse Exit Wet Bulb, °F	126	127	126	127
Reactor Inlet Flue Gas Flow, scfm	360	360	360	360
SO₂ REMOVAL, %				
In-Duct	51	19	64	23
System (Duct + Baghouse)	80	26	96	31
SORBENT UTILIZATION, %				
Flue Gas Analyzers	53	18	47	17
Ash Analysis	—	19	—	12

TABLE 8

**TEST CONDITIONS AND RESULTS, ONCE-THROUGH (NO RECYCLE) TESTS
WITH SPECIALLY PREPARED (HIGH SURFACE AREA) LIMES**

Test SO-	1	2	3	SA	8	8A	14A	14B
Run Time, hr	2.6	2.9	3.4	1.2	0.8	1.0	2.0	2.0
Sorbent	R.K. (a)	R.K. (a)	Mississippi	Mississippi	ISGS (b)	ISGS (b)	ISGS (b)	ISGS (b)
Bet Surface Area, m ² /g	39.2	39.2	24.4	24.4	35.0	35.0	40.6	40.6
SORBENT DATA								
Fresh Ca/S Mole Ratio	1.55	2.03	1.49	2.05	1.46	1.92	1.53	2.00
Fresh Feedrate, lb/hr	8.31	11.03	8.14	11.05	8.34	11.16	8.40	11.01
DUCT FLUE GAS CONDITIONS								
In-Duct Residence Time, Sec	2.6	2.6	2.6	2.6	2.6	2.6	2.6	2.6
Reactor Inlet SO ₂ Content, ppmv-dry	1493	1507	1489	1474	1492	1511	1483	1493
Approach to Saturation, °F								
Duct Exit	9	10	11	11	9	10	8	10
Baghouse Exit	13	13	18	17	15	15	14	15
CONTACTOR AND BAGHOUSE TEMPERATURES								
Contactator Inlet Temp, °F	280	280	281	280	280	281	283	281
Contactator Exit Temp, °F	128	128	129	128	129	129	128	129
Duct Exit Temp, °F	135	136	138	138	137	138	136	138
Baghouse Exit Temp, °F	138	138	144	143	142	142	141	142
Baghouse Exit Wet Bulb, °F	125	125	126	126	127	127	127	127
Duct Inlet Flue Gas Flow, scfm	360	360	360	360	360	360	360	360
SO₂ REMOVAL, %								
In-Duct	46	52	51	64	60	71	58	67
System (Duct + Baghouse)	70	77	80	96	83	88	86	94
SORBENT UTILIZATION, %								
Flue Gas Analyzers	46	38	53	47	57	46	56	47
Ash Analysis	46	43	—	—	—	—	—	—
TGA Analysis	—	—	—	—	—	—	45	45

(a) Rheinische Kalksteinwerke GmbH

(b) Illinois State Geological Survey

TABLE 9
TEST CONDITIONS AND RESULTS, RECYCLE TEST
WITH HIGH SURFACE AREA LIME (ISGS)

Test	13	20
Run Time, hr	115	52
Fresh Sorbent	MISSISSIPPI	ISGS (b)
BET SA, m ² /g	24.4	40.6
SORBENT DATA		
Fresh Ca/S Mole Ratio (a)	1.21	1.20
Fresh Feedrate, lb/hr	6.29	6.29
Recycle Feedrate, lb/hr	52.92	52.86
Recycle Ratio, lb recycle/lb fresh lime	8.41	8.40
Recycle Ratio, dry basis	6.89	6.88
Recycle Available Ca/S, Mole Ratio (a)	1.71	1.36
Total Available Ca/S, Mole Ratio (a)	2.92	2.56
Water Addition, lb/hr	5.89	5.89
lb Water/lb Recycle Sorbent	0.12	0.12
DUCT FLUE GAS CONDITIONS		
In-Duct Residence Time, sec	2.7	2.7
Duct Inlet SO ₂ Content, ppmv-dry	1501	1508
Approach to Saturation, °F		
Duct Exit	4	2
Baghouse Exit	23	21
Solids Loading, gr/scf	20.3	20.3
Contactor Inlet Temp, °F	281	280
Contactor Exit Temp, °F	130	126
Duct Exit Temp, °F	131	130
Baghouse Exit Temp, °F	149	148
Baghouse Exit Wet Bulb, °F	126	127
Duct Inlet Flue Gas Flow, scfm	340	340
SO₂ REMOVAL, %		
In-Duct	87	80
System (Duct + Baghouse)	90	91
SORBENT UTILIZATION, %		
Steady State (c)	75	76
Flue Gas Analyzers (d)	69	74
Ash Analysis (e)	69	75
TGA Analysis (f)	71	73

(a) Includes all calcium in sorbents not tied up with sulfur (e.g., Ca(OH)₂ and CaCO₃).

(b) Illinois State Geological Survey.

(c) Based on flue gas analysis and fresh sorbent feed rate/composition, assuming steady-state

(d) Based on flue gas analysis, and fresh and recycle sorbent feed rates/compositions.

(e) Based on baghouse solids analysis (S,Ca).

(f) Based on baghouse solids analysis (TGA).

TABLE 10
VARIABLES EXAMINED IN THE BENCH-SCALE HYDRATION PROGRAM

Process Variables	Variable Control Point		
	(-) Lower	(+) Upper	(0) Center
Feed Lime Size	1/8"x3/4"	3/4"x1 1/2"	1/8"x1 1/2"
Water Temperature, °F	160	200	180
Lime Feed Rate, lb/min	1.3	2.7	2.0
Product Moisture, wt %	0.1 - 0.5	1.5 - 2.0	1.0 - 1.5

TABLE 11

**MISSISSIPPI LIME HYDRATED IN DRAVO PILOT PLANT
HYDRATION CONDITIONS**

Dravo Sample No.	Trial	Process Conditions							
		Factorial Codes				Actual Variable Value			
		Feed Lime Size	Water Temp	Lime Feed Rate	Target Moisture	Feed Lime Size, in.	Water Temp, °F	Lime Feed Rate, lb/hr	Target Moisture, wt %
23	1	-	-	-	-	1/8 x 3/4	160	1.3	0.28
20	2	+	-	-	-	3/4 x 1 1/2	160	1.3	0.32
21	3	-	+	-	-	1/8 x 3/4	200	1.3	0.10
33	4	+	+	-	-	3/4 x 1 1/2	200	1.3	0.56
35	5	-	-	+	-	1/8 x 3/4	160	2.7	0.42
34	6	+	-	+	-	3/4 x 1 1/2	160	2.7	0.34
26	8	+	+	+	-	3/4 x 1 1/2	200	2.7	0.28
29	9	-	-	-	+	1/8 x 3/4	160	1.3	1.82
30	10	+	+	-	+	3/4 x 1 1/2	160	1.3	1.70
27	11	+	-	-	+	1/8 x 3/4	200	1.3	1.20
36	12	-	+	-	+	3/4 x 1 1/2	200	1.3	1.40
22	13	-	-	+	+	1/8 x 3/4	160	2.7	0.89
31	14	+	-	+	+	3/4 x 1 1/2	160	2.7	1.68
24	15	-	+	+	+	1/8 x 3/4	200	2.7	2.42
25	16	+	+	+	+	3/4 x 1 1/2	200	2.7	1.10
19	17a	0	0	0	0	1/8 x 1 1/2	180	2.0	0.54
37	17b	0	0	0	0	1/8 x 1 1/2	180	2.0	0.34
28	17c	0	0	0	0	1/8 x 1 1/2	200	2.0	1.17

TABLE 12

**BLACK RIVER LIME HYDRATED IN DRAVO PILOT PLANT
HYDRATION CONDITIONS**

Dravo Sample No.	Trial	Process Conditions					
		Factorial Codes			Actual Variable Value		
		Feed Lime Size	Water Temp	Target Moisture	Feed Lime Size, in.	Water Temp, °F	Target Moisture, wt %
41	1	-	-	-	1/8 x 3/4	160	0.35
40	2	+	-	-	3/4 x 1 1/2	160	0.35
47	3	-	+	-	1/8 x 3/4	200	0.46
45	4	+	+	-	3/4 x 1 1/2	200	0.32
43	5	-	-	+	1/8 x 3/4	160	1.96
44	6	+	+	+	3/4 x 1 1/2	200	1.36
48	7	+	-	+	3/4 x 1 1/2	160	1.44
49	8	-	+	+	1/8 x 3/4	200	1.54
39	9a	0	0	0	1/8 x 1 1/2	180	0.61
42	9b	0	0	0	1/8 x 1 1/2	180	0.56
46	9c	0	0	0	1/8 x 1 1/2	180	0.77
50	9d	0	0	0	1/8 x 1 1/2	180	0.74

TABLE 13
MISSISSIPPI LIME HYDRATED IN DRAVO PILOT PLANT
DESULFURIZATION RESULTS

Dravo Sample No.	Desulfurization Results		
	Laboratory Unit, Ca Utilization	Pilot Plant	
		In-Duct Removal, %	System Removal, %
23	61	34.4	64.4
20	42	45.8	69.4
21	48	33.3	61.7
33	62	37.8	69.9
35	58	30.4	62.2
34	66	38.2	68.5
26	43	38.6	70.8
29	61	41.7	66.8
30	69	42.7	74.8
27	55	34.4	67.8
36	51	49.1	69.7
22	58	45.3	69.3
31	65	60.5	77.5
24	67	43.9	69.7
25	47	42.3	75.3
19	43	38.5	66.6
37	68	35.2	67.2
28	64	35.5	68.6
Avg of Centerpoints =	58.3	36.4	67.5
Std. Deviation of CP =	13.43	1.82	1.03

TABLE 14
BLACK RIVER LIME HYDRATED IN DRAVO PILOT PLANT
DESULFURIZATION RESULTS

Dravo Sample No.	Desulfurization Results		
	Laboratory Unit Ca Utilization	Pilot Plant	
		In-Duct Removal, %	System Removal, %
41	43	45.0	63.2
40	57	40.3	63.0
47	44	43.6	63.7
45	52	43.4	64.3
43	46	51.2	77.8
44	46	45.8	68.1
48	57	44.3	65.1
49	53	49.4	72.8
39	43	42.7	65.2
42	50	41.6	64.9
46	46	45.2	67.9
50	47	41.2	66.0
Avg of Centerpoints =	47	42.7	66.0
Standard Deviation of CP =	2.9	1.80	1.35

TABLE 15

**TEST CONDITIONS AND RESULTS, ONCE-THROUGH (NO RECYCLE) TESTS
WITH HYDRATED LIMES PRODUCED FROM MISSISSIPPI QUICKLIME
IN THE DRAVO PILOT HYDRATOR**

Test SO-	15	16	17	18	19	20	21	22	24	25
Run Time, hr	1.3	1.3	0.9	1.0	1.5	1.0	0.9	1.3	1.5	1.5
Sorbent BET SA, m ² /g	16.3	19.5	13.9	16.6	16.3	15.2	14.0	14.0	14.5	13.6
Dravo Sample No.	22	24	20	31	32	38	29	36	19	21
SORBENT DATA										
Fresh Ca/S Mole Ratio	1.51	1.47	1.51	1.49	1.50	1.49	1.50	1.49	1.50	1.51
Fresh Feedrate, lb/hr	8.27	8.26	8.26	8.25	8.29	8.26	8.25	8.27	8.26	8.29
DUCT FLUE GAS CONDITIONS										
In-Duct Residence Time, s	1.3	1.3	1.3	1.3	1.3	1.3	1.3	1.3	1.3	1.3
Duct Inlet SO ₂ Content, ppmv-dry	1500	1494	1496	1473	1496	1492	1497	1496	1498	1494
Approach to Saturation, °F										
Duct Exit	8	8	7	8	7	8	7	7	8	6
Baghouse Exit	13	13	14	13	14	16	16	15	14	13
Contactor Inlet Temp, °F	280	280	281	280	279	280	281	280	280	280
Contactor Exit Temp, °F	129	128	128	128	128	128	128	128	128	129
Duct Exit Temp, °F	136	136	135	136	135	136	135	135	136	135
Baghouse Exit Temp, °F	140	140	141	140	141	143	143	142	141	141
Baghouse Exit Wet Bulb, °F	127	127	127	127	127	127	127	127	127	128
Duct Inlet Flue Gas Flow, scfm	360	360	360	360	360	360	360	360	360	360
SO₂ REMOVAL, %										
In-Duct	45	44	46	61	52	50	42	49	39	33
System (Duct + Baghouse)	69	70	69	78	73	73	67	70	67	62
SORBENT UTILIZATION, %										
Flue Gas Analyzers	46	47	46	52	49	49	45	47	44	41
Ash Analysis	42	44	50	45	46	48	44	50	45	43
TGA Analysis	43	39	47	46	43	47	40	45	45	42

TABLE 15 (Continued)

**TEST CONDITIONS AND RESULTS, ONCE-THROUGH (NO RECYCLE) TESTS
WITH HYDRATED LIMES PRODUCED FROM MISSISSIPPI QUICKLIME
IN THE DRAVO PILOT HYDRATOR**

Test SO—	26	27	28	29	30	31	32	33	34	35
Run Time, hr	1.0	1.3	1.3	1.0	1.0	1.3	1.5	1.3	1.3	1.3
Sorbent BET SA, m ² /g	14.8	16.0	17.3	15.8	15.0	15.0	15.3	15.4	16.3	16.4
Dravo Sample No.	23	25	26	27	28	30	33	34	35	37
SORBENT DATA										
Fresh Ca/S Mole Ratio	1.50	1.57	1.52	1.51	1.49	1.49	1.51	1.51	1.52	1.51
Fresh Feedrate, lb/hr	8.30	8.29	8.32	8.31	8.30	8.30	8.31	8.31	8.26	8.30
DUCT FLUE GAS CONDITIONS										
In-Duct Residence Time, s	1.3	1.3	1.3	1.3	1.3	1.3	1.3	1.3	1.3	1.3
Duct Inlet SO ₂ Content, ppmv—dry	1502	1417	1501	1497	1500	1500	1496	1502	1493	1497
Approach to Saturation, °F										
Duct Exit	7	8	8	7	9	9	8	9	8	9
Baghouse Exit	14	15	15	14	15	15	14	15	15	15
Contactor Inlet Temp, °F	279	281	280	281	281	280	280	280	280	280
Contactor Exit Temp, °F	129	128	128	127	128	128	128	129	129	128
Duct Exit Temp, °F	135	136	136	135	137	138	137	138	137	137
Baghouse Exit Temp, °F	141	142	142	141	142	143	142	143	143	142
Baghouse Exit Wet Bulb, °F	127	127	127	127	127	128	128	128	128	127
Duct Inlet Flue Gas Flow, scfm	360	360	360	360	360	360	360	360	360	360
SO₂ REMOVAL, %										
In-Duct	34	42	39	34	36	43	38	38	30	35
System (Duct + Baghouse)	64	75	71	68	69	75	70	69	62	67
SORBENT UTILIZATION, %										
Flue Gas Analyzers	43	48	47	45	46	50	46	45	41	44
Ash Analysis	42	48	41	41	51	45	—	51	40	42
TGA Analysis	45	53	43	43	53	—	50	55	45	46

TABLE 16

**TEST CONDITIONS AND RESULTS, ONCE-THROUGH (NO RECYCLE) TESTS
WITH HYDRATED LIMES PRODUCED FROM BLACK RIVER QUICKLIME
IN THE DRAVO PILOT HYDRATOR**

Test SO-	37	38	39	40	41	42	43	44	45	46	49	50
Run Time, hr	1.0	1.0	1.0	1.0	1.1	1.2	0.9	0.9	0.7	1.0	1.5	2.0
Sorbent BET SA, m ² /g	12.3	15.2	14.4	14.1	13.0	13.0	13.1	11.8	13.3	14.4	12.7	14.6
Dravo Sample No.	45	46	44	39	42	43	40	41	47	48	49	50
SORBENT DATA												
Fresh Ca/S Mole Ratio	1.49	1.47	1.46	1.46	1.47	1.45	1.48	1.49	1.49	1.45	1.48	1.48
Fresh Feedrate, lb/hr	8.32	8.31	8.31	8.30	8.29	8.31	8.31	8.32	8.31	8.30	8.37	8.36
DUCT FLUE GAS CONDITIONS												
In-Duct Residence Time, s	1.3	1.3	1.3	1.3	1.3	1.3	1.3	1.3	1.3	1.3	1.3	1.3
Duct Inlet SO ₂ Content, ppmv-dry	1491	1506	1496	1504	1500	1504	1496	1495	1487	1495	1492	1498
Approach to Saturation, °F												
Duct Exit	10	10	10	11	11	12	10	10	10	10	12	12
Baghouse Exit	14	16	16	17	18	17	16	17	16	17	18	19
Contactor Inlet Temp, °F	283	283	279	280	280	283	280	281	281	281	300	300
Contactor Exit Temp, °F	129	128	128	128	128	128	128	127	128	128	131	131
Duct Exit Temp, °F	138	138	138	139	139	140	138	138	138	138	140	140
Baghouse Exit Temp, °F	141	143	143	144	145	144	143	144	143	144	145	146
Baghouse Exit Wet Bulb, °F	127	127	127	127	127	127	127	127	127	127	127	127
Duct Inlet Flue Gas Flow, scfm	360	360	360	360	360	360	360	360	360	360	360	360
SO₂ REMOVAL, %												
In-Duct	43	45	46	43	42	51	40	45	44	44	49	41
System (Duct + Baghouse)	64	68	68	65	65	78	63	63	64	65	73	66
SORBENT UTILIZATION, %												
Flue Gas Analyzers	43	46	47	45	44	54	43	42	43	45	49	44

TABLE 17

TEST CONDITIONS AND RESULTS, RECYCLE SIMULATION TESTS WITH ADDITIVES IN RECYCLE SORBENT TREATMENT WATER

Test	13A	13B	13C	15	16	17B
Run Time, hr	39	41	35	42	24	64
Fresh Sorbent	Mississippi	Mississippi	Mississippi	Mississippi	Mississippi	Mississippi
	Hydrate	Hydrate	Hydrate	Hydrate	Hydrate	Hydrate
Additive	NaCl	NaCl	NaCl	Na ₂ CO ₃	CaCl ₂	NONE
Na(Ca)/Fresh Ca, mol	0.025	0.03	0.03	0.03	0.03	0.00
lb Water/lb Recycle Sorbent	0.12	0.12	0.12	0.12	0.12	0.12
Sorbent Data						
Fresh Ca/S Mole Ratio (a)	1.04	1.07	1.24	1.22	1.25	1.22
Fresh Feedrate, lb/hr	5.36	5.60	6.48	6.39	6.44	6.37
Recycle Feedrate, lb/hr	53.41	55.76	53.99	53.24	53.63	53.54
Recycle Ratio, lb recycle/lb fresh lime	9.96	9.96	8.33	8.33	8.33	8.41
Recycle Ratio, dry basis	8.16	8.15	6.82	6.82	6.82	6.89
Recycle Available Ca/S, Mol Ratio (a)	1.49	1.84	1.33	1.23	1.21	1.40
Total Available Ca/S, Mol Ratio (a)	2.53	2.91	2.57	2.45	2.46	2.62
Water Addition, lb/hr	5.95	6.21	6.01	5.93	5.97	5.96
Additive Addition, lb/hr	0.10	0.13	0.15	0.13	0.28	0.00
Duct Flue Gas Conditions						
In-Duct Residence Time, sec	2.7	2.7	2.7	2.7	2.7	2.7
Duct Inlet SO ₂ Content, ppmv-dry	1487	1503	1500	1503	1485	1500
Approach to Saturation, °F						
Duct Exit	3	3	6	4	3	2
Baghouse Exit	22	43	9	10	11	10
Solids Loading, gr/scf	20.2	21.1	20.7	20.5	20.6	20.6
Contactors Inlet Temp, °F	281	281	281	282	281	281
Contactors Exit Temp, °F	128	126	129	127	127	129
Duct Exit Temp, °F	131	130	134	132	131	130
Baghouse Exit Temp, °F	149	169	136	137	138	137
Baghouse Exit Wet Bulb, °F	127	126	127	127	127	127
Duct Inlet Flue Gas Flow, scfm	340	340	340	340	340	340
SO₂ Removal, %						
In-Duct	65	59	92	79	65	84
System (Duct + Baghouse)	84	75	99+	93	97	92
Sorbent Utilization, %						
Steady State (b)	80	70	81	76	78	76
Flue Gas Analyzers (c)	73	67	74	75	76	73
Ash Analysis (d)	76	71	75	76	76	72
TGA Analysis (e)	79	73	77	76	82	73

(a) Includes all calcium in sorbents not tied up with sulfur (e.g., Ca(OH)₂ and CaCO₃).

(b) Based on flue gas analysis and fresh sorbent feed rate/composition, assuming steady-state.

(c) Based on flue gas analysis, and fresh and recycle sorbent feed rates/compositions.

(d) Based on baghouse solids analysis (S,Ca).

(e) Based on baghouse solids analysis (TGA).

TABLE 18

**SUMMARY OF RECYCLE TEST RESULTS,
ADDITIVES IN RECYCLE SORBENT TREATMENT WATER**

Test	Additive	Na(Ca)/ Fresh Ca, mol	Fresh Ca/S, mol	Recycle Ratio (a)	Total Ca(OH) ₂ /S mol Ratio	Baghouse Approach °F	SO ₂ Removal, %		Sorbent Util., % (c)
							Duct	System(b)	
13A	NaCl	0.025	1.0	8.2	2.0	22	65	84	78
13B	NaCl	0.03	1.1	8.2	2.1	43	59	75	72
13C	NaCl	0.03	1.2	6.8	1.2	9	92	99	76
15	Na ₂ CO ₃	0.03	1.2	6.8	2.0	10	79	93	76
16	CaCl ₂	0.03	1.3	6.8	2.1	11	65	97	79
17B	None	0.00	1.2	6.9	2.2	10	84	92	73

Common Conditions: SO₂ Inlet Concentration = 1500 ppmv(dry),
0.12 lb Water/lb Recycle Sorbent,

(a) lb dry recycle/lb fresh lime

(b) Duct + baghouse

(c) Based on baghouse solids analysis

TABLE 19

**TEST CONDITIONS AND RESULTS, ONCE-THROUGH TESTS
WITH ADDITIVES INCORPORATED DURING HYDRATION**

Test SO—	3	3A	4	4A	5	5A	6	6A
Run Time, hr	3.4	1.2	3.3	1.5	2.0	0.4	2.6	1.8
Hydrate	Mississippi	Mississippi	Mississippi	Mississippi	Mississippi	Mississippi	Mississippi	Mississippi
Hydrate Source	Commercial	Commercial	Pilot	Pilot	Pilot	Pilot	Pilot	Pilot
Additive	None	None	NaCl	NaCl	Na ₂ CO ₃	Na ₂ CO ₃	None	None
Additive Conc., Na/Ca mol	0.0	0.0	0.14	0.14	0.14	0.14	0.0	0.0
Sorbent BET SA, m ² /g	24.4	24.4	11.7	11.7	6.5	6.5	15.1	15.1
SORBENT DATA								
Fresh Ca/S Mole Ratio	1.49	2.05	1.35	1.83	1.39	1.87	1.45	1.97
Fresh Feedrate, lb/hr	8.14	11.05	8.14	11.03	8.14	11.01	8.08	10.96
DUCT FLUE GAS CONDITIONS								
In-Duct Residence Time, sec	2.6	2.6	2.6	2.6	2.6	2.6	2.6	2.6
Duct Inlet SO ₂ Content, ppmv—dry	1489	1474	1500	1493	1497	1507	1495	1490
Approach to Saturation, °F								
Duct Exit	11	11	10	12	9	10	9	9
Baghouse Exit	18	17	18	20	19	21	18	19
Contactor Inlet Temp, °F	281	280	282	279	281	281	281	281
Contactor Exit Temp, °F	129	128	128	128	129	127	129	128
Duct Exit Temp, °F	138	138	137	138	138	138	138	138
Baghouse Exit Temp, °F	144	143	144	145	145	146	144	145
Baghouse Exit Wet Bulb, °F	128	128	128	125	128	125	128	128
Duct Inlet Flue Gas Flow, scfm	360	360	360	360	360	360	360	360
SO₂ Removal, %								
In-Duct	51	64	53	60	41	48	37	43
System (Duct + Baghouse)	80	96	97	99	63	74	60	71
Sorbent Utilization, %								
Flue Gas Analyzers	53	47	72	54	45	40	42	38

(a) Dravo Lime Co.

(b) Weight %

TABLE 19 (Continued)

**TEST CONDITIONS AND RESULTS, ONCE-THROUGH TESTS
WITH ADDITIVES INCORPORATED DURING HYDRATION**

Test SO ₂ -	48A	48B	45	9	9A
Run Time, hr	1.8	2.0	0.7	1.8	1.7
Hydrate	Black River	Black River	Black River	Black River	Black River
Hydrate Source	Pilot	Pilot	Pilot	Commercial	Commercial
Additive	Hydrator (a)	Hydrator (a)	Hydrator (a)	Hydrator	Hydrator
Additive Conc., Na/Ca mol	Sugar	Sugar	None	None	None
Sorbent BET SA, m ² /g	2.3 (b)	2.3 (b)	0.0	0.0	0.0
	6.2	6.2	13.3	14.2	14.2
SORBENT DATA					
Fresh Ca/S Mole Ratio	1.40	1.87	1.49	1.50	2.02
Fresh Feedrate, lb/hr	8.23	11.00	8.31	8.39	11.20
DUCT FLUE GAS CONDITIONS					
In-Duct Residence Time, sec	2.6	2.6	2.6	2.6	2.6
Duct Inlet SO ₂ Content, ppmv-dry	1494	1492	1487	1488	1475
Approach to Saturation, °F					
Duct Exit	7	7	10	12	14
Baghouse Exit	13	12	16	18	20
Contactor Inlet Temp, °F	300	300	281	282	280
Contactor Exit Temp, °F	131	131	128	129	130
Duct Exit Temp, °F	134	134	138	139	141
Baghouse Exit Temp, °F	139	138	143	144	146
Baghouse Exit Wet Bulb, °F	126	126	127	126	126
Duct Inlet Flue Gas Flow, scfm	360	360	360	360	360
SO₂ Removal, %					
In-Duct	38	44	44	53	58
System (Duct + Baghouse)	47	54	64	72	82
Sorbent Utilization, %					
Flue Gas Analyzers	33	29	43	48	40

(a) Dravo Lime Co.

(b) Weight %

ADVANCED COOLSIDE PROCESS

Figure 1. Schematic of the Advanced Coolside Process.

Figure 2. Schematic of Advanced Coolside Pilot Plant.

Figure 3. Schematic of Second Generation Contactor Design.

Figure 4. Schematic of Third Generation Contactor Design.

Figure 5. Schematic of Lab Desulfurization Unit.

Figure 6. Duct and Baghouse SO₂ Removals in Once-Through (No Recycle) Tests with Five Commercial Hydrated Limes at a 1.5 Ca/S mol Ratio.

Figure 7. Duct and Baghouse SO₂ Removals in Once-Through (No Recycle) Tests with Five Commercial Hydrated Limes at a 2.0 Ca/S mol Ratio.

Figure 8. Effect of Lime Surface Area on SO₂ Removals at a 2.0 Ca/S mol Ratio in Once-Through Tests of Five Different Commercial Hydrated Limes.

Figure 9. Duct and Baghouse SO₂ Removals in Once-Through Tests with Specially Prepared (High Surface Area) Sorbents at a 1.5 Ca/S mol Ratio.

Figure 10. Duct and Baghouse SO₂ Removals in Once-Through Tests with Specially Prepared (High Surface Area) Sorbents at a 2.0 Ca/S mol Ratio.

Figure 11. Porosity vs BET Surface Area for Hydration Tests.
▲ = Hydrated Mississippi Quicklime. ■ = Hydrated Black River Quicklime

Figure 12. Duct and Baghouse SO₂ Removals in Once-Through Tests at a 1.5 Ca/S mol ratio with Additives Incorporated During Hydration.

Figure 13. Duct and Baghouse SO₂ Removals in Once-Through Tests at a 2.0 Ca/S mol Ratio with Additives Incorporated During Hydration.