

## ADVANCED IN-DUCT SORBENT INJECTION PROCESS FOR SO<sub>2</sub> CONTROL

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### SUMMARY

This paper describes the status of development of an advanced duct-sorbent-injection process for the control of SO<sub>2</sub> emissions from coal-fired power plants. The technical objective of the project is to develop a low-capital-cost process capable of over 90% SO<sub>2</sub> removal as a retrofit option for compliance with the 1990 Clean Air Act Amendments. A complementary objective is to achieve sufficiently high sorbent utilization (60% with hydrated lime) so that levelized costs are lower than wet limestone scrubbing costs over a wide range of coal types and plant sizes.

The SO<sub>2</sub> removal and sorbent utilization objectives were achieved. The original performance targets of 90% SO<sub>2</sub> removal and 60% sorbent utilization were exceeded in 0.3 MWe pilot plant operations through a combination of equipment design improvements and sorbent recycle optimization. The 90% SO<sub>2</sub> removal target was achieved at sorbent utilizations of 70-75%. Up to 99% SO<sub>2</sub> removal was attained at 60% sorbent utilization. A simplified equipment design was tested and its operability was confirmed in pilot plant operation.

An interim economic evaluation was completed based on these results. Projected capital costs are approximately 40% lower than wet limestone scrubbing costs over the range of coal sulfur contents (1.5-3.5%) and plant sizes (160-500 MWe) evaluated. Levelized SO<sub>2</sub> control costs are competitive with wet limestone scrubbing over the range of cases studied. Potential design and operating improvements were identified which can reduce capital and levelized costs. These improvements will be evaluated in ongoing pilot plant development work. Current work also includes the development and testing of improved sorbents.

The advanced duct-sorbent-injection process (Advanced Coolside) involves flue gas humidification to the adiabatic saturation point using a contacting device which simultaneously removes fly ash from the flue gas. A sorbent (hydrated lime), injected into the highly humid flue gas downstream of the contactor, captures SO<sub>2</sub> before being removed in the existing particulate collector. The high humidity allows high SO<sub>2</sub> removal. High sorbent utilization is achieved by sorbent recycle. Greater recycle is possible than for previous duct-sorbent-injection processes because the fly ash is removed by the contactor prior to sorbent injection.

### BACKGROUND

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)<sup>1,3</sup> and the HALT process (Dravo)<sup>4</sup> and through the DOE duct injection technology development program.<sup>5</sup> 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% SO<sub>2</sub> removal at 2/1 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 Station<sup>3</sup> showed that an SO<sub>2</sub> 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 attractiveness of duct sorbent injection for site-specific applications.<sup>6</sup> However, the applicability as a compliance option for the Clean Air Act or other regulations can be expanded by improving SO<sub>2</sub> removals and sorbent utilizations. The performance targets for developing an advanced process (90% SO<sub>2</sub> removal and 60% sorbent utilization) represent a substantial improvement over previous technology.

The Advanced Coolside process is being developed using a 1000 acfm pilot plant.<sup>7</sup> The pilot plant was used in previous development of the Coolside process;<sup>1,2</sup> it was modified to include all elements of the Advanced Coolside process. Process development has focused on improving the design of the contactor and on improving sorbent utilization by optimizing sorbent recycle. A test program to investigate sorbent improvement was recently initiated. This report will discuss progress in these areas, results of the interim economic study and approaches for future process improvement.

### DESCRIPTION OF ADVANCED COOLSIDE PROCESS

Figure 1 shows a schematic of the Advanced Coolside process. The process achieves higher SO<sub>2</sub> 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<sub>2</sub> capture near the saturation point. Because the flue gas is already humidified prior to sorbent injection, there is no strict residence time requirement for droplet evaporation. SO<sub>2</sub> is removed in the duct and by the sorbent collected in the existing ESP or baghouse. The heat of reaction between SO<sub>2</sub> and hydrated lime raises the temperature of the flue gas by roughly 9°F for each 1000 ppm of SO<sub>2</sub> removed. Therefore, it is possible to operate the particulate collector at a practical approach to saturation without flue gas reheat. However, because hydrated lime activity is highly sensitive to the approach to saturation, this reaction heat effect can also act as a limiting mechanism for SO<sub>2</sub> capture.

The spent sorbent is captured by the existing particulate collector as a dry powder. It can be disposed of with the fly ash or separately. Sorbent recycle is an integral component of the Advanced Coolside process. Recycle sorbent is quite active for SO<sub>2</sub> capture at high humidity. The potential for recycle is increased because fly ash is removed separately before sorbent injection. Furthermore, recycle sorbent performance can be improved by a simple physical pre-treatment step prior to re-injection; the nature of this pre-treatment step is currently a proprietary feature of the process.

Design optimization has focused on the flue gas/water contactor. For the initial pilot plant testing the contacting device was a Waterloo scrubber.<sup>9</sup> This is a commercially available device, marketed by Turbotak, Inc., and used primarily for removal of submicron particles. The Waterloo scrubber consists of a conditioning zone, a centrifugal fan and a mist eliminator, and uses two-fluid nozzles to finely atomize water sprays at a liquid/gas ratio of about 1 gal/1000 acf.

## DISCUSSION

Recycle Optimization. The improvement in desulfurization performance which allowed project performance targets to be exceeded resulted primarily from recycle optimization. By more fully exploiting recycle, sorbent utilization efficiencies of 70-75% were attained, while maintaining SO<sub>2</sub> removal around 90%. Also, high SO<sub>2</sub> removals ranging from 90% to over 99% were attained, while maintaining sorbent utilization of 60%.

Recycle optimization tests were conducted in the 1000 acfm pilot plant in a semi-continuous manner. Spent sorbent was removed frequently from the pilot baghouse. A portion of the material was discarded and the remainder, after pretreatment, was returned in a batch to the recycle feeder. Test duration was sufficiently long to assure that steady-state continuous recycle was simulated closely (typically 20-70 hr).

Tables 1 and 2 list process conditions and results for pilot recycle optimization tests. Tests 1 through 4 (Table 1) were conducted with reheat before the baghouse (to a 25°F approach) to minimize baghouse SO<sub>2</sub> removal. The purpose was to simulate conditions in a retrofit application with an existing ESP. In this case, SO<sub>2</sub> removal in the ESP would be limited by gas phase mass transfer. Based on literature information and on theoretical calculations, an ESP removal of 30% of the SO<sub>2</sub> remaining in the ESP inlet gas is a reasonable assumption. As shown in Table 1, SO<sub>2</sub> removal in the baghouse with reheat averaged 5% (absolute). Tests 5-9 (Table 2) were conducted with no baghouse reheat. The 9 to 12°F baghouse approach temperature was a result of the flue gas temperature rise from the heat of reaction. In these tests SO<sub>2</sub> removal in the baghouse was greater than with reheat, although the large majority of SO<sub>2</sub> was still removed in the duct.

The recycle test results indicate that for systems with an existing ESP, 90% SO<sub>2</sub> removal can be achieved at sorbent utilizations of 70-75%, substantially higher than the original target of 60% utilization. For example, with a fresh Ca/S mol ratio of 1.2, duct and system SO<sub>2</sub> removals were 87% and 90%, respectively (Test 2, Table 1).

The results also indicate that high efficiency SO<sub>2</sub> removal can be attained in systems with a baghouse operated at close approach. For example, 99% SO<sub>2</sub> removal was attained at 61% sorbent utilization (Test 9, Table 2). In this test most of the SO<sub>2</sub> removal (88%) occurred in the duct. The capability to achieve very high SO<sub>2</sub> removal may be attractive to new units using a baghouse for fly ash collection.

In the recycle tests in Tables 1 and 2, recycle ratios ranged from 3.3 to 6.9 lb/lb fresh lime. Relatively high recycle ratios are possible because fly ash is removed upstream of sorbent injection. Total dust loading ranged from 9.5 to 14.5 gr/scf. Pilot testing indicated that recycle sorbent particles tended to agglomerate during handling, pretreatment and reaction; this could improve the ability of an existing ESP to handle higher dust loadings.

As shown in Tables 1 and 2, the recycle tests were relatively long-term. With one exception, operating durations ranged from 21 to 115 hr. This allowed process operability to be evaluated. It also provides added confidence in data reliability.

Data reliability also was confirmed by comparing utilizations based on gas analysis with those based on solids analysis. As shown in Tables 1 and 2, utilizations by the two independent methods agreed very well. This confirms the accuracy of process performance data; it also confirms that steady-state continuous recycle conditions were established. In addition, in-duct SO<sub>2</sub> removal data for selected run periods were confirmed by manual flue gas sampling using EPA Method 6.

Design Optimization. A major portion of the process development is devoted to contactor simplification. The contactor is a key capital cost component, and the contacting device initially tested was designed for more stringent applications (i.e., submicron particulate control) than required for Advanced Coolside. Because the process is applied upstream of an existing particulate collector, some fly ash slippage through the contactor is acceptable. It is only necessary to remove a large portion of the particulate mass (ca. 90%) to avoid recycling much of the inert fly ash. Approaches to reduce the capital and operating

cost of the contactor included eliminating the fan, an integral component of the original Waterloo scrubber system, and redesigning the contactor to reduce water and atomization air requirements.

Preliminary pilot plant studies indicated that these approaches are feasible. Tests were conducted using the original Waterloo scrubber system with and without its centrifugal fan under a wide range of atomizing air pressures and water flow rates. The test results (Figure 2) indicated that high flue gas relative humidities can be achieved with or without the fan, as long as sufficient water droplet surface area is generated in the contactor. The test results also showed that the atomization energy can be reduced to below typical operating conditions (40-45 psig) with a relatively minor effect on flue gas humidity. Particulate removal tests indicated that removal efficiency was not sensitive to the nozzle operating conditions over the ranges tested and that the scrubber fan was not needed to achieve fly ash removal greater than 90 wt %. These results indicate that there was flexibility for design and operating modifications.

Based on the tests using the original contactor, a mechanically simpler contactor was designed by Turbotak Inc. (Figure 3). The new contactor consists of a spray chamber and a downstream mist eliminator. Most of the particles and water droplets are removed in the spray chamber. The mist eliminator removes remaining droplets from the flue gas. The Waterloo scrubber fan was eliminated, significantly reducing the cost of the contactor.

Tests were performed which verified the humidification performance, particulate collection efficiency, and operability of the simplified contactor. Optimization tests were conducted to reduce atomization air pressure and flow and water flow relative to the design conditions of Turbotak. Table 3 shows the result of using the alternative operating conditions identified in these tests. Water and air flow requirements were reduced by about half. The air pressure requirement was reduced from 45-50 to ~30 psig, while maintaining humidification (>95% relative humidity) and fly ash removal efficiency (> ca. 90%). These alternative operating conditions will result in lower operating and capital costs.

Operability Observations. Pilot plant operating experience in tests up to 115 hr in duration is a positive indication of the operability and retrofit potential of the Advanced Coolside process. Although the pilot plant is not of sufficient scale to make a complete assessment of process operability, observations of pilot plant operation provide initial information on key operability issues.

The contactor operability was simplified by the elimination of the fan. The mist eliminator was washed periodically to maintain contactor pressure drop at about 1.5 inches of H<sub>2</sub>O.

Accumulation of solids on the duct walls was not an operating problem, even at very close approach to saturation and with different duct configurations having short straight-run residence times (<0.5 sec) and numerous changes in flow direction. There was generally a light surface coating of dry solids. At bends, there was somewhat more accumulation. The amount of solids on the duct surface tended to reach a steady value after 10 to 30 hr of operation, after which the rate of accumulation approached zero. The solids were loose and easily removed.

No major problems were encountered in preparing, handling and feeding the recycle sorbent. Operability of the pneumatic transport system was similar to that with hydrated lime. Operability of the recycle handling system was observed to deteriorate at very high sorbent utilization (>70%). This was alleviated by adding the fresh lime to the recycle material during pre-treatment and co-injecting the sorbents.

Baghouse operability was good at the close approaches to adiabatic saturation (down to 10°F) investigated in this program. The material did have a tendency to compact under compression at the lowest baghouse approach temperature, an important consideration for a larger scale design.

Sorbent Optimization. Sorbent improvement can increase the attractiveness of the Advanced Coolside process in several ways. Increasing sorbent utilization reduces sorbent usage and waste disposal requirements. Increasing sorbent activity can reduce the required level of sorbent recycle and could increase the applicability of the process for high SO<sub>2</sub> removal levels. Finally, the results of sorbent studies could allow use of lower cost sorbents by reducing process sensitivity to sorbent source.

Pilot plant tests reported previously in this paper were all conducted with a single commercial hydrated lime. A sorbent optimization test program was recently begun. The program includes work in three areas: a lime hydration study, evaluation of alternate sorbents, and evaluation of additive enhancement.

The objectives of the lime hydration study are to determine the effect of hydration variables on the properties of hydrated lime and to determine the effect of lime properties on desulfurization performance. The hydration study is being conducted in cooperation with Drayo Lime Co. using their continuous pilot hydrator. Hydration variables being investigated in a statistical experimental design include the following: quicklime source, quicklime grind size, hydration water temperature, residual H<sub>2</sub>O in the product, and hydrator residence time. Hydrated limes will be characterized for chemical composition and physical properties such as particle size, surface area, and pore size. Desulfurization performance will be measured in laboratory reactors and in the pilot plant.

Evaluation of alternate sorbents will include testing of different commercial hydrated limes and testing of other sorbents, for example, specially prepared high surface area hydrated limes. Recycle tests were conducted for two commercial hydrated limes. In these tests at 1.2 Ca/S mol ratio, system SO<sub>2</sub> removals (with baghouse reheat to simulate ESP removal) were 90% and 86% for the hydrated limes with surface areas of 22 and 14 m<sup>2</sup>/g, respectively. Also, once-through screening tests of different commercial hydrated limes from different geographic regions and with varying surface areas showed only small differences in SO<sub>2</sub> removals. These results suggest that process performance is relatively insensitive to

surface area and to commercial lime source. This may be an economic advantage, allowing use of the lowest cost sorbent available.

Previous laboratory studies<sup>7</sup> simulating Advanced Coolside process conditions indicated that sodium-based additives can substantially increase the utilization of hydrated lime (by over 20% absolute). In the current test program, different approaches for additive promotion will be investigated, including addition to lime during hydration. Based on previous lab studies and literature information, additives to be evaluated include  $\text{Na}_2\text{CO}_3$ ,  $\text{NaCl}$ , and  $\text{CaCl}_2$ . Chloride additives are of interest because they could be generated by neutralization of contactor recycle water. One pilot plant test was conducted with  $\text{NaCl}$  promotion. Results are encouraging, indicating that sorbent utilization can be increased to 80-85% using very small amounts of additive — 0.025 Na/S mol/mol, about 1/15 of that employed in the conventional Coolside process.<sup>1,3</sup> Further testing is under way using different additives and additive dosages, and varying process conditions.

**Process Economics.** An interim process economic study was completed based on current process performance data with a commercial hydrated lime and a conceptual process design. The objectives for this study were to confirm the potential economic advantages of the Advanced Coolside process and to identify priorities for further process development. A final economic study will be conducted at the conclusion of the pilot-scale development program.

The economic study compared costs of Advanced Coolside with limestone wet scrubbing. Economic assumptions (Table 4) were selected to assure comparison on an equivalent basis. The limestone wet FGD costs are based on a design which includes forced oxidation and a single absorber module. Both processes were evaluated for 90%  $\text{SO}_2$  removal efficiency, an assumed capital life of 30 years and using the same retrofit factors. The analysis was based on an 'nth' plant design philosophy, using an 18% contingency for each process.

The economic study confirmed a substantial capital cost advantage for the Advanced Coolside process. Figure 4 shows that for a 2.5% sulfur coal the capital cost was about 40% less than forced oxidation limestone scrubbing, over the 150-500 MWe range of plant sizes studied. The relative difference in capital cost was about the same for 1.5 and 3.5% sulfur coals. The lower capital cost can be important to utilities in making compliance decisions because it reduces financial and regulatory risk.

The economic study quantified the potential  $\text{SO}_2$  control cost advantages of the Advanced Coolside process. Figure 5 shows that the process has a lower levelized cost (\$/ton  $\text{SO}_2$  removed) than limestone wet FGD over a wide range of coal sulfur contents and plant sizes. The cost differential ranged from 21% for 1.5% sulfur coal and a 150 MWe plant, to 11% for 2.5% sulfur and 250 MWe, to breakeven for 3.5% sulfur and 500 MWe.

The Interim study also indicated that there is potential for further improvement of the Advanced Coolside process and identified areas for improvement with the greatest potential impact on economics, including reduction in sorbent cost and reduction in equipment capital cost for certain process systems. Areas for equipment cost reduction include further contactor optimization and improvement in other systems on which optimization studies have not yet focused (e.g., recycle handling, waste handling, and flue gas handling). The goal of further development is to establish at least a 20% levelized cost advantage over wet FGD over a wide range of compliance situations. This would make it more attractive for utilities to employ a newer, less established technology.

#### FUTURE WORK

Based on the process economic study, the focus of future process development will be to increase the cost advantage of Advanced Coolside over commercial technology through equipment design optimization and sorbent improvement. For the economic study, Turbotak, Inc. developed preliminary full-scale designs for the simplified contactor based on the test results with the original contactor. The results of pilot tests using the new contactor will be used by Turbotak to develop a commercial design to further reduce costs. Equipment design optimization efforts will be expanded to look at other systems with potential impact on process capital cost, as identified in the economic study. The sorbent improvement work under way will continue as described above. The goals are to reduce sorbent usage and to allow use of lower cost sorbent sources. Another area for future investigation is air toxics control, particularly that of mercury. A literature analysis under way suggests that the Advanced Coolside process has potential for Hg reduction. The capability for air toxics control would provide an additional incentive to use this technology for  $\text{SO}_2$  compliance.

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TABLE 1. Advanced Coolside Pilot Plant Recycle Tests with Flue Gas Reheat Prior to the Baghouse.

Test	1	2	3	4
Test Duration, hr	36	115	13	73
<b>Process Conditions</b>				
Fresh Ca/S, mol	1.4	1.2	1.5	1.2
Recycle Ratio, lb/lb fresh lime	4.5	6.9	4.4	6.7
Recycle Pretreatment	Yes	Yes	Yes	Yes
Baghouse Approach Temp., °F	23	23	24	22
Hydrated Lime	A	A	A	B
<b>Process Performance</b>				
SO <sub>2</sub> Removal, %, In-Duct	83	67	84	80
System	90	90	90	86
Baghouse	7	3	6	6
Sorbent Utilization, %, By Gas Analysis	63	75	60	70
By Solid Analysis	63	70	59	71

Common Condition: SO<sub>2</sub> Content: 1500 ppm

TABLE 2. Advanced Coolside Pilot Plant Recycle Tests with No Flue Gas Reheat Prior to the Baghouse.

Test	5	6	7	8	9
Test Duration, hr	40	28	21	25	23
<b>Process Conditions</b>					
Fresh Ca/S, mol	1.2	1.5	1.2	1.6	1.6
Recycle Ratio, lb/lb fresh lime	3.3	3.5	4.9	3.9	3.6
Recycle Pretreatment	Yes	Yes	Yes	Yes	Yes
Baghouse Approach Temp., °F	9	12	9	11	12
Hydrated Lime	A	A	A	A	A
<b>Process Performance</b>					
SO <sub>2</sub> Removal, %, In-Duct	60	70	61	91	88
System	84	90	88	97	99
Baghouse	24	20	7	6	11
Sorbent Utilization, %, By Gas Analysis	67	61	71	80	61
By Solid Analysis	68	63	68	58	61

Common Condition: SO<sub>2</sub> Content: 1500 ppm

TABLE 3. Optimization of Contactor Operating Conditions.

	Base Design	Alternative
<b>Conditions</b>		
Nozzle Water Flow	1.13 gpm/1000 acfm	0.6 gpm/1000 acfm
Nozzle Air Pressure	45-50 psig	30 psig
Nozzle Air Flow	17 acfm/1000 acfm	9 acfm/1000 acfm
<b>Performance</b>		
Exit Humidity	>98%	>98%
Fly Ash Collection	>95%	~95%

TABLE 4. Key Assumptions of Interim Process Economic Study.

	Advanced Coolside	Forced Oxidation Wet FGD
Delivered Sorbent Cost	\$60/ton, 7% Inerts (hydrated lime)	\$15/ton (limestone)
Waste Disposal Cost	\$6.50/ton	\$6.50/ton
SO <sub>2</sub> Removal	90%	90%
Capacity Factor	65%	65%
Capital Life	30 years	30 years
Retrofit Factor	Medium (1.22-1.34)	Medium
Location Factor	1.08	1.08
Design Philosophy	'nth' plant, 18% capital contingency	'nth' plant, 18% capital contingency
Sparing	Auxiliary equip. only, no major equip.	Auxiliary equip. only, no major equip.
Indirect Costs	37.2% of direct	37.2% of direct

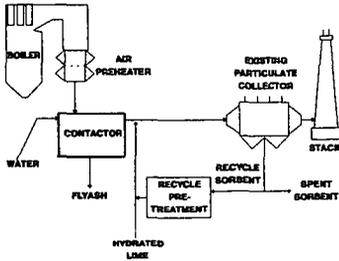


Figure 1. Advanced Coalside Process Schematic.

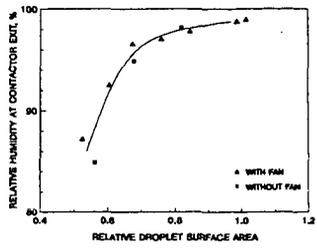


Figure 2. Initial Pilot Test Data for Contactor Simplification.

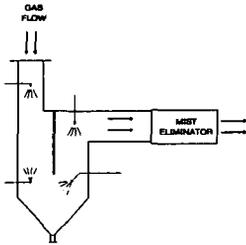


Figure 3. Simplified Contactor Design.

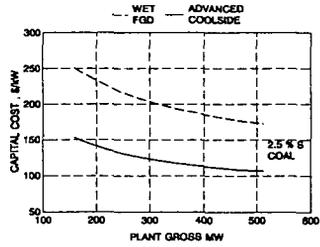


Figure 4. Comparison of Capital Costs for Advanced Coalside and Wet Limestone Forced Oxidation FGD at 2.5% Coal Sulfur Content and Varying Plant Sizes.

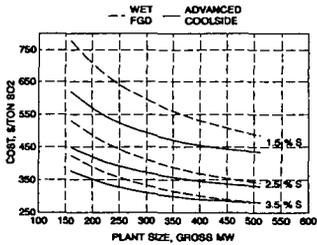


Figure 5. Comparison of Levelized SO<sub>2</sub> Control Costs for Advanced Coalside and Wet Limestone Forced Oxidation FGD as a Function of Coal Sulfur Content and Plant Size.