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INTRODUCTION

Flue-gas desulfurization (FGD) systems based on spray drying are a relatively recent addition to the spectrum of sulfur dioxide (SO_2) control options available to utility and industrial boiler operators. Such systems appear to offer advantages over wet lime/limestone systems in a number of areas: low energy consumption, low capital cost, high reliability, and production of a dry waste that is easily handled and disposed of. These advantages have promoted rapid acceptance of dry scrubbers for applications using western low-sulfur coal, but uncertainties regarding the performance and economics of such systems for control of high-sulfur-coal emissions have slowed adoption of the technology in the Midwest and East. At Argonne National Laboratory (ANL) we have had more than eight years of operating experience with an industrial-scale dry scrubber used with a boiler firing high-sulfur (3.5%) midwestern coal. This paper describes our operating experience with that system and summarizes several research programs that have utilized it.

BACKGROUND

In 1979, Argonne was directed by the U.S. Department of Energy (DOE) to convert the largest boiler (No. 5) at the site steam plant to fire coal. That unit, a spreader stoker design rated at 170,000 lb/h of steam (the equivalent of about 20 MWe), had been installed as a coal-fired unit in 1965 but was converted to fire gas or oil in 1973. The reconversion involved refurbishing the coal-handling system and the boiler (stokers, grate, etc.) and upgrading the flue-gas-cleaning (FGC) system. The original design was limited to multiclones for particulate-matter control and reinjection to the boiler, but Argonne's desire to burn Illinois high-sulfur coal required the addition of SO_2 control.

Before selecting a specific FGC system, Argonne conducted a comparative study of four scrubber types (each with a baghouse): wet lime, wet limestone, double alkali, and lime spray drying. The systems were compared in terms of cost, performance capability, reliability, manpower requirements, and degree of commercialization. Except for its very early commercialization status, dry scrubbing was clearly the best choice. System simplicity and dry-waste production were two of the major factors that influenced the final decision to ask for bids on a spray-dryer/fabric-filter system. The contract was subsequently awarded to Niro Atomizer, Inc., working in conjunction with Joy Manufacturing. A letter of intent was issued in November 1980, and construction was 95% complete by November 1981. The final contract cost was approximately \$3.1 million.

Although the FGC system was built to bring boiler No. 5 into environmental compliance, the system also was highly instrumented and has been used in several research efforts. A preliminary system characterization was conducted for the U.S. Environmental Protection Agency (EPA) in 1982-1983, and its performance with very-high-sulfur coal was tested in 1983 in cooperation with the Conoco Coal Research Division. Recently, we conducted an in-depth performance characterization as part of a DOE-sponsored research program to develop technologies for the combined removal of nitrogen oxides (NO_x) and (SO_2).

DESIGN, CONSTRUCTION, AND OPERATION

The FGC system was provided on a turn-key basis by Niro Atomizer. System features include a high-speed rotary atomizer, a pulse-jet fabric filter, and recycling of the waste to improve sorbent utilization. Figure 1 is a diagram of the system; for more detailed information, see Reference 1. Construction and initial operation went smoothly, with the acceptance tests being completed in March 1982. Table 1 gives a typical coal analysis for the fuel fired during those tests. Table 2 gives the test results. The regulatory emission limits for boiler No.5 are 1.8 lb/10^6 Btu for SO_2 and ≤20% opacity for particulate matter. These emission limits were easily met. The improved SO_2 performance at higher power levels resulted from the use of less excess air (higher concentration of pollutant) and a higher inlet temperature, permitting the use of a greater slurry feed rate.

Since initial start-up, operation of the system has generally lived up to the original expectations. However, a number of lessons have been learned (some of which have resulted in system modifications) that may prove valuable to others building and operating spray-dryer systems.

OPERATING PERSONNEL

Argonne's original plans called for the addition of eight operators (two per shift for four shifts) and three maintenance men to be assigned exclusively to the FGC system. Budget restrictions at the Laboratory have forced us to operate with two part-time operators per shift, each of whom has responsibility for other systems in the steam plant. Maintenance is handled by the crew normally assigned to the plant. Although additional personnel would be advantageous at times, the system has proven to be so easy to operate that the reduced staffing has not been a significant problem. For major maintenance, such as replacement of bags in the fabric filter, outside contractor personnel are usually brought in.

SORBENT SPECIFICATIONS

Lime is purchased with a specification calling for 90% available calcium. Material purchased from one supplier proved to have excessive amounts of dead-burned lime and other inert substances, which caused jamming of the slaker. However, no problems have been encountered with material that meets the specification.

With any lime, it is necessary to prevent the inert components or "grits" from entering the system. Our grits screen following the slaker suffered frequent failures due to deposits buildup until the housing was modified for easier operator inspection and cleaning. Grits screening is no longer a problem area.

ATOMIZER

Atomization is accomplished by spraying the lime slurry through holes in the rim of a rapidly spinning (14,000 rpm) wheel. The holes are actually tubular, carbide-lined inserts. These inserts must be replaced periodically before the carbide wears through, or significant damage to the wheel can very quickly occur. Currently, we rotate the inserts 90-120 degrees in their sockets every six months to equalize wear and replace them about every two years.

The atomizer gear drive includes a number of very-high-speed components. In maintenance, strict cleanliness must be observed, and no dirt or other impurities can be tolerated in the lubricating oil. Some problems with excessive bearing wear were noticed early in our operation. Bronze bushings were used to replace some made of babbitt, and no further problems have been encountered,

INSTRUMENTATION

Nondispersive, infrared continuous-emission analyzers (measuring SO_2, carbon dioxide (CO_2), and nitric oxide (NO)) were originally installed at the boiler exit and on the stack. These analyzers proved difficult to calibrate for satisfactory agreement with measurements taken by the standard extractive EPA methods, and they also required a higher level of maintenance than was feasible for the available staff. Therefore, they were replaced by an extractive system with sample conditioning using dilution with dry air. The system measures SO_2, CO_2, NO, and nitrogen dioxide (NO_2). (The NO_2 measurement capability was required for our current research on combined NO_x/SO_2 control.) Overall, this system has proven to be quite reliable, requiring no more than normal maintenance of the analyzers and periodic cleaning of the dilution-probe filters.

BAGHOUSE

Most of the problems associated with the baghouse have been related to corrosion, which in turn is related to the harsh winter weather at the site and our desire to operate the spray dryer with a low outlet temperature for good SO_2 removal and sorbent utilization. Some of the corrosion in the outlet plenum of the baghouse was clearly associated with stiffener ribs welded to the outside. Although these ribs are covered by several inches of insulation, they still form a low-resistance path for heat loss. (Later designs have placed the ribs inside.) We coated the inside of the plenum with a vinyl ester paint to protect the surface, and we routinely raise the outlet temperature of the spray dryer by about 10°F during the winter. It also has been necessary to insulate the isolation dampers for the baghouse compartments in order to avoid condensation problems at those points.

The original bags, made of felted fiberglass, suffered massive failures after about nine months of service; the reasons could not be fully determined, although acid attack and excessive cleaning may have contributed to the bag failures. Subsequently, 16-oz woven-fiberglass bags were installed, and cleaning was switched from the continuous on-line mode to pressure-actuated off—line operation controlled by a microprocessor. Since these changes were made, bag life has been about 18 months or more. Recently, snap-ring bags were installed to eliminate corrosion problems associated with bag clamps. Also, the venturis located above the bags as part of the pulsing system were eliminated, and the compressed-air headers were lowered to place them directly above the bag openings. This configuration has proven successful over several years of operation.

The switch to pressure-actuated cleaning had one unforeseen side effect. At low boiler loads, the flue-gas flow was reduced to such an extent that an excessively thick dust cake built up before cleaning was initiated. The amount of dust deposited in the hopper was sufficient to overload the conveyor system. Adjustment of the cleaning setpoint as a function of boiler load provided the immediate solution, and we subsequently adjusted conveyor speeds to handle all loadings.

PROCESS CHARACTERIZATION AND RESEARCH

HIGH-SULFUR COAL TESTS

In April 1983, working in cooperation with the Conoco Coal Research Division, Argonne conducted a two-week test of the spray-dryer system using a high-sulfur (nominally 4.5%) coal supplied by the Consolidation Coal Co. A typical analysis of that coal is given in Table 3. The test program had three objectives: (1) 90% or greater SO_2 removal for at least 100 continuous hours, (2) 95% or greater SO_2 removal at an external stoichiometry (based on fresh lime feed) of 1.35 or less, and (3) determination of whether 70% or greater SO_2 removal could be achieved in the spray dryer alone (an important consideration for retrofit applications involving an electrostatic precipitator). All three objectives were realized. In addition, analysis of the monitoring and sampling data revealed the following:

The stoichiometry required for a given degree of removal is generally dependent on the coal sulfur content (see Fig. 2).

The percentage removal of SO_2 is approximately the same in the spray dryer and the baghouse (see Fig. 3), confirming the importance of reactions in the dust cake on the bags.

Available alkali in the recycled waste contributes 15-20% of the total (internal) stoichiometry. This fraction decreases at very high removals, where operation approaches zero recycling in order to maximize the fresh lime feed.

The ratio of calcium sulfite to calcium sulfate in the waste is about 9 to 1 (rather than 3 to 1, as in a wet system) because of the short drying time (2-4 s) for droplets.

Resistivities of the waste particles at 150°F are on the order of 5×10^7 Ω•cm, which is typical of fly ash from high-sulfur coal and should pose no problem for collection by an electrostatic precipitator.

A complete description of the test results can be found in Reference 2.

WASTE-LEACHATE TESTS

Waste from the Argonne FGC system is mixed with ash from the boiler multiclones and placed in an on-site landfill. In order to determine the extent and nature of any potential leachate, various mixtures of ash and spent sorbent were subjected to the EPA Extraction Procedure (EP) Toxicity Test. Concentrations of 22 different elements in the leachate were determined using an atomic absorption spectrometer. No element exceeded the EPA hazardous-waste limit in any of the samples, although chromium levels were close to the maximum in one case.

Figures 4-6 show some typical results from the tests. In general, three different pH-sensitive trends were observed: (1) metal concentration increased with increasing pH, (2) metal concentration decreased with increasing pH, and (3) a maximum was observed at a pH of about 5. The pH is related to the relative fraction of sorbent, so the data are useful in determining the partitioning of elements between the ash and spray-dryer waste. Some elements, such as cadmium, are clearly found in both the waste and ash but tend to be immobilized at high pH, indicating that the waste may be useful in impounding chemical wastes containing like metals. A complete description of the tests and results is given in Reference 3.

Argonne also conducted an investigation of the fixation properties of the waste. Various blends of spent sorbent, ash, and water were prepared and cured for periods of 7, 14, and 28 days. The maximum compressive strengths observed were about 175 psi at 28 days for samples with 36% water added to a 90%-waste/10%-ash mixture.

COMBINED NO_x/SO_2 CONTROL

Spray-dryer/fabric-filter technology integrates the control of SO_2 and particulate matter in one system. The addition of NO_x control to such a system would provide a relatively simple solution to the reduction of three major pollutants resulting from coal combustion. To investigate the feasibility of such a concept, ANL led a research program that involved laboratory investigation of chemical additives and process modifications at ANL, intermediate-scale spray-dryer tests at the Pittsburgh Energy Technology Center, and large-scale field tests at Argonne's 20 MW facility.

The laboratory and intermediate-scale research identified several sodium-based chemical additives that could enhance the NO_x removal potential of lime ($Ca(OH)_2$). Process conditions that included high spray-dryer exit temperatures, high levels of SO_2 in the flue gas, and thick filter cakes in the baghouse were also identified as beneficial for combined removal. In addition to these laboratory results, this line of research was spurred by reports of brown plumes (NO_2) from a western utility operating a spray dryer system that uses soda ash as the sorbent, and initial data from Niro Atomizer on the effect of caustic soda in a lime-based spray dryer for combined NO_x/SO_x removal (4). On the basis of these data, it was decided to conduct a field test of NaOH addition with elevated spray-dryer exit temperatures at a scale sufficiently large to support decisions by private industry regarding further technology development and application. An initial series of tests was conducted in August 1986 aimed at confirming the data reported by Niro Atomizer, attempting to identify the key variables associated with combined removal, and ascertaining the most favorable conditions for a combined removal process. Further tests were conducted during the spring and summer of 1988 to confirm and refine the previous results.

1986 Test Program

Following a three-week period of baseline data acquisition under normal operating conditions, the outlet temperature from the spray dryer was increased over a one-week period in 20-degree increments from its normal value of approximately 150°F to a final temperature of about 210°F with no NaOH addition. This was done gradually to minimize the risk of major system upsets, but it also provided data needed to separate temperature effects from those due to the additive. Once the target temperature was reached, and the system stabilized (for about 12 hours), initial caustic injection commenced and continued for a period of two days. The addition rate was 5 wt % of the lime (as $Ca(OH)_2$) addition rate. The NaOH was introduced into the slurry mix tank in a 50 wt % solution. Next, the spray-dryer outlet temperature was maintained at 210°F and the caustic addition rate was increased to 10 wt %. These conditions were maintained for approximately two more days. The final phase of the program involved a gradual reduction in the SO_2 level through a transition to low-sulfur coal. In this manner, the SO_2/NO_x ratio was decreased from nearly 6 to approximately 2. The test conditions are summarized in Table 4.

Sulfur dioxide removals were maintained between 60% and 70% throughout the test in order to maintain compliance with the operating permit. Inlet SO_2 levels to the spray dryer were typically 1500 to 1600 ppm (corrected to 6% O_2). The only exceptions were during the final phase when SO_2 inlet levels were decreasing gradually to a low value of about 400 ppm. During that period the milk of lime and NaOH feed rates were manually held constant, giving removals that actually approached 100% near the end of the test.

Inlet NO_x levels varied from about 250 to 290 ppm (corrected to 6% O_2) during the tests. Inlet nitrogen dioxide levels were less than 10 ppm.

Baghouse cleaning cycles were controlled as usual by the buildup of pressure across the filter. However, the lengths of the cycles were observed to vary considerably with process conditions.

During all phases of the test, significant process parameters were recorded by the data acquisition system and extensive process stream samples were taken for chemical analysis.

1988 Test Program

Analysis of the data from the 1986 tests indicated that several areas warranted closer study. These included:

Better definition of the temperature at which significant NO_x removal begins to occur. The lowest possible spray-dryer outlet temperature for combined removal is desirable in order to minimize lime consumption.

The efficacy of lower rates of NaOH addition. The lowest feasible additive consumption is also economically advantageous.

The relationship between NO_x removal and fabric filter pressure drop (cake thickness).

Operation over longer time periods at any given condition to insure that the data represent steady state conditions.

In preparation for further tests, numerous improvements were made to the monitoring instrumentation. These changes included acquisition of a more complete and reliable set of gas analyzers for measurements between the spray dryer and the baghouse. Also, additional sampling ports were added so that the outlet gas stream from a single compartment of the baghouse could be monitored and the powder collected in that compartment could be sampled.

The test program (Table 5) was designed to investigate temperatures intermediate to those studied in 1986, to look at a lower level of NaOH addition (2.5 wt %), and to maintain each set of conditions for at least three days to allow time for the system chemistry to approach steady state through the recycle process. The experimental procedures were basically the same as those employed in 1986, except that fewer samples were taken for analysis based on the consistency seen in the earlier data. Although a total test duration of 28 days is indicated, the program actually spanned two months due to a number of boiler outages that required frequent system shutdowns. As in the earlier tests, SO_2 removals were controlled to maintain compliance with the operating permit and generally averaged about 70%. The inlet SO_2 levels were slightly higher at about 1800 ppm (6% O_2), and inlet NO_x levels were also slightly higher at 315-380 ppm. Baghouse cleaning cycles were again initiated on the basis of pressure drop, although adjustments to the controller were made to maximize the cycle length (and hence cake thickness) as much as possible without overloading the powder conveying system once cleaning took place.

Results

Effects of Temperature. The spray-dryer outlet temperature is one of the most important variables for system performance. Normal lime-based spray-dryer operation involves outlet temperatures that are 20-40°F above the adiabatic saturation temperature. For SO_2, lower temperatures are beneficial since removals increase at a constant stoichiometry (calcium to sulfur molar ratio) as the approach to saturation decreases. However, there is no appreciable removal of NO_x at these temperatures, as shown for 155°F in Figure 7 from the 1986 tests.

As the temperature was increased through 170°F, no noticeable change in NO_x removal was observed. Chemical analysis of the recycle powder gave nitrates and nitrites levels of about 200 ppm for each species, indicating a minor degree of removal and establishing a baseline for comparison with results from higher temperatures.

At 180°F a dramatic transition was encountered with a very rapid increase in NO removal with temperature as shown in Figure 8. Concurrent with the increase in NO removal, a net production of NO_2 was observed. This is shown in Figure 9 for several temperatures during the 1986 tests. The NO_2 production appeared to take place in the fabric filter, as did the increased NO removal. The net effect for total NO_x was a decrease (removal), but at a somewhat lower level than that observed for NO, as shown in Figure 7.

As the temperature was increased further, the NO_x removals increased, although the rate of increase slowed considerably above 190°F. Further evidence of the removals can be seen in the nitrates levels found in the recycle powder (Figure 10), which increased from about 200 ppm at low temperatures to approximately 4000 ppm at 210°F. The level of nitrites stayed more nearly constant, indicating the importance of NO_2 in the removal mechanism. However, attempts to use these data to achieve a material balance for nitrogen in the system have not been successful, indicating that there must exist other "sinks." This could include a reduction mechanism leading to N_2 or reactions leading to the formation of N-S compounds. This latter possibility is corroborated by the strong dependence of NO removal on SO_2 level discussed in a later section.

Changes were also noted in the properties of the powder collected in the baghouse. As shown in Table 6, increasing temperature produced a drier, more porous powder with increased surface area. From a macroscopic point of view, the changes were manifest as a reduced pressure drop through the filter cake for any given amount of powder on the bags. For example, Argonne's baghouse normally undergoes a cleaning cycle about every one and one-half hours. At a spray-dryer outlet temperature of 210°F, the interval between initiation of cleaning cycles expanded to about three hours for the same pressure-drop setpoint. Note that the particulate loading had actually increased due to the increased sorbent stoichiometry required to maintain SO_2 removal.

For these tests, the stoichiometry is best expressed as an "Equivalence Ratio" (5) defined as:

$$\frac{\text{Moles of Available Calcium} + \text{Moles/2 of Sodium}}{\text{Moles of } SO_2 + \text{Moles/2 of Nitrogen Oxides}}$$

At a spray-dryer outlet temperature of 155°F and SO_2 removal of 70%, the system internal equivalence ratio (based on both fresh sorbent feed and recycled material) was 1.02. At 190°F, the SO_2 removal had decreased (in the 1986 tests) to 58% with an internal equivalence ratio of 1.10, while at 210°F the ratio had increased still further to 1.30 for a removal of 61%. At that point, the external equivalence ratio (based on fresh lime feed only) was about 0.9.

Effect of NaOH Addition. The most noticeable effect from the addition of NaOH to the system was an increase in filter cake porosity (lower pressure drop) that was in addition to the increase brought about by the higher spray-dryer outlet temperatures. This effect led to further increases in the intervals between cleanings of the baghouse. Upon addition of NaOH at the 5 wt % level, the time between cleanings increased from three to nearly six hours (Figure 11), and then to almost 8 hours when the NaOH addition was increased to 10 wt %. Analyses of the particles comprising the filter cakes indicated further changes in the surface properties of the particles beyond those produced by temperature alone, as shown in Table 6.

Nitrogen oxides removal increased with the addition of NaOH as shown in Figure 12. The effect was most dramatic at the highest temperatures, but was still appreciable even at 180°F. At 190°F, 5 wt % NaOH addition increased total NO_x removal by about 23%, while at 200°F the increase is about 53%. Increased filter cake thickness is certainly part of the reason for the increase, but other mechanisms that have not yet been identified may also have been significant.

Preliminary evaluation of the 1988 data indicates that there was little if any statistically significant improvement in NO_x removal as a result of increasing the NaOH addition rate from 2.5% to 5.0%. This is in agreement with the earlier tests, which indicated very little improvement in going from 5.0% to 10% addition. Thus, significant NO_x-removal enhancement may be possible with still lower additive levels and, hence, reduced operating costs.

Filter-Cake Effects. Another key parameter was the thickness of filter cake that could be maintained on the bags. During the extended (6 hr) period between bag cleanings noted previously, steadily increasing removals of SO_2, NO, and NO_x were observed. A portion of that increase is shown in Figure 13. Since the buildup in the filter cake thickness was essentially an increase in the amount of available sorbent that a NO_x molecule could come into contact with while it was in the baghouse, it seems reasonable that any increases in thickness would result in an increase in the removal of NO_x, all other conditions being equal.

However, practical average removals will be less than those indicated in Figure 13 for two reasons. First, cleaning of the bags removes most of the dust cake and thereby reduces the removal rates to minimum values from which they gradually increase as more powder is collected. This gives a cyclic removal profile that closely parallels the baghouse pressure drop, as shown in Figure 14 from the 1988 tests. An average NO_x removal of about 35% was attained in those tests over an extended period. Second, the powder handling capability of the baghouse conveying system sets a practical limit on the amount of powder that can be allowed to accumulate before cleaning. In the 6 hr and 8 hr cycles noted previously, overloading of the conveyors and spillage of the powder occurred when cleaning was finally initiated. This would not be acceptable as a normal operating condition, although system hardware modifications could be made to increase the powder handling capacity if necessary.

Effect of SO_2/NO_x Ratio. During the final phase of the 1986 tests, the SO_2 content of the flue gas was gradually decreased by blending in low-sulfur coal. As indicated in Figure 15, the SO_2 level in the flue gas and/or the ratio of SO_2 to NO_x had a strong influence on both NO and total NO_x removal, with the higher SO_2 levels clearly improving removals. Analysis of the 1988 data, taken at a still higher SO_2/NO_x ratio of about 6.5:1, gives average NO_x removals significantly above those seen in 1986. Further research is needed to positively identify the reaction products and give an understanding of the chemical mechanism.

SUMMARY

In summary, Argonne's spray-dryer/fabric-filter system has proven itself in both routine operation and as a versatile test facility. The various research programs conducted to date have indicted that:

Dry scrubbers can be operated easily and with a high degree of reliability.

Sulfur dioxide removals sufficient to meet New Source Performance Standards for high-sulfur coal can be achieved with acceptable stoichiometries.

Under normal operating conditions, the percentage SO_2 removal in the baghouse is approximately the same as that in the spray dryer.

The dry waste produced is nonhazardous and easily handled.

The potential exists for an integrated control system based on spray drying that combines high levels of SO_2 and particulate-matter control with modest levels of NO_x control.

Detailed costs for combined NO_x/SO_2 and particulate-matter control have not been determined. However, a preliminary evaluation indicated that (for Argonne's system) the operating costs exclusive of capital charges would be about 20% higher than those associated with baseline operation (6). An earlier evaluation for SO_2 and particulate-matter control only (using Electric Power Research Institute utility costing guidelines) yielded costs of $686 per ton of SO_2 removed (1985 $). Of that amount, about 37% was associated with the baghouse (7).

In closing, it should be noted that more detailed information about the ANL system, spray-drying technology in general, and the NO_x/SO_2 field tests is included in several reports recently issued by ANL. These include two field test reports and a spray-dryer handbook, which are given in the reference list as References 1, 6, and 7.

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TABLE 1. TYPICAL COAL CHARACTERISTICS

Coal Parameter	Value
Heating Value (Btu/lb)	12,027
Constituents (%)	
Moisture	9.59
Ash	7.40
Carbon	66.98
Hydrogen	4.65
Nitrogen	1.48
Sulfur	3.32
Chlorine	0.06
Oxygen	6.52

TABLE 2. RESULTS OF FGD SYSTEM ACCEPTANCE TESTS

Pollutant	Power Level (% MCR[a])	Outlet Concentration (lb/10^6 Btu)
Sulfur Dioxide	70	0.60[b]
	82	0.27[c]
Particulate Matter	70	0.010
	82	0.005

[a] Maximum Continuous Rating.

[b] 90% removal.

[c] 96% removal.

TABLE 3. HIGH-SULFUR COAL ANALYSIS
(as-received basis)

Coal Parameter	Value
Heating Value (Btu/lb)	12,171
Constituents (%)	
Moisture	5.4
Ash	8.9
Carbon	70.2
Hydrogen	4.8
Nitrogen	1.3
Sulfur	4.2
Oxygen	5.2

TABLE 4. 1986 FIELD TEST PROGRAM

Spray Dryer Exit Temp. (°F)	NaOH Addition (wt %)	Duration (days)
155	none	20[a]
170	none	2
190	none	2
210	none	2
210	5	2
210	10	2
210	10	2[b]

[a] Baseline characterization.

[b] Transition to low-sulfur coal.

TABLE 5. 1988 FIELD TEST PROGRAM

Spray Dryer Exit Temp. (°F)	NaOH Addition (wt %)	Duration (days)
160	none	6[a]
180	none	3
180	2.5	3
190	2.5	3
190	5.0	3
160	none	4[a]
180	5.0	3
200	5.0	3

[a] Baseline characterization.

TABLE 6. PROCESS CHANGES AFFECT POWDER PROPERTIES AND BAGHOUSE OPERATION

			Powder Properties		
Spray Dryer Outlet Temp. (°F)	Caustic Addition (wt %)	Cleaning Interval (hr)	Moisture (%)	Surface Area (m^2/g)	Pore Diam. Vol. Median (µm)
155	0	1.5	1.6	15.9	3.4
190	0	2.0	1.4	20.2	4.5
210	0	3.0	1.2	24.4	4.1
210	5	6.0	1.2	26.5	7.8

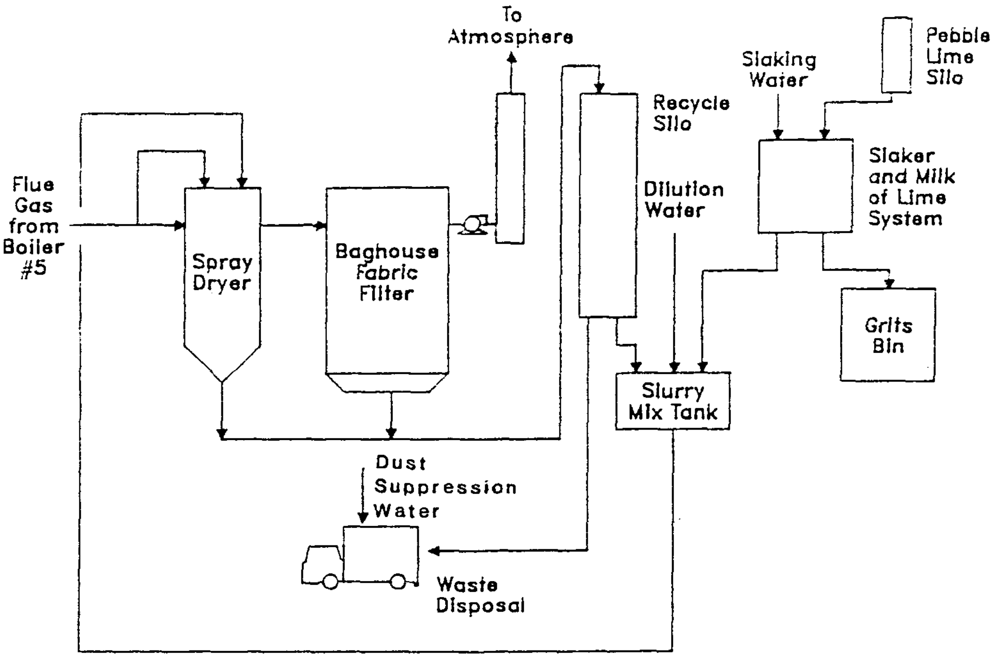

Figure 1. Process Diagram for the ANL Spray-Dryer/Fabric-Filter System

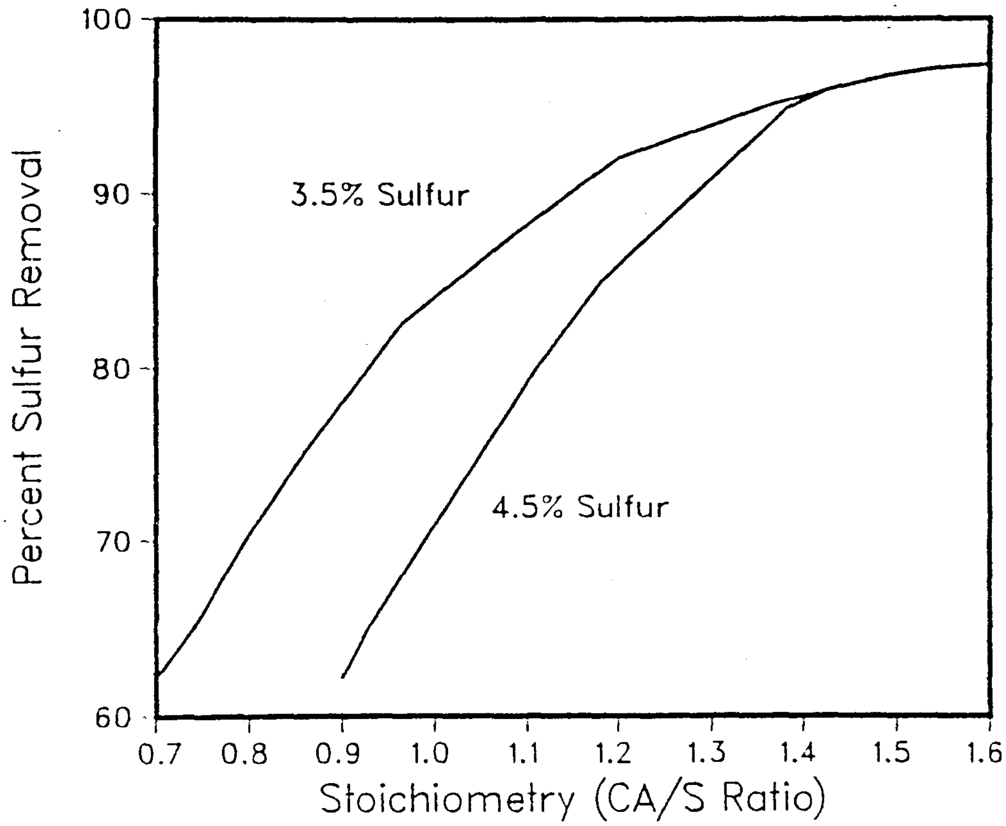

Figure 2. Effect of Coal Sulfur Content on Spray-Dryer Performance

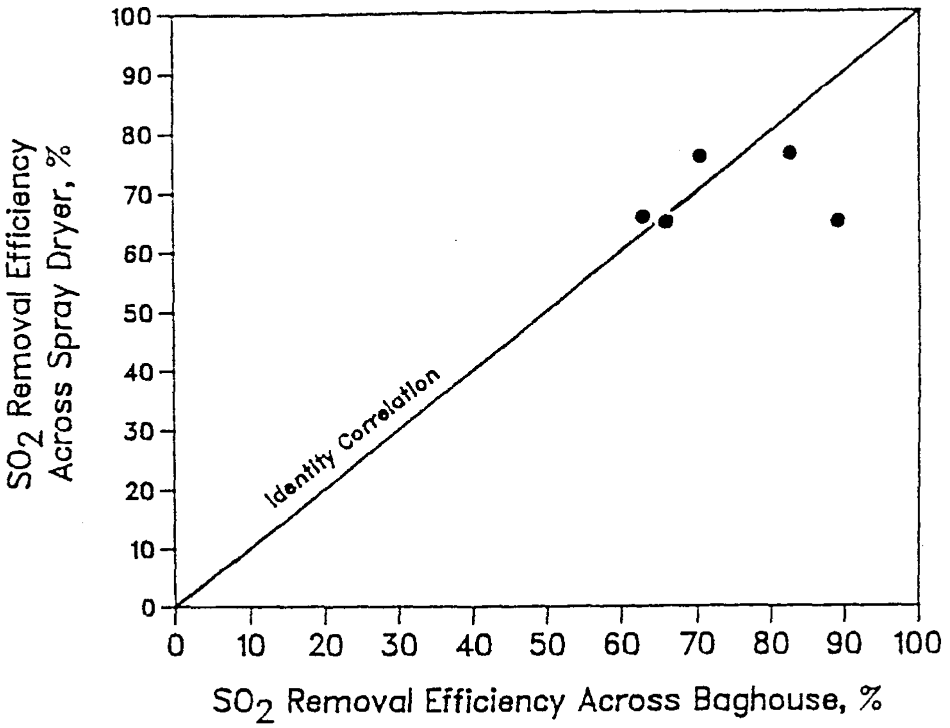

Figure 3. Comparison of Percentage SO$_2$ Removal in Spray Dryer and Baghouse

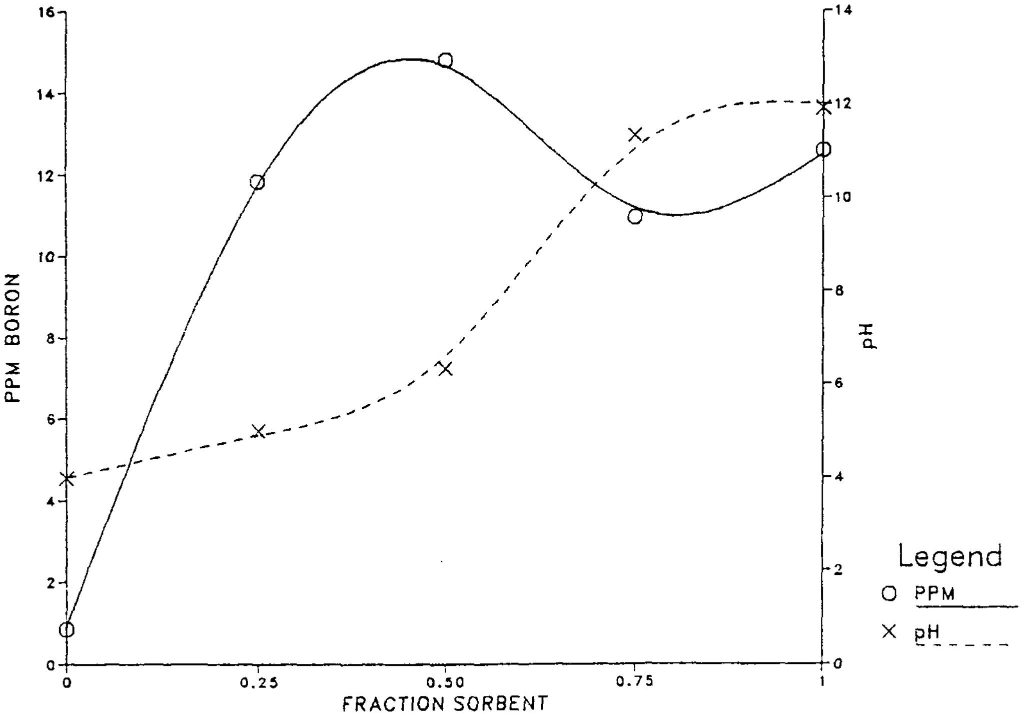

Figure 4. Boron Concentration in Waste Leachate

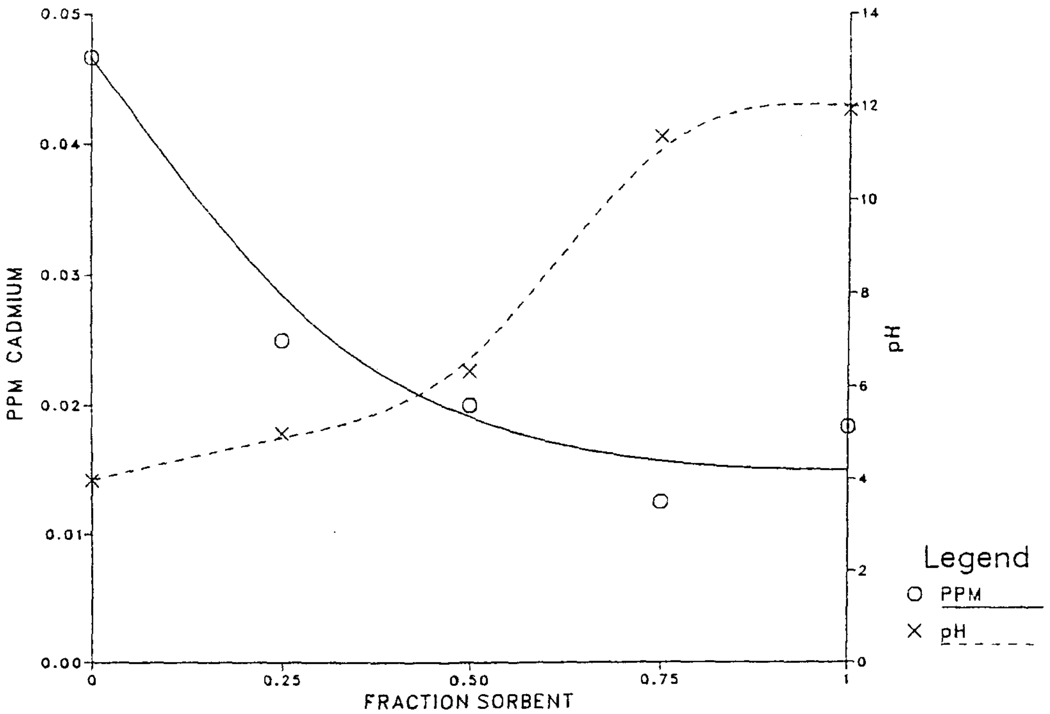

Figure 5. Cadmium Concentration in Waste Leachate

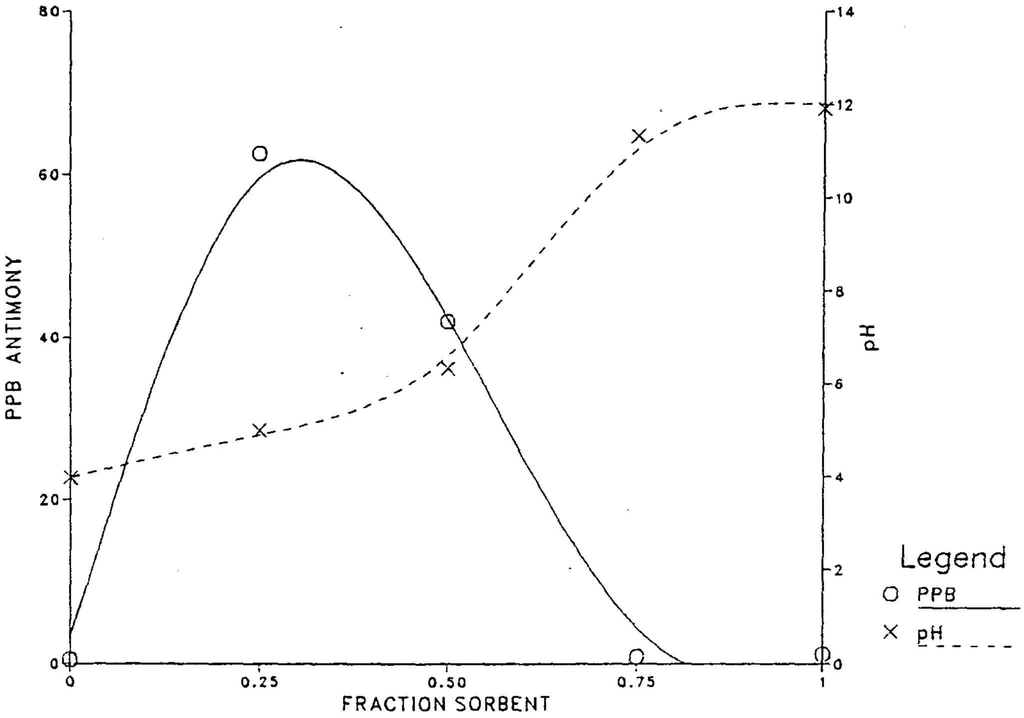

Figure 6. Antimony Concentration in Waste Leachate

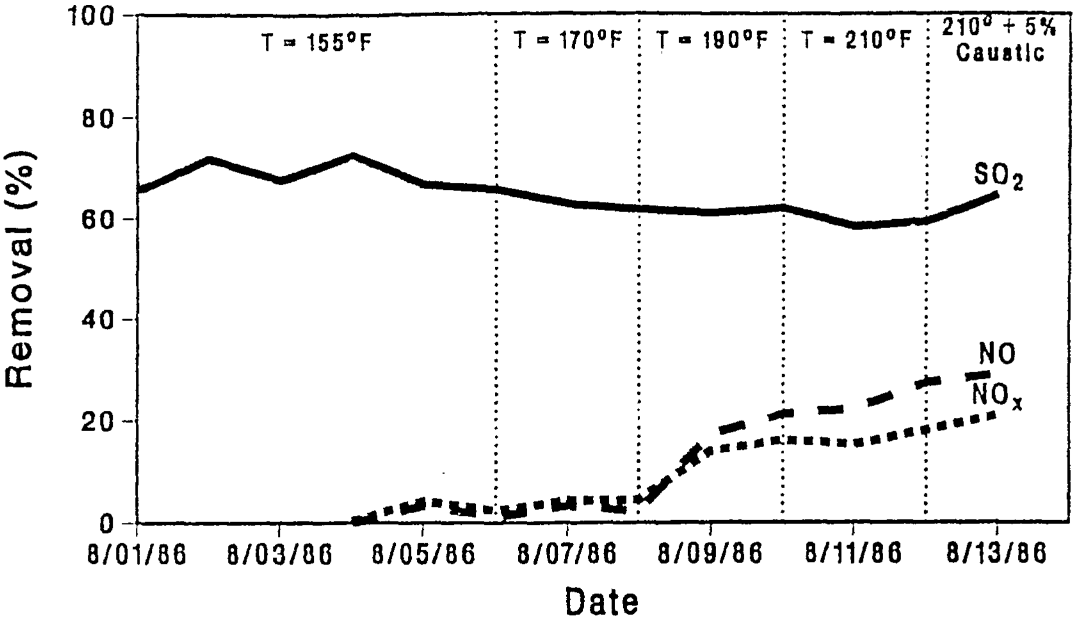

Figure 7. Spray-Dryer Outlet Temperature is Critical for Combined SO_2/NO_x Removal (1986 Tests)

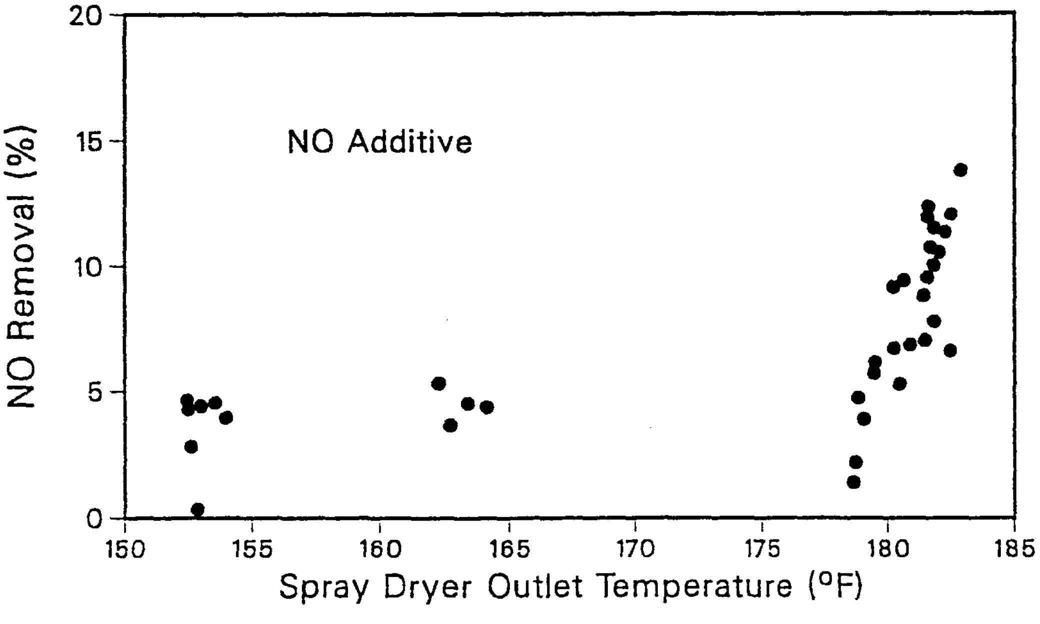

Figure 8. NO Removal Increases Sharply at about 180°F (1988 Tests)

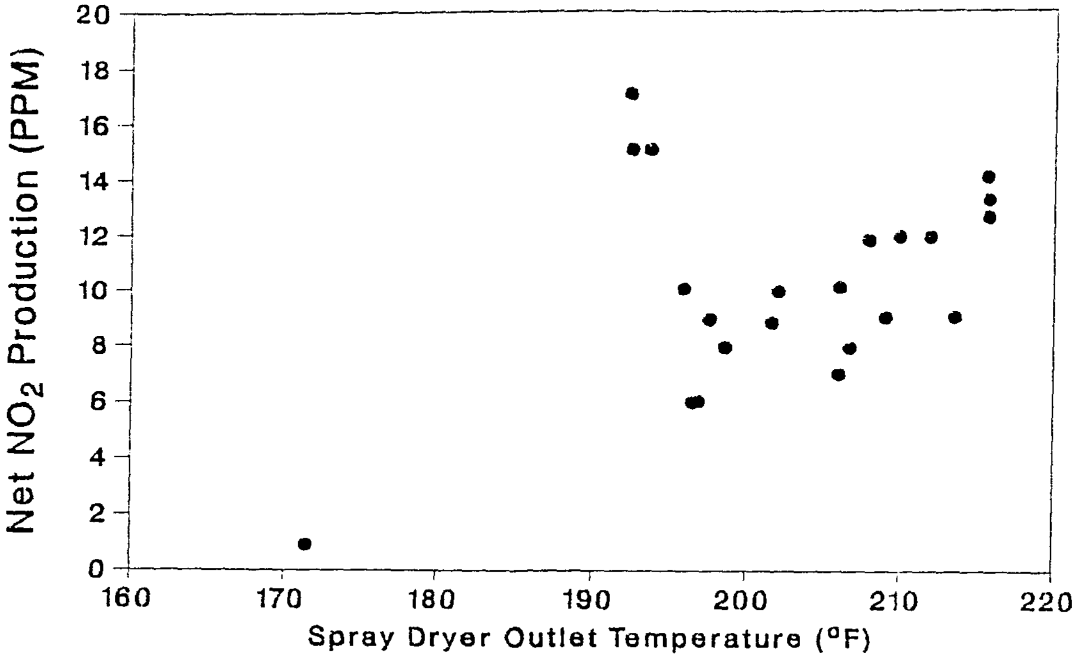

Figure 9. NO_2 Production Accompanies NO_x Removal

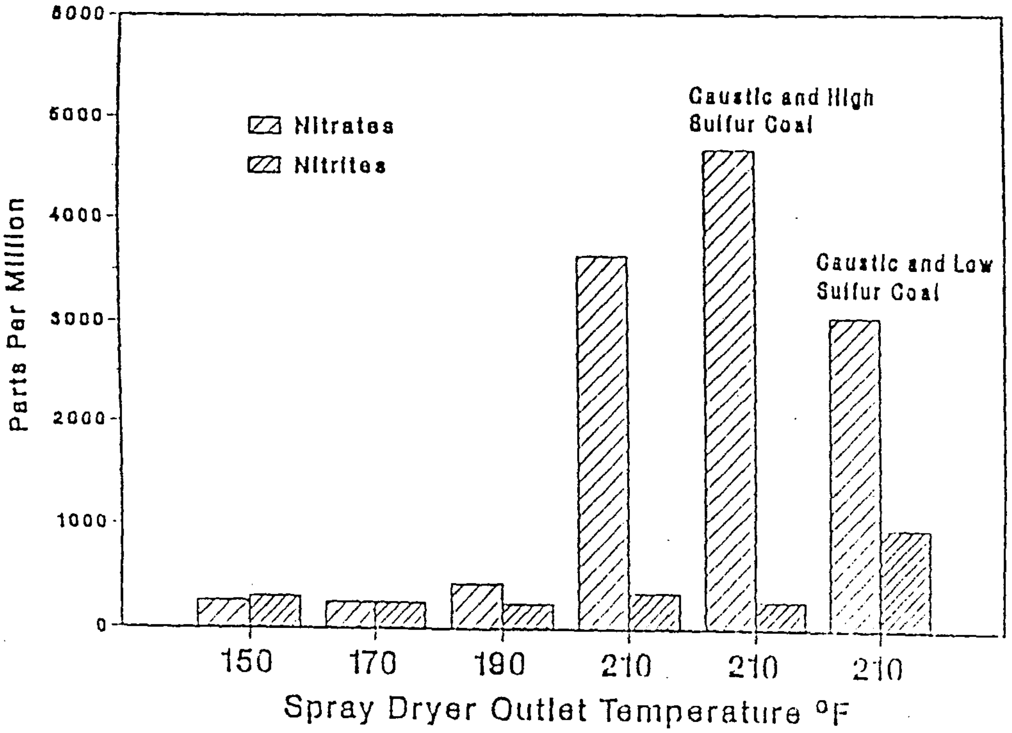

Figure 10. Concentration of Nitrites/Nitrates in the Recycle Powder Changes with NO_x Removal

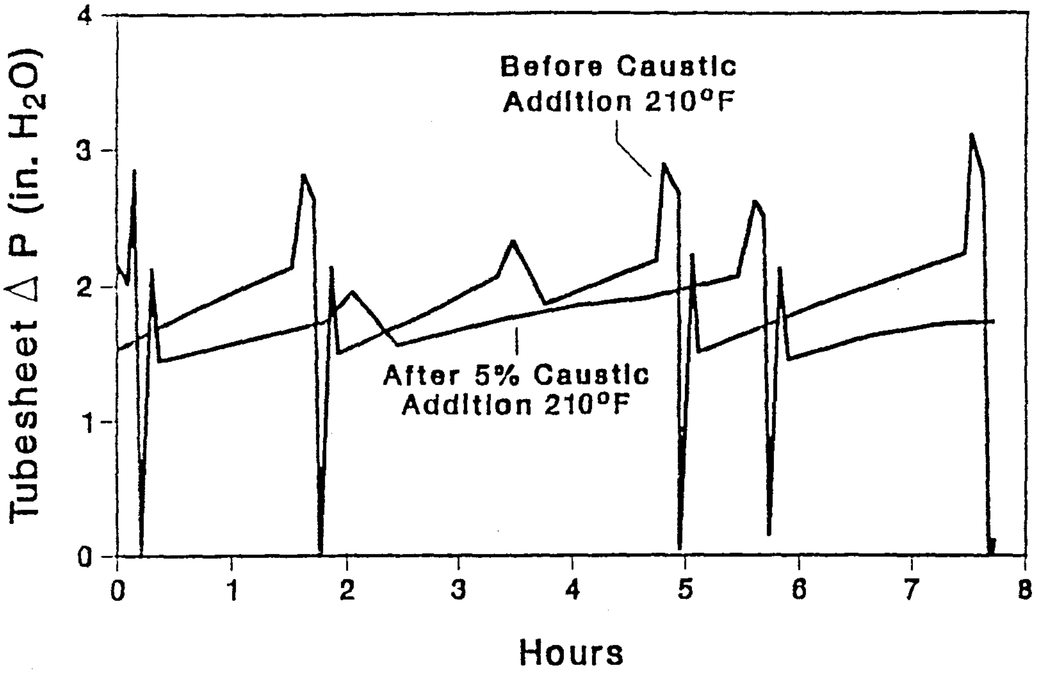

Figure 11. NaOH Addition Affects Filter Cake Properties, Allowing Longer Cycles Between Cleanings

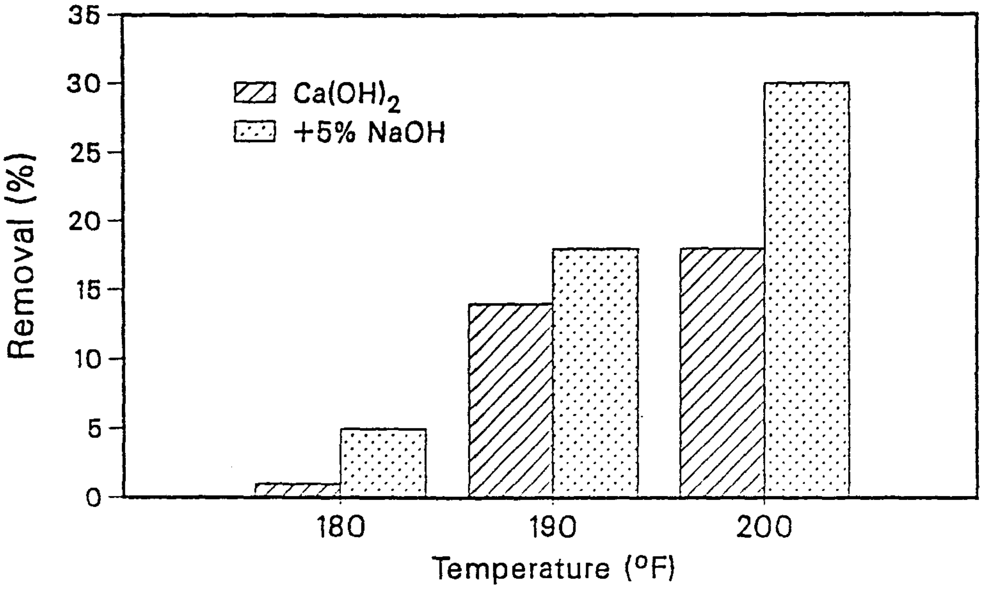

Figure 12. Additive Effects are more Significant at Higher Temperatures

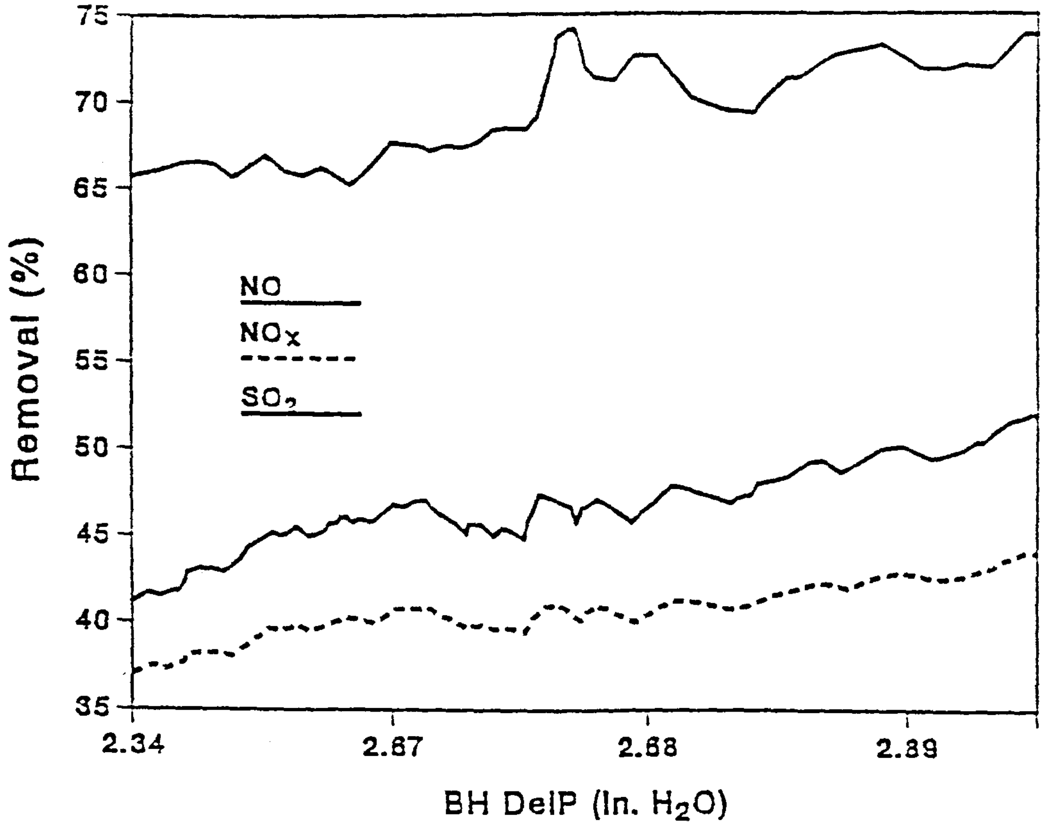

Figure 13. Removals Increase with Increasing Cake Thickness (Baghouse Pressure Drop)

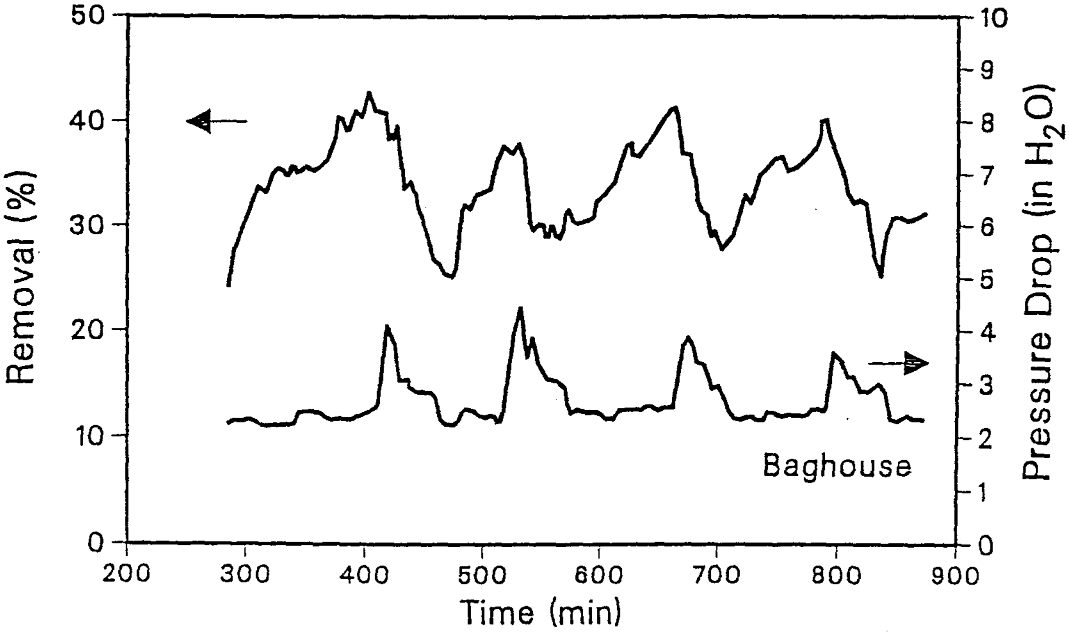

Figure 14. NO_x Removal Varies Significantly Between Baghouse Cleaning Cycles (200°F, 5 % NaOH)

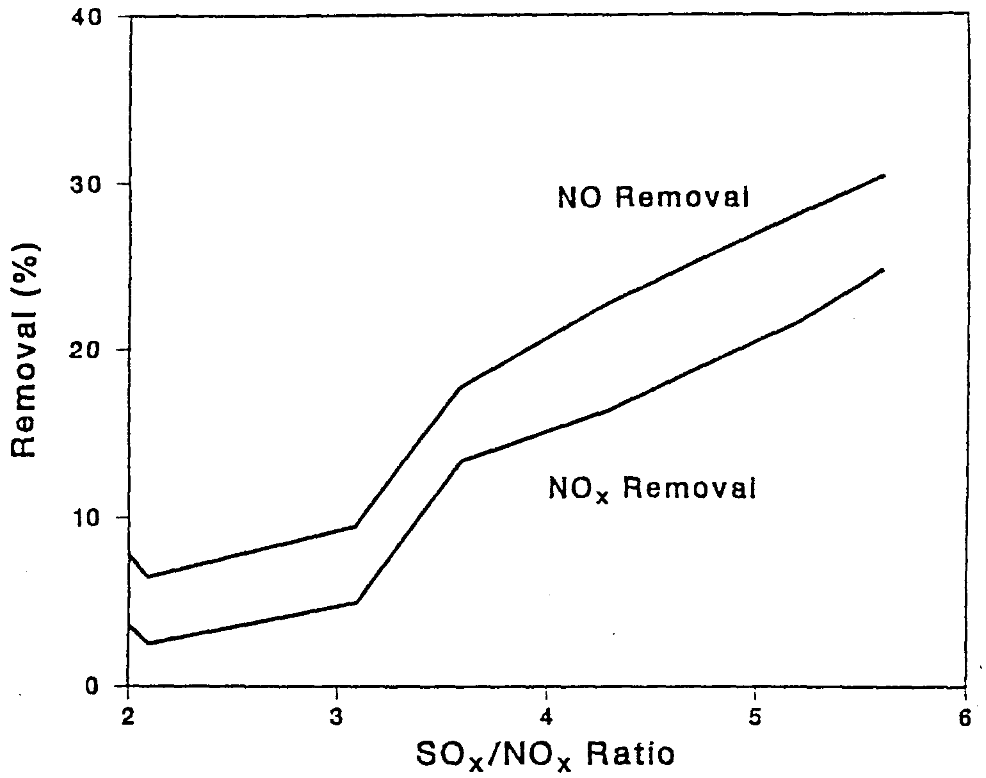

Figure 15. Sulfur Dioxide Levels Strongly Influence NO$_x$ Removal