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Pilot-Scale Testing of a New Sorbent for Combined SO2/NOx Removal

Final Report

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DISCLAIMER

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This report contains no proprietary information.

Pilot-Scale Testing of a New Sorbent for Combined SO_2 and NOx Removal

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EXECUTIVE SUMMARY

1. A new regenerable sorbent concept for SO_2 and NOx removal was pilot-tested at Ohio Edison's Edgewater generating station at a 1.5 to 2-MWe level. A radial panel-bed filter of a new dry, granular sorbent was exposed to flue gas and regenerated in an experimental proof-of-concept program. The project was co-funded by Sorbent Technologies Corporation and the Ohio Coal Development Office, which contributed $360,000.

2. The project was successful in demonstrating the new sorbent's ability to achieve 90% SO_2 removal, 30% NOx removal, and over 80% removal of residual particulates with realistic approach temperatures and low pressure drops.

3. The sorbent utilizations seen in the program were lower than originally expected, primarily due to a highly uneven gas flow distribution through the panel-bed and the need to regenerate in air rather than methane for safety reasons. The purpose of this pilot project was to discover such design considerations, which can now be alleviated in further development and demonstration work.

4. Based on the results of this project, the retrofit cost of this technology is expected to be on the order of $400 per ton of SO_2 and $900 per ton of NOx removed. This assumes that gas distribution is even and methane regeneration is used for a 30% average utilization. For a 2.5%-sulfur Ohio coal, this translates to a cost of approximately $17 per ton of coal.

5. Two by-product streams were generated in the process that was tested: a solid, spent-sorbent stream and a highly-concentrated SO_2 or elemental-sulfur stream. While not within the scope of the project, it was found possible to process these streams into useful products. The spent sorbent materials were shown to be excellent substrates for soil amendments; the elemental sulfur produced is innocuous and eminently marketable.

6. Because this was a temporary pilot-scale effort, the effects of this specific project on near-term Ohio coal use is marginal. However, the data and experience gained are very important for the further development of this technology and for potential long-term environmental and coal-industry benefits.

7. To develop and refine the regeneration process further, contracts have been awarded to Sorbent Technologies Corporation by both the U.S. Environmental Protection Agency and the Department of Energy. On the sorption side, the next step is scaling up the unit. This is being pursued in Switzerland, which has stricter waste-disposal laws than the U.S., where NEFF has awarded a corporate associate a grant to confirm the technology and then to install a commercial unit at an industrial site if appropriate. In the meantime, Sorbent Technologies continues to look for support in demonstrating the agricultural value of the spent sorbents.

1. INTRODUCTION

Existing flue gas desulfurization technologies for coal-burning power plants have many weaknesses:

- they do not remove nitrogen oxides;
- they produce large masses of waste materials;
- they can cause water pollution problems;
- they can add to particulate control problems; and
- they are difficult to retrofit at existing plants.

As environmental regulations tighten and industry moves toward more sustainable combustion technologies, these limitations may restrict the ability of coal, particularly higher-sulfur coals, to compete in the marketplace.

In this project Sorbent Technologies Corporation (Sorbtech) of Twinsburg, Ohio investigated a new concept for the dry, simultaneous removal of SO_2, NOx, and residual particulates from flue gases. Key to the concept is a new dry, regenerable sorbent consisting of magnesium oxide coated onto large, granular vermiculite or perlite particles. The new materials are called MagSorbents. Because of their large size and granularity, they can be applied to the flue gas stream in a simple panel-bed mode. Because they are regenerable, large volumes of wastes are not produced. And while they are primarily designed for 90% SO_2 removal, they can simultaneously remove a not-insignificant amount of NOx.

1.1 Background

Magnesium oxide (MgO), slurried with water, has long been known to react effectively with sulfur dioxide (SO_2). MgO-water slurries are currently being employed commercially at facilities in the U.S. and Japan to remove SO_2 from power plant flue gases. MgO has the advantage that it may be regenerated and recycled. It reacts with SO_2 to form $MgSO_3$ primarily, and $MgSO_4$. These compounds break down into MgO and SO_2 when heated above 500°C. However, when employed in slurry form, MgO must be de-watered and dried before regeneration. During regeneration, temperatures must be controlled closely to minimize dead-burning of the very fine pure magnesia particles, which reduces the reactivity of the material. In current practice, problems are frequently encountered in handling the slurries, in treating the sludges that are produced, and in handling the fine particulates after regeneration. Importantly, significant quantities of MgO lose their reactivity during processing as a result of dead-burning the materials.

Several years ago, Sorbtech discovered that MgO could be effectively coated onto relatively inexpensive carrier phases having large surface areas, such as expanded vermiculite or perlite. These combinations possessed some unique characteristics when given a high-temperature conditioning treatment. The combinations demonstrated the ability to remove SO_2 and NOx in the dry state when the flue gas was humidified. They were found to be able to capture more than 90 percent of the SO_2, 30 percent of the NOx, and much of the fine soot and ash particles that conventional dust-collection systems fail to remove. During exposure, they changed color as they sulfated, turning from white to gold, as shown in Figure 1. Moreover, the sorbents demonstrated some unique properties during regeneration. When regeneration was performed in air, the sorbed SO_2 and NOx were given off. When regeneration was carried out in a reducing environment, however, the NOx was destroyed, converted to nitrogen and water. Further, in a reducing environment, a significant portion of the SO_2 was converted directly to elemental sulfur. See Tables 1.1 and 1.2 for the expected chemical reactions.

The new materials are naturally granular. Because of this granularity and their high reactivity, they can be simply applied to gas streams as a thin, dry bed. The granularity makes porosity high and pressure drops low. The pressure drop of gases flowing three feet-per-second through dry panels one-foot-thick is only a few inches, water gauge.

The development of the MagSorbent process progressed through a series of stages. MagSorbent materials were first exposed to actual flue gases in 1986 when 4-inch diameter by 8-inch long beds were placed in a tiny slipstream of flue gas at Ohio Edison's Gorge power plant in Akron, Ohio. Following these runs, progressively larger beds were exposed to larger slipstreams. During 1987, a 0.1-MWe slipstream was treated by employing 8-inch by 8-inch by 4- to 10-inch beds and in 1989, a 0.5-MWe slipstream was treated by employing 36-inch by 36-inch by 4- to 12-inch beds of multiply-regenerated sorbent. In all cases, excellent SO_2 removals were observed. The objective of the current project was to scale up the process further, to approximately the 2-MWe level.

The initial development of the new technology was supported by Sorbent Technologies Corp. and by the U.S. Environmental Protection Agency. Later development and demonstration of the technology at the 0.1 MWe scale was supported by the Ohio Coal Development Office (OCDO) of the State of Ohio's Department of Development and Sorbtech. The U.S. Department of Energy funded the demonstration of the technology at the 0.5 MWe level at Ohio Edison's Gorge power plant in Akron, Ohio. The U.S. Environmental Protection Agency, Department of Energy, and OCDO have or are supporting further work on the sorbent regeneration.

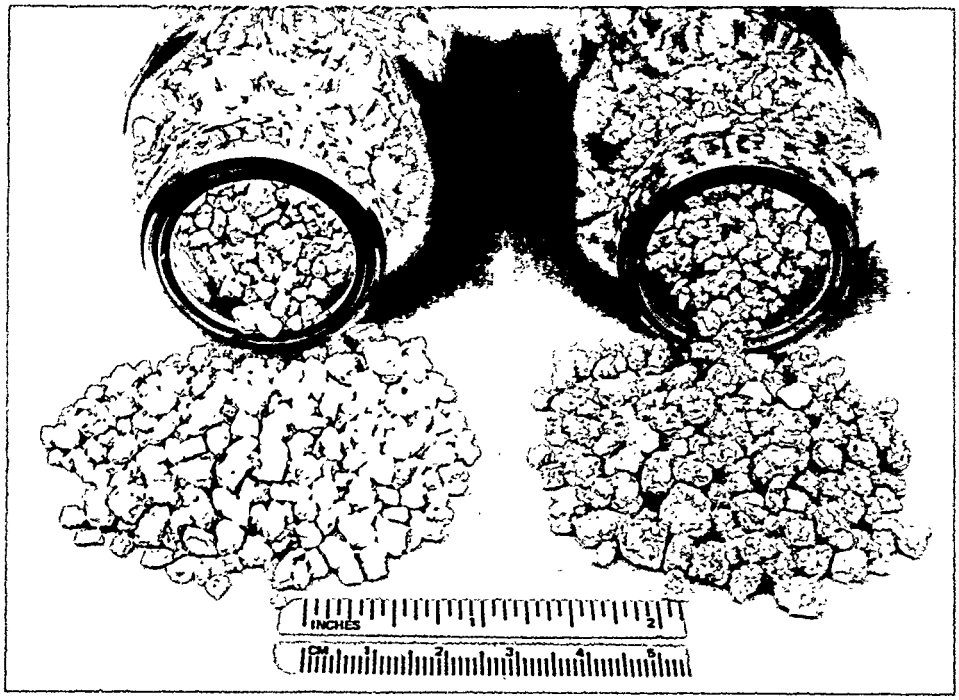


Figure 1.1 MgO-vermiculite MagSorbent.
Spent sorbent, when regenerated, regains the appearance of fresh sorbent.

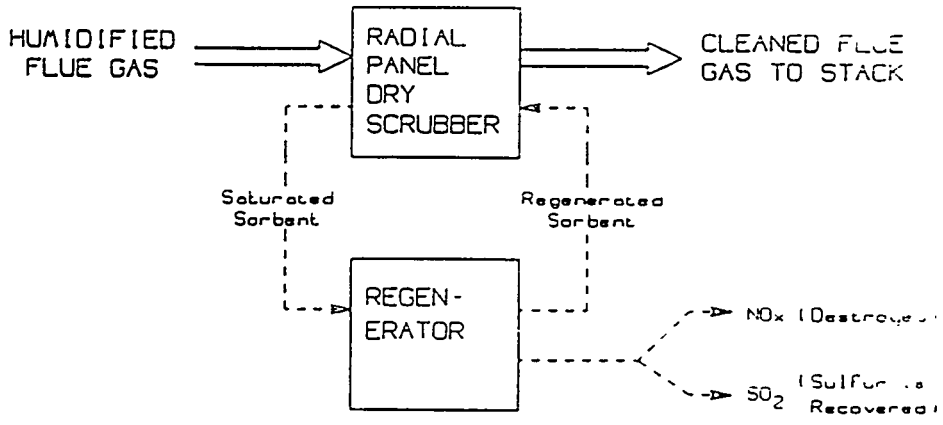


Figure 1.2 The MagSorbent dry-scrubbing process.

Table 1.1 MagSorbent SO_2 Chemistry.

Chemical analyses and X-ray diffraction studies have indicated that two reactions are principally responsible for SO_2 capture:

$$MgO + SO_2 \rightarrow MgSO_3 \quad (1)$$
$$MgO + SO_2 + \tfrac{1}{2}O_2 \rightarrow MgSO_4 \quad (2)$$

During exposure to a typical flue gas, approximately 90 percent of the SO_2 results in magnesium sulfite ($MgSO_3$); about 10 percent in magnesium sulfate ($MgSO_4$).

The magnesium sulfite phase readily decomposes back into MgO and SO_2 upon heating to temperatures above 550°C (1022°F) in air:

$$MgSO_3 \rightarrow MgO + SO_2 \quad (3)$$

The magnesium sulfate phase likewise will decompose into MgO and SO_2 upon heating in air, but requires temperatures in excess of 900°C (1652°F). If CO, H_2 or methane is present in the environment, however:

(1) the sulfate decomposition temperature is decreased to about 700°C (1292°F), and
(2) elemental sulfur is produced in significant amounts.

Methane is commonly reformed with heat and moisture (steam):

$$CH_4 + H_2O \rightarrow CO + 3H_2 \quad (4)$$

In such a reducing environment, the following MagSorbent regeneration reactions are believed to occur, based on materials balance experiments:

$$2MgSO_3 + CO + 3H_2 \rightarrow S_2 + 2MgO + 3H_2O + CO_2 \quad (5)$$
$$2MgSO_4 + 2CO + 4H_2 \rightarrow S_2 + 2MgO + 4H_2O + 2CO_2 \quad (6)$$

The valuable elemental sulfur is thus recovered. Small amounts of H_2S and COS can also occur during the regeneration of MagSorbents in a reducing environment, but these can be minimized by controlling the regeneration conditions.

Table 1.2 MagSorbent NOx Chemistry.

Flue gas NOx is removed by two mechanisms:

(1) physical sorption of the individual NO or NO_2 species onto the MagSorbent, and

(2) chemical reaction of NO or NO_2 with the MgO phase, particularly when oxygen and moisture are present.

Physical sorption appears to be favored at lower temperatures, below 150°C (302°F). NO, of course, is the dominant NOx specie found in flue gases. Kent State University researchers indicated that a single nitrogen species, magnesium nitrate $Mg(NO_3)_2$, was produced when MagSorbent samples were exposed to NO in a simulated flue gas stream. Their results suggest that the following reaction is important in the presence of moisture:

$$2MgO + 4NO + 3O_2 \rightarrow 2Mg(NO_3)_2 \qquad (7)$$

Desorption can be carried out at about 300°C (572°F). Upon heating exposed samples in air, the sorbed NO and NO_2 are released. Under such oxidizing conditions, sorbed NO is released as NO and sorbed NO_2 is released as NO_2.

Upon heating NOx-exposed MagSorbent in an environment containing CO, H_2, or methane, the nitrate appears to be reduced as follows:

$$Mg(NO_3)_2 + 6CO \rightarrow MgO + N_2 + 6CO_2 \qquad (8)$$
$$Mg(NO_3)_2 + 5H_2 \rightarrow MgO + N_2 + 5H_2O \qquad (9)$$

The NOx is thus destroyed.

1.2 Technology Description

It was found possible to employ MagSorbents in a very simple process to treat flue gases. Two principal steps are involved, dry sorption and regeneration. The process is shown schematically in Figure 1.2.

In the dry scrubbing step, flue gas, after exiting an existing particulate cleaning system, such as an electrostatic precipitator, is humidified. The flue gas then passes through a sorber containing a panel-bed of MagSorbent. In the sorber, SO_2, NOx, and residual particulates are simultaneously removed. The dry, treated flue gas then goes to the stack.

In the regeneration step, saturated sorbent can be continually removed from the sorber and conveyed to a thermal regenerator. During regeneration, the released NOx is converted to nitrogen and water and the released SO_2 is partially converted to elemental sulfur. Conversion of the remaining SO_2 to elemental sulfur can be achieved by a modified Claus process or by a new process currently under development at Sorbtech. After regeneration, the renewed sorbent is screened and returned to the sorber.

The new technology appears to have the following advantages, in comparison with currently used methods with coal-burning boilers:

1. The sorbents are used in a dry state.
2. The sorbents are regenerable.
3. Useful by-products may be produced.
4. Fine particulates are also removed.
5. The technology is readily retrofitable back-end process.
6. The technology is applicable to all coals, regardless of sulfur content.
7. Capital and operating costs may be lower than comparable technologies.

1.3 Project Objectives and Plan

The main objective of the project described herein was to integrate the components of the MagSorbent Process and to demonstrate flue-gas clean-up at high levels for extended time periods at a relatively large scale. The objective was to demonstrate that the MagSorbent technology will satisfactorily remove SO_2, NOx and particulates simultaneously from a 2-MWe flue gas stream with performance indicating promising full-scale economics. Specific goals sought included removals of:

- 90 percent of flue gas SO_2;
- 30 percent of flue gas NOx; and
- 75 percent net of residual particulates;

while achieving attractive utilizations and generating no objectionable wastes.

The project consisted of: the preparation of large quantities of the new sorbent; the performance of preliminary studies to define the equipment designs to be employed; the design, procurement, installation and shake-down of new pilot facilities; and the performance of parametric studies and life-cycle tests.

1.4 Project Team and Co-sponsors

The project team involved in the pilot-scale testing of the new sorbent consisted of Sorbent Technologies Corporation (Sorbtech) and Ohio Edison Company. The Ohio Coal Development Office (OCDO)/Ohio Department of Development, an important sponsor, provided approximately 50 percent of the overall project funding. OCDO supports the research and development of coal-related technologies that encourage the use of Ohio coal. Sorbtech, which conducted and co-sponsored the project, also provided about 50 percent of the project funding, all in the form of cash.

Two sites were primarily involved in the project, Sorbtech's research and engineering facilities in Twinsburg, Ohio and Ohio Edison Company's Edgewater power plant in Lorain, Ohio.

Ohio Edison, also a co-sponsor, provided the host site for the pilot plant. In addition to the space required for the 2-MWe pilot demonstration system, Ohio Edison provided electric power, process water, flue gas, and technical assistance.

2. DESIGN STUDIES

Work leading up to this project provided an insight into the performance that might be expected in a 2-MWe pilot plant. However, it left some questions requiring answers, particularly with respect to the selection of key pieces of large-scale process equipment. In laboratory, field, and 0.5 MWe pilot tests, sorption was accomplished in all cases using a simple panel bed of MagSorbent. Regeneration was accomplished by using trays or baskets of sorbent that were exposed in furnaces on a batch basis or by supplying sorbent continuously to a pilot-sized rotary kiln. Although satisfactory sorption and regeneration were achieved by these methods, they were considered by no means optimal and suitable for larger-scale operations. For this reason, some preliminary studies were deemed necessary to evaluate alternate equipment approaches for the 2-MWe pilot plant. Evaluations centered on examining different sorber designs, regenerator designs, and sorbent handling approaches for the pilot plant.

2.1 Sorber Design Evaluations and Selection

Sorbents may be exposed to flue gases in a variety of ways. Common approaches employed in the past include: (1) replaceable static fixed beds; (2) slowly moving beds; (3) dry injection with entrainment; (4) slurry injection; and (5) fluidized beds. Because the large quantities of flue gases with significant concentrations of SO_2 from coal-burning power plants require large quantities of sorbent, the first approach, the use of static fixed beds, would appear impractical. A continuous system will be required. The four other approaches permit continuous operation.

MagSorbent particles are relatively large in size, 1/8-in being typical. Prior experience has shown that MagSorbents can be entrained in flue gas streams, but entrainment performance increases with decrease in particle size. Larger particles tend to drop out from the gas stream. Because of the relatively large size of MagSorbent particles, dry or wet injection approaches were not considered in the project. The two remaining approaches, fluidized beds and slowly moving beds, were then studied. More specifically, a circulating fluidized bed design (CFB) and two slowly moving-bed (a flat panel bed and a radial panel bed) designs were considered. The three designs are shown schematically in Figure 2.1.

2.1.1 Fluidized Bed Studies

A fluidized bed is the design employed by the NOXSO Corporation in its process for contacting sorbent with flue gases. The U.S. Department of Energy (DOE) likewise employs a fluidized bed to contact its sorbent with flue gases in the Copper Oxide Process.

The University of Cincinnati has built a bench-scale circulating fluidized bed facility for desulfurization research. In order to examine the feasibility of using MagSorbents in a fluidized bed, arrangements were made to conduct a series of exploratory runs in this facility. Two different sorbent sizes were examined, 1/8 to 1/4-inch and -10 mesh.

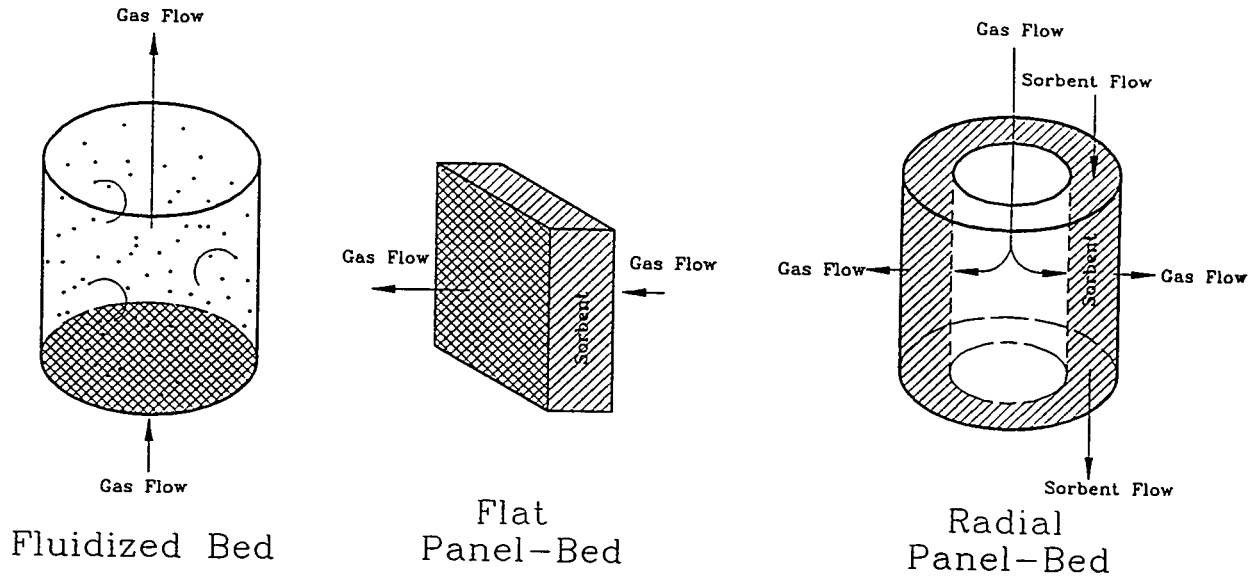


Figure 2.1 Three sorber designs considered for the 2-MWe pilot plant.

A number of major problems were encountered in employing the new sorbents in a CFB of University of Cincinnati's design. One problem was particle classification within the fluidized bed. Smaller particles continually circulated into and out from the bed, while larger particles dropped to the bottom of the bed and remained there during the duration of the runs. To compound the problem, humidification, when employed, was only effective on the stationary, large particles at the bottom of the bed, where the moisture entered. The smaller particles saw little or no moisture. The result was an initial, reasonable SO_2 removal, but a rapid fall-off in SO_2-removal efficiency. Of the two sorbent sizes examined, the -10 mesh, gave the better SO_2 and NOx removal results.

Surprisingly, during several runs NOx removals of 40 to 60 percent were observed.

The most severe problem observed was sorbent attrition. Attrition was not the result of the mechanical break-up of particles, but instead, the result of separating or stripping off the MgO or $MgSO_3$ phase from the vermiculite carrier phase. The CFB unit in combination with cyclones proved to be an excellent method for reclaiming the $MgO/MgSO_2$ and vermiculite species, as separate phases. The two cyclones in the system collected the products, almost pure $MgO/MgSO_3$ from one cyclone and almost pure vermiculite from the other.

On the basis of the results of the circulating fluidized-bed tests it must be concluded that the CFB is not a suitable unit for sorbing SO_2 from flue gases with the new sorbent. It did, however, indicate that the system can be effective in separating spent sorbent into vermiculite and MgO or $MgSO_3$ phases for possible by-product uses.

2.1.2 Flat-Panel Bed Studies

A flat panel is perhaps the simplest design one might consider for a sorber. In a typical flat-panel design, a sorbent bed is supported between two parallel screens or louvers. Sorbent is moved between the screens or louvers by simultaneously extracting saturated material from the bottom of the bed and adding fresh material to the top.

To evaluate the large-scale practicality of this design, a series of test runs were performed to determine the effects of changes in flue gas velocity on the integrity of a flat panel bed and on the pressure drop across the bed. Air at room temperature was blown through a MagSorbent bed of 1/8 to 1/4-inch particles. The bed, supported between parallel stainless steel screens having an open area of approximately 60 percent, was approximately 12 inches long and had a surface area of about 60 square inches. The results of these runs are summarized in Table 1.

In the face velocity range of 0 to 5 feet per second (fps), the pressure drop measured roughly in direct proportion to increase in gas velocity. The bed remained static, essentially motionless, with increasing velocities up to about 2.5 fps. With velocities greater than 5 fps, open spaces often formed and closed within the bed through which gases passed freely.

Table 2.1 Integrity and pressure drop across a 12-inch MagSorbent bed.

Gas Face Velocity (fps)	Bed Condition	Pressure Drop, ΔP (in. W.G.)
1.0	Good	0.8
2.0	Good	2.0
2.5	Good	2.5
3.0	Slightly fluidized at inlet	3.0
5.0	Heavily agitated	5.0

To retain a coherent bed with a relatively low pressure drop, it is clear that the velocity of the flue gas passing through a panel bed should be 2.5 fps or less. Because flue gases in power plant duct generally have face velocities more than an order of magnitude above 2.5 fps, it will be necessary to expand the duct approaching the panel bed significantly to reduce the gas velocity. To achieve a low gas velocity with a flat panel bed, the bed face will by necessity have a large cross-section. A very large flat bed may be impractical from a space standpoint. Difficulties in uniformly feeding sorbent to and removing sorbent from the bed and in attaining uniform gas flow through the bed would probably be encountered.

2.1.3 Radial Panel Bed Studies

To circumvent the potential problems described above, it was suggested that the panel bed be formed into a tubular shape. As such, the tubular shape or radial-panel design would greatly reduce the space requirements. With such a design, flue gases pass first into the space inside the radial panel bed and then radially through the bed and into a chamber outside the bed.

A review of the technical literature disclosed that a unit of similar design has been and is being used commercially today. The unit, called an Electroscrubber, is being employed to remove particulates from flue gases, particularly flue-gas particles that have a tendency to ignite in a baghouse or electrostatic precipitator. Lumber mills have been principal users. The beds in electroscrubbers generally consist of limestone gravel, and, optionally, an electrostatic metal grid that induces charges onto particles in the bed. Sulfur dioxide removal is not an object of these units.

The general Electroscrubber design appears to have several advantages over other designs. These advantages include the ability to treat large volumes of flue gas with a small unit having a very small footprint, a small pressure drop (several inches maximum), gentle handling of the bed material resulting in little or no attrition, and the effective removal of particulates in the flue-gas stream. It was predicted that this type of unit, coupled with the new MagSorbent materials, could provide effective combined removal of SO_2, and NOx, as well as residual particulates.

2.1.4 Sorber Cold-Flow Modelling

To evaluate the radial panel-bed design, a series of models were prepared and were evaluated. The principal model was a cold-flow unit constructed of wood, plexiglass and metal. The model was of the same height and general dimensions of a unit suitable for the pilot plant, but was only a one-quarter pie-section of the unit. A drawing of the cold-flow model is given in Figure 2.2.

The cold-flow model was employed to evaluate both sorbent and gas flows through the unit. Important observations that were made during cold-flow tests included the following:

1. With the initial design (the design employed commercially), the sorbent did not flow downward through the sorber uniformly. Although sorbent along the inside screen flowed well, material in the outside regions did not. Some outside material did not flow at all.

2. Changing the design of the bottom hopper geometry significantly improved sorbent flow through the unit. After several variations were examined, a different bottom hopper design was adopted. With this design, sorbent passed down vertically through the unit uniformly across the entire cross-section in the sorbing region of the bed. Sorbent flow was uniform with no gas passing through the bed and with gas flows of up to 3 fps. With flows above 3 fps, small holes sometimes developed in the bed.

3. Sorbent could be easily conveyed pneumatically from the sorber bottom to the top and recycled through the unit. The bed normally remained stable during recycling.

4. The pressure drops across the 12-inch sorbent bed were surprisingly low. Pressure drop (ΔP) measurements were made for different gas velocities and for different bed-support structures. Plots of ΔP for different gas velocities and for different support arrangements are given in Figure 2.3. The pressure drop, of course, increased with gas face velocity. Using a louver-microscreen combination showed a slightly lower pressure drop than using two screens to hold the bed. Pressure drop was found to be very sensitive to the amount of net open area at the sorbent/support interface. The louver-microscreen combination possessed a larger percentage open area than the screens, which probably explains its slightly lower pressure drops.

On the basis of the results of the various sorber design studies, the radial panel-bed was selected as the sorber design for the 2-MWe pilot plant.

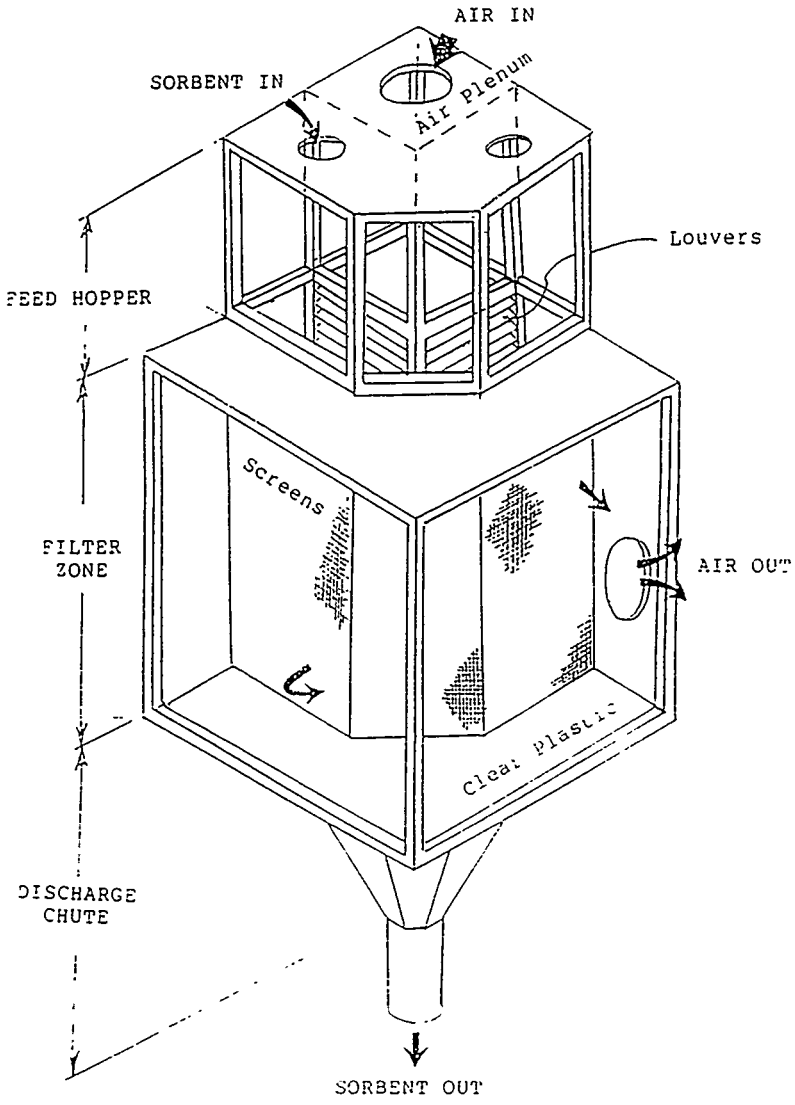


Figure 2.2 Cold-flow model.

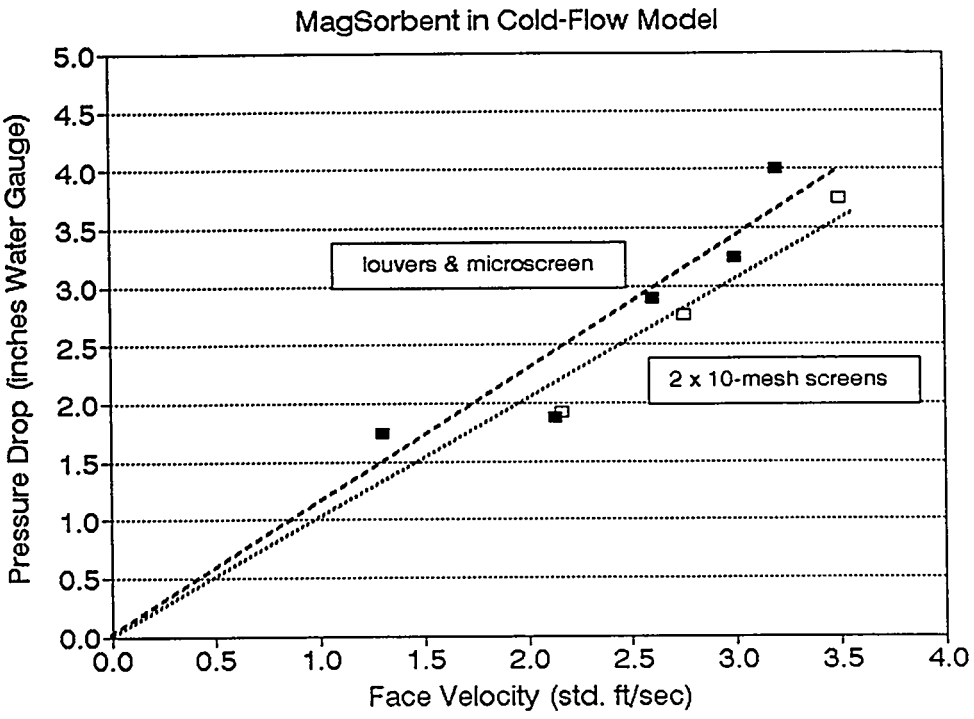


Figure 2.3 Pressure drop across a 12-inch sorbent bed as a function of gas velocity.

2.2 Regenerator Design Evaluations and Selection

Regeneration of MagSorbents saturated with SO_2 and NOx, is accomplished by heating the sorbents in air or in a reducing-gas environment, such as methane, for about 20 minutes at a temperature of 650°C or higher. During regeneration, the gases expelled from the sorbents must be cooled to remove elemental sulfur and combusted to destroy any reducing gases that may be carried out in the regeneration gas. Prior to this project, most regenerations were carried out on a batch basis using specially-fitted muffle furnaces or laboratory glassware. For pilot plant or commercial installations, the use of muffle furnaces or glassware is clearly inappropriate. For this reason, other regeneration designs were considered. More specifically, four designs: a Torbed; a rotary kiln; a vertical tube unit; and a moving belt unit were examined as possible designs for the pilot plant. Figure 2.4 shows these various designs.

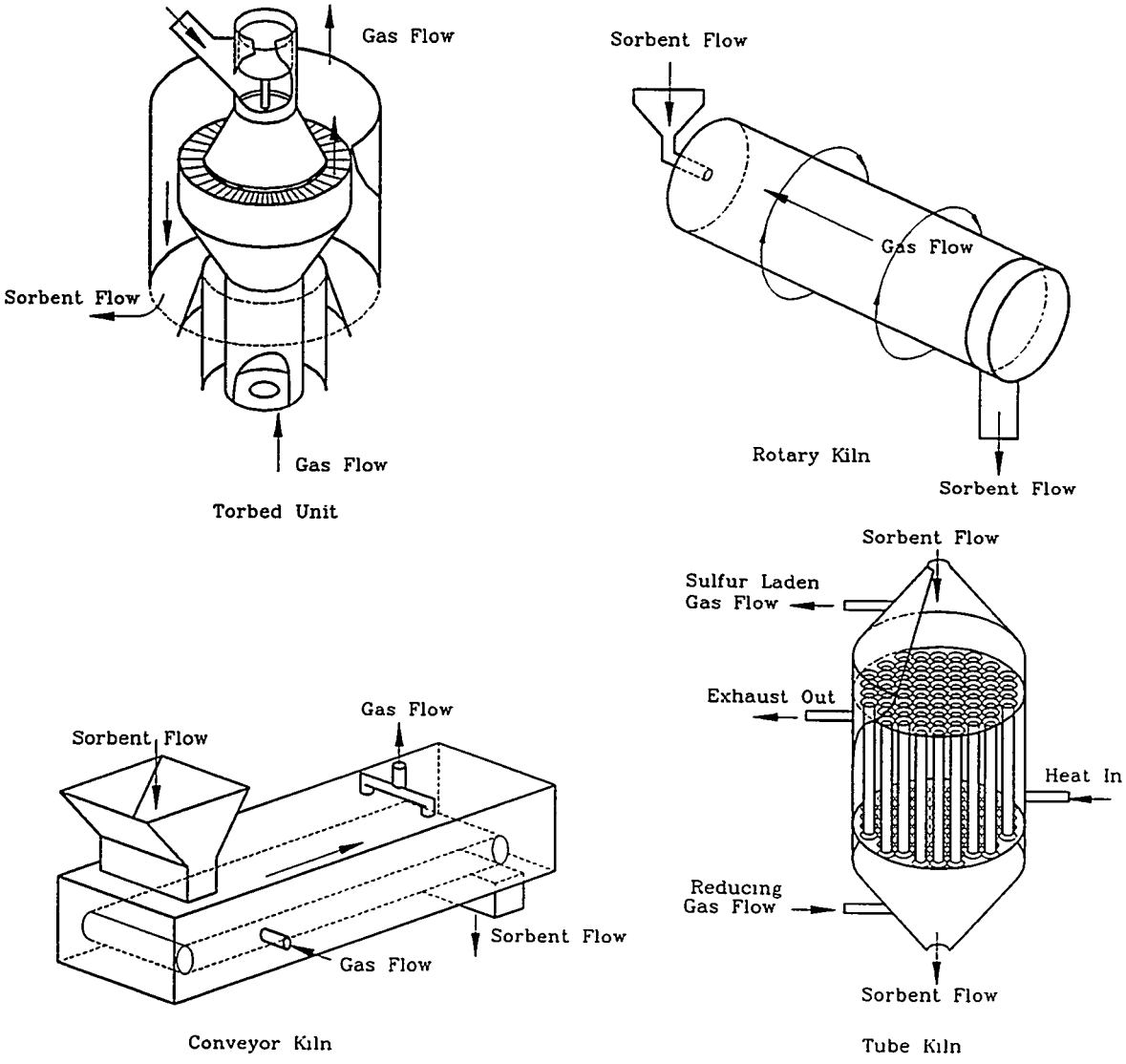


Figure 2.4 Four regenerator designs considered for the 2-MWe pilot plant.

2.2.1 Torbed Regeneration

The Torbed, or toroidal bed, is a new materials-processing unit developed in England by the Davy McKee Corporation. It involves a new concept in rapid heat transfer. The principle of the Torbed combines hovercraft and fluidized-bed techniques to support a gently rotating bed of material. The potential attractiveness of the Torbed is that large quantities of spent sorbent may be regenerated very quickly in a relatively small unit. Several Torbed units are presently being operated commercially, expanding vermiculite and perlite ores.

Davy McKee possesses a small Torbed unit in which it performs tests on materials supplied by potential users. Actual samples of MagSorbents saturated with SO_2 at Ohio Edison's Gorge power plant were sent to Davy McKee for testing. Regeneration tests were performed in air at 750°C, at 780°C, and at 800°C for various processing times. The test facility was not equipped to carry out regenerations in a reducing environment. Samples of the processed materials were returned to Sorbtech for evaluation. At Sorbtech, the samples were evaluated in a laboratory SO_2-resorption test apparatus to determine if the sorption abilities of the materials were restored. Several samples were also re-regenerated in glassware to determine if any additional sulfur was released. The results of the laboratory SO_2-resorption tests are summarized in Table 2.

On the basis of the results of these Torbed studies, the following observations and conclusions were made:

1. Satisfactory regeneration occurred during all Torbed tests in air, as indicated by SO_2-resorption test results and by chemical analyses of the regenerated materials. Processing times of 30 or 60 seconds at 750°C or 780°C appeared to yield a reasonably reactive regenerated sorbent.

2. Regeneration in air decomposed essentially all $MgSO_3$ in the samples to MgO and SO_2, but it did not affect the $MgSO_4$, which was present in significantly lesser amounts. Re-regeneration of samples in methane, however, reduced the $MgSO_4$ present to MgO, SO_2, H_2S and elemental sulfur.

3. Unfortunately, significant amounts of fines were produced during the Torbed runs, especially with the longer processing time. The large amount of observed particle break-up suggests that Torbed processing may be too harsh for regenerating saturated MagSorbent particles.

Table 2.2 Results of laboratory resorption tests on Torbed-regenerated materials.

	SO_2 Level (ppm) in Gas Exiting Sorbent Bed**			Average SO_2 Removed for 30-Min Test
	After 10 Min	After 20 Min	After 30 Min	
Fresh Sorbent (45 wt% MgO-55 Vermiculite)	0	100	600	93%
Fresh Sorbent (Saturated & Reg., 550°, 30 min,air)	0	500	1100	81%
Saturated Sorbent* before Torbed Tests	700	1000	1800	55%
Saturated Sorbent* - Regenerated in Torbed in Air				
750°C, 60 sec	0	400	800	87%
750°C, 120 sec	0	750	> 900	82%
750°C, 480 sec	0	250	600	92%
780°C, 30 sec	0	200	750	91%
780°C, 60 sec	0	375	600	89%
780°C, 120 sec	0	375	675	89%
800°C, 30 sec	50	700	> 1200	79%
800°C, 60 sec	100	450	> 1000	83%
800°C, 120 sec	300	1000	> 1400	70%
Saturated Sorbent - Regenerated in Lab Furnace				
- In Air - 780°C, 30 min	200	300	400	91%
- In Methane - 780°C, 30 min	0	0	100	99%
Saturated Sorbent - Torbed-Regenerated in Air (780°C,120 sec)				
- and Re-regenerated in Air (780°C, 30 min)	50	200	400	94%
- and Re-regenerated in Methane (780°C, 30 min)	0	300	600	92%

* Sorbent was partially saturated with SO_2 (> 50%) at the Gorge Power Plant of Ohio Edison.

** The SO_2 sorption test consists of exposing a 5-g sample of sorbent to a simulated flue gas containing 2500 to 2800 ppm SO_2 at 4 l/min and approximately 120°F.

2.2.2 Rotary Kiln Regeneration

Rotary kilns are common units used to process materials continuously with high heat. Generally a rotary kiln consists of a large-diameter metal tube or chamber rotating slowly along its central axis. The tube is tilted slightly to cause material introduced at the upper end to move through the tube and eventually exit through the lower end. It may have internal fins or lifters. Heat is applied to materials either directly, by employing a burner at one end of the chamber, or indirectly, by heating the metal tube using external heaters. Rotary kilns are commonly used today to calcine carbonate ores to produce lime (CaO) and magnesia (MgO).

A small indirectly-heated rotary kiln was employed by Sorbtech to regenerate saturated MagSorbents in the earlier 0.5 MWe demonstration project. The rotary kiln proved to be suitable for regenerating saturated MagSorbent in a methane environment in the 0.5 MWe project. A methane-nitrogen gas was supplied to the kiln at its exit end and passed countercurrently to the direction of sorbent flow through the kiln. The regenerator gas, containing elemental sulfur, SO_2, H_2S, CO_2, nitrogen and water vapor, left the kiln through a pipe at the upper end of the kiln chamber.

Like the Torbed, the rotary kiln produced fines during the processing of sorbents. The amount of fines that was produced with the rotary kiln, however, was less than that produced with the Torbed. Most fines appeared to be generated by the kiln's feed screw, not the kiln itself, and this could probably be modified. The inherent motion of the kiln, however, will always produce some fines.

A disadvantage of the rotary kiln is its relatively slow processing rate unless the equipment is very large. A 24-hour period was needed to process one drum of sorbent using a Combustion Engineering pilot-scale kiln having an 8-foot tube length and an approximately 3-inch internal diameter. Moreover, indirectly heating a kiln is a relatively inefficient process. Heat is not transferred to the sorbent very cost-effectively. While use of a rotary kiln is feasible in scaled-up systems, it was decided to look elsewhere.

2.2.3 Vertical Tube Regeneration

Another design suggested for the sorbent regenerator is the vertical tube unit shown in Figure 2.4. Variations on this equipment design have been successfully employed in the past to heat-process large quantities of materials. It is presently being used, for example, in Germany to regenerate SO_2-saturated activated coke in an oxygen free atmosphere. In this equipment, saturated sorbent material being processed is first supplied to the top of a bundle of vertical tubes. The material then would pass downward through the tubes by gravity while being heated by a gentle flow of heated gas passing upward through the material, as well as by highly-heated gas surrounding the tubes. The regenerated sorbent would be collected in a chamber below the tubes.

Some laboratory trials were conducted in which saturated MagSorbent was placed inside various diameter tubes and the tubes were heated externally. The results of these trials indicated that because the vermiculite is such a good thermal insulator, the tubes had to be very narrow to fully regenerate the sorbent. Further, the Europeans have indicated that above 450°C, robust materials of construction would be a significant problem. So while this approach shows promise, the significant development effort it would require was beyond the scope of the project.

2.2.4 Conveyor-Belt Regeneration

In the 0.5 MWe project, another regeneration approach was examined, the use of a conveyor-kiln. A conveyor-kiln is simply a furnace chamber with an entrance end and an exit end, through which material is conveyed on a belt or on trays. Conveyor-kilns may be operated on a batch or continuous basis.

A series of trials were performed in a small flat-bed kiln that was designed and constructed. As with the rotary kiln, good regenerations could be achieved with this unit. An advantage of this type of kiln over the rotary kiln appeared to be that larger quantities of sorbent could be processed per unit time for a given size of equipment.

In this project, beds of sorbent having different thicknesses were processed through the laboratory kiln. Thermocouples placed within the beds at different locations provided bed-temperature profiles as a function of kiln temperature and bed thickness. The results of these tests indicated that sorbent-bed thicknesses in a conveyor-kiln should be limited to a maximum of about one-inch. Because MagSorbent materials have excellent insulating properties, heat is not conducted well from particle to particle. If bed thicknesses exceed one-inch, longer furnace times are required to achieve complete regeneration.

While not particularly elegant, the conveyor-kiln concept proved simple and effective. It was the design chosen for the 2-MWe Edgewater pilot plant.

2.3 Pneumatic Transport Studies

The results of earlier work indicated that the best way to move sorbent between the sorber and the regenerator and from storage to an FGD system was pneumatically. Such an approach results in the high efficiency, low cost, and a relatively low degree of attrition.

A series of experiments were performed to determine what gas-flow rates and velocities should be employed in a pneumatic system. In addition, the experiments were performed to determine how these conditions are affected by sorbent particle size and what attrition rates might be expected.

Samples of MagSorbent were pneumatically conveyed through two systems:

1) A horizontal system consisting of approximately 30 feet of two-inch (ID) PVC pipe with two sharp right-angle turns and a severely agitated collection chamber.

2) A horizontal-vertical system consisting of 18 feet of horizontal two-inch pipe coupled with a 15 feet vertical section of similar pipe terminating in a collection vessel.

A vacuum system was employed to provide gas flow. By varying the cross-sectional area of the in-gas duct, it was possible to vary and control the gas flow rate and velocity. In the first system, gas was drawn through the system by suction; in the latter system, gas was blown through the piping. In either case, the gas flow rates achievable were about 0 to 40 ACFM.

Observations that were made in these experiments included the following:

1) The sorbent moved rapidly and with relative ease through the piping. Only a relatively low gas-flow rate, 20 ACFM, was necessary to effectively move the material through 2" ID horizontal piping.

2) Finer sizes of sorbent required slightly higher gas flow rates and velocities than coarser sorbents to carry and lift them effectively. For example, a flow rate of 33 ACFM or more and a face velocity of 1500 fpm was needed to propel 100 percent of the fine (-10 mesh) sorbent upward 15 feet, while coarse sorbent (1/8 to 1/4 inch) was moved upward effectively with a 27 ACFM gas stream at a velocity of 1225 fpm.

3) Serious sorbent attrition was not a major problem in any of the runs. As one would expect, however, some sorbent break-up did occur, since the tests were somewhat exaggerated in severity. In each run, many impacts of the sorbent with the piping and collection-vessel walls occurred, and sorbent velocities were high. In horizontal piping runs, where sorbent samples were cycled 20 times, the percentage of the fines (-28 mesh) fraction of fresh sorbent samples increased from 0.9 percent to 6.7 percent (or 0.34 percent/cycle). For dried, SO_2-saturated sorbent samples, on the other hand, the fines fraction increased from 0.3 percent to 10.9 percent after 20 cycles (or 0.53 percent/cycle). Less attrition was observed in the horizontal-vertical runs. A summary of data collected in the pneumatic runs is presented in Table 2.3.

Table 2.3 Attrition of sorbents with pneumatic conveying.

Material: Coarse Fresh Sorbent
Test: Horizontal Pneumatic System

Mesh Size	Starting Material	After 5 Cycles	After 10 Cycles	After 15 Cycles	After 20 Cycles
+14	97.7%	94.7%	94.0%	90.0%	89.0%
-14 +28	1.4%	2.6%	2.2%	4.0%	4.3%
-28	0.9%	2.7%	3.8%	6.0%	6.7%
Total	100.0%	100.0%	100.0%	100.0%	100.0%

Material: Coarse Fresh Sorbent Saturated with SO_2
Test: Horizontal Pneumatic System

Mesh Size	Starting Material	After 5 Cycles	After 10 Cycles	After 15 Cycles	After 20 Cycles
+14	99.4%	93.4%	91.0%	88.7%	86.4%
-14 +28	0.3%	1.5%	2.7%	3.1%	2.7%
-28	0.3%	5.1%	6.3%	8.2%	10.9%
Total	100.0%	100.0%	100.0%	100.0%	100.0%

Material: Coarse Fresh Sorbent
Test: Horizontal/Vertical Pneumatic System

Mesh Size	Starting Material	After 5 Cycles
+ 9	95.0%	90.0%
- 9 + 48	5.0%	7.9%
-48 +100	0.0%	0.5%
-100	0.0%	1.6%
Total	100.0%	100.0%

Material: Fine Fresh Sorbent
Test: Horizontal/Vertical Pneumatic System

Mesh Size	Starting Material	After 5 Cycles
+ 9	0.0%	0.0%
- 9 + 48	98.0%	95.1%
-48 +100	0.7%	0.6%
-100	1.3%	4.3%
Total	100.0%	100.0%

All data are averages for multiple samples.

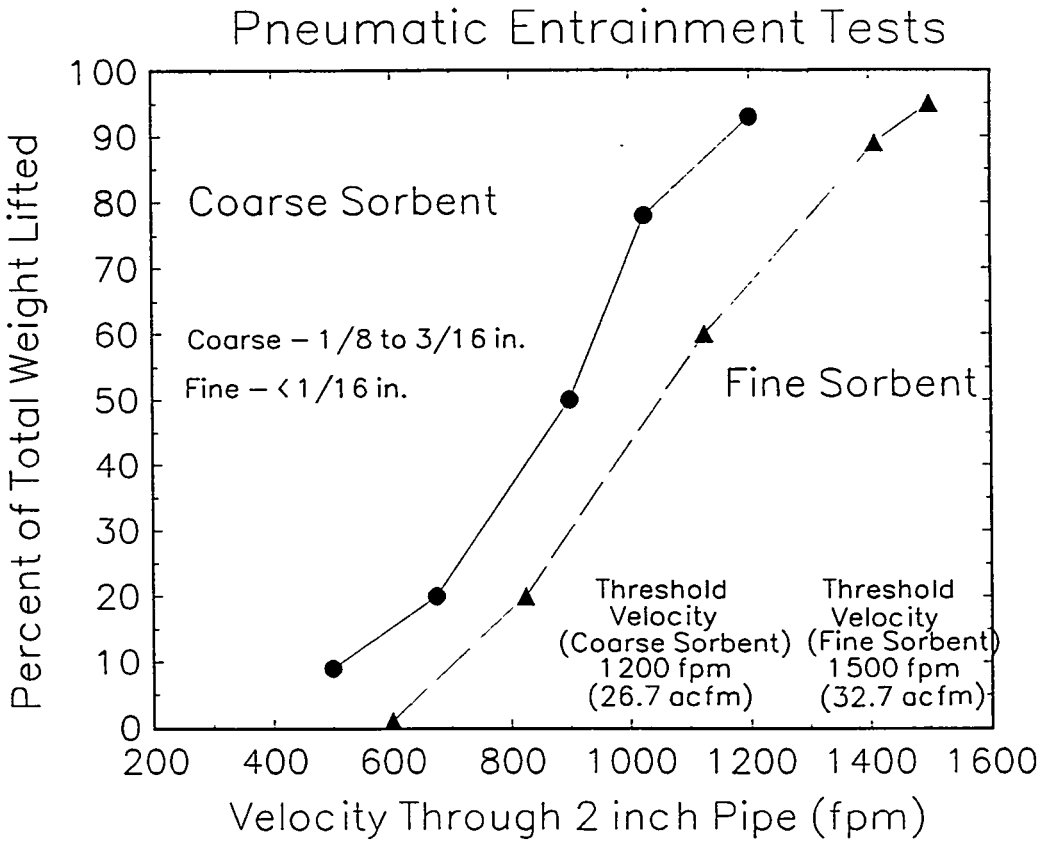


Figure 2.5 Gas velocities required to lift sorbents 15 feet vertically.

2.4 Pilot-Plant Site

The original site offered by Ohio Edison for the project pilot plant was the fourth floor of its Gorge station, located in Akron, Ohio. After the pilot-plant drawings for this facility were prepared, but before purchase orders for equipment were placed, Ohio Edison announced that it was closing the Gorge plant. Ohio Edison, in turn, offered two sites at its Edgewater station, located in Lorain, Ohio, for the project's pilot plant. One site was on the roof; the second was in the ID fan building. The fan building site was selected, shown in the lower left of Figure 2.6, by the trailer. This proved to be an excellent location for the pilot plant, until the Edgewater station itself was prematurely mothballed in April, 1993.

The Ohio Edison Edgewater personnel were very cooperative hosts.

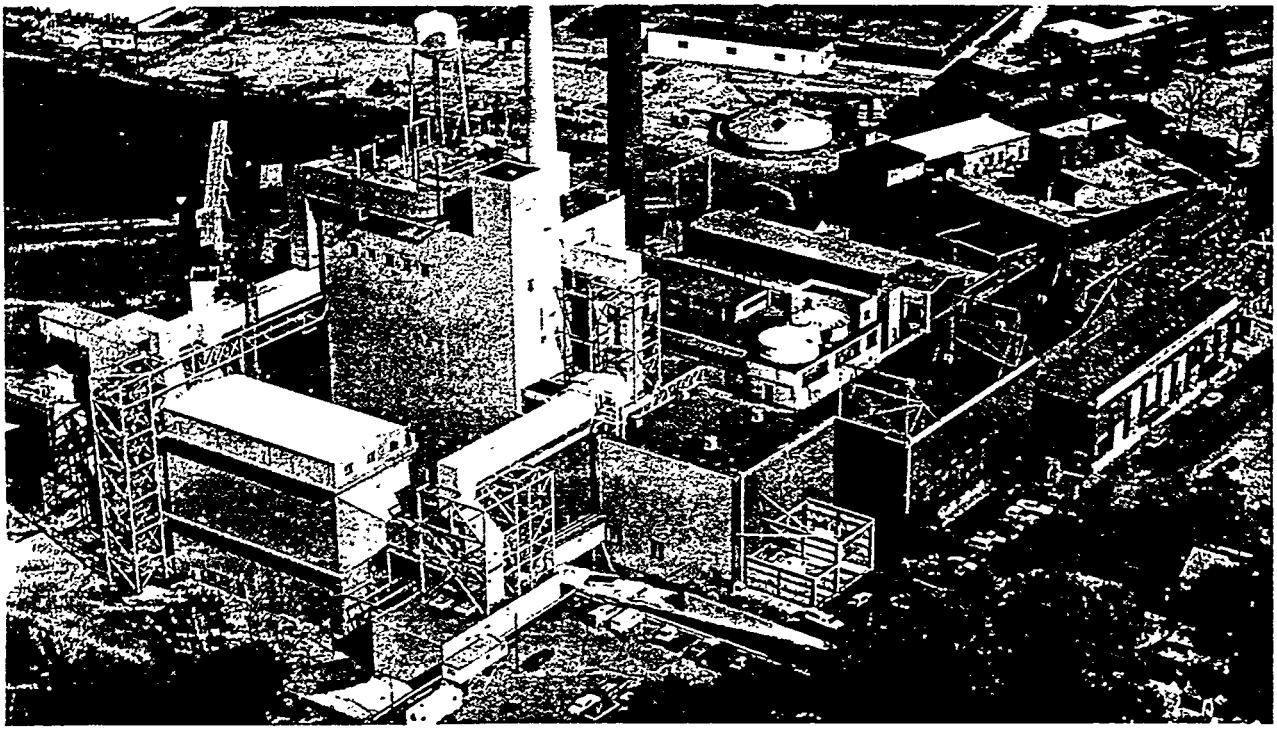


Figure 2.6 Ohio Edison's Edgewater power plant, the project's location.

3. SORBENT PREPARATION

MagSorbents are sorbents consisting of magnesium oxide (MgO) coated onto individual expanded vermiculite or perlite particles. Vermiculite and perlite are industrial minerals that differ in origin and chemistry, but they share several similar characteristics. Both are relatively inexpensive and both expand upon heating to many times their original size. Vermiculite expands like an accordion; perlite pops like popcorn. Individual expanded vermiculite and perlite particles have high external and internal surface areas because of the expansions.

MagSorbents are prepared by first mixing water with the expanded vermiculite or perlite particles. MgO is then blended into the combinations. The combinations are mixed for a short time and then allowed to set for several hours. Afterwards, the combinations are heated to 550°C and held at this temperature for about 20 minutes. This latter conditioning treatment results in a recrystallization of the MgO, forming tiny crystals, with high porosity of the composite materials. The conditioning treatment also appears to improve the bonding of the MgO phase to the vermiculite or perlite substrates.

3.1 Raw Materials

Magnesium oxides are marketed in a variety of types and qualities. Commercial-grade MgO is produced either from seawater and brine wells, from the mined minerals magnesite ($MgCO_3$) or brucite ($Mg(OH)_2$), or as a process by-product. Seawater, brine-well, and by-product MgO can be relatively pure. Mined and calcined MgO, on the other hand, generally contains more than 5 percent impurities, principally $MgCO_3$, CaO and SiO_2. Mined and calcined MgO, however, is usually significantly less expensive than higher-purity MgO.

Two grades of MgO were employed in the project. One was low-purity MAGOX^R grade 93HR325, supplied by Premier Refractories and Chemicals, Inc. of King of Prussia, Pennsylvania; the second was high-purity Elastomag^R grade 170, supplied by Morton Thiokol, Inc. of Danvers, Massachusetts. Data on these materials are provided in Table 3.1.

All vermiculite used in the project was coarse grade (nominally 1/8 to 1/4 inch), supplied by either Strong-Lite Products Corporation of Seneca, Illinois or the Thermorock Corp. of New Eagle, Pennsylvania. Strong-Lite supplied expanded vermiculite produced from African Palabora ores. Though not used in this project, similar sorbents can be made from American Grade #2 vermiculites. Carolina Vermiculite is one possible supplier. The perlite used in the project was coarse grade (1/8 to 3/16 inch), supplied by the National Perlite Products Company of Malad City, Idaho, a subsidiary of Oglebay Norton Company, of Cleveland, Ohio. Typical vermiculite and perlite analyses are given in Table 3.2.

Table 3.1 Magnesium oxide raw materials.

Material:	MAGOX^R 93HR325		Material:	ELASTOMAG^R 170	
Supplier:	Premier Refractories and Chemicals, Inc.		Supplier:	Morton Thiokol, Inc.	
Source:	Calcined Magnesite		Source:	Seawater	
Composition:	(Loss-Free Basis)		Composition:	(Loss-Free Basis)	
MgO*	93.0	wt%	MgO	98.0	wt%
CaO	2.5	wt%	Calcium, as CaO	1.3	wt%
R_2O_3	1.5	wt%	Chloride, as Cl	0.15	wt%
SiO_2	3.0	wt%	(Ignition Loss	6.0	wt%)
Bulk Density	60-70 lb per cu ft		Bulk Density	18 lb per cu ft	
Melting Point	> 2800°C		Specific Gravity	3.2	
Water Solubility	6.2 mg/L		Surface Area (BET)	141-188 m^2/g	
pH (10% H_2O slurry)	10.5				
Particle Size	Mostly - 325 mesh		Particle Size	99.9% - 325 mesh 46.0% - 1.25 μ	

* A small percentage, less than 5%, of this MgO may be in $MgCO_3$ form.

Table 3.2 Typical chemical analyses of vermiculite and perlite (wt%).

Palabora Vermiculite		Idaho Perlite	
SiO_2	39.37%*	SiO_2	75.5%
TiO_2	1.25%	TiO_2	0.1%
Al_2O_3	12.08%	Al_2O_3	11.6%
Fe_2O_3	5.45%	FeO_3	0.5%
FeO	1.17%	MgO	Trace
MnO	0.30%	CaO	1.1%
MgO	23.37%	Na_2O	1.8%
CaO	1.46%	K_2O	3.6%
Na_2O	0.80%	H_2O	5.7%
K_2O	2.46%		
$H_2O+105°C$	5.18%		
H_2O-105°C	6.02%		
CO_2	0.60%		

3.2 Pilot Plant Sorbents

A total of 126 barrels of fresh MagSorbent was prepared at Sorbent Technologies Corporation's laboratories for use at the pilot plant. This material was prepared over an 18-month period. In addition, 18 barrels of fresh expanded vermiculite was supplied to the pilot plant for equipment start-up trials. Of the 126 barrels of fresh sorbent, 39 had the composition 45 wt% MgO-55 wt% Vermiculite, 27 had the composition 50 wt% MgO-50 wt% Vermiculite, 46 had the composition 60 wt% MgO-40 wt% Vermiculite, and 14 had the composition 50 wt% MgO-50 wt% Perlite.

All MagSorbent materials were prepared using procedures as described in U.S. Patent No. 4,721,582. Materials for the pilot plant were prepared on a batch basis. Briefly, the procedures included the following steps:

1) expanded vermiculite or perlite was mixed with water;
2) MgO was blended into the mixtures;
3) the combinations were allowed to air dry for several hours; and
4) the combinations were then heated (conditioned) in a kiln at 550°C for 20 to 30 minutes and screened.

A small cement mixer was employed for mixing and blending the components. Heat conditioning was carried out in a conveyance kiln using large metal trays to hold the sorbent particles.

4. PILOT-PLANT DESIGN, CONSTRUCTION, AND START-UP

The Edgewater proof-of-concept pilot plant was designed to treat a slipstream of up to 2-MWe of flue gas removed from Ohio Edison's main flue-gas duct at its No. 4 Unit. At full power, Ohio Edison's main duct carried approximately 104 MWe of flue gas. The pilot-plant was designed to remove flue gas containing SO_2 from the exit side of the ID fan and to return treated gas to the entrance side of the fan. Thus, a natural draw of flue gas would occur through the system. However, to assure that satisfactory gas flowed at all times, a separate ID fan was incorporated into the pilot-plant slipstream duct design. When the utility was operating at low capacity, the Sorbtech unit would process about 5 to 10 percent of the plant's flue gas.

Figure 4.1 is a schematic flow diagram of the pilot plant. The two principal circuits, sorption and regeneration, are shown at the top and bottom of the diagram, respectively.

4.1 Sorption System

The principal components of the sorption system were: (1) the slipstream ductwork; (2) an in-line humidification spray; (3) the sorber; (4) an in-line fan; and (5) an in-line velocity meter. Gate valves were placed at the entrance and exits of the slipstream duct to control the flow of gas through the system and to isolate the system from Ohio Edison's main duct when the pilot plant was not operating.

Slipstream Ductwork. The entrance duct, before the sorber, was constructed of Type 304 stainless steel, and had a cross-sectional area of 30 inches by 30 inches. The exit duct, after the sorber, was made of carbon steel, and had a cross-sectional area of 18 inches by 18 inches.

Humidifier. The pilot-plant humidifier design incorporated the ability to add moisture to the flue gas to decrease the gas temperature and to control the approach to adiabatic saturation.

Sorber. The design adopted for the pilot-plant sorber was a radial panel bed. It was essentially a small-scale version of a commercial electroscrubber filter without its internal electrical grid and without its special external recycle circuit, but with a modified bottom.

In-Line Fan. The in-line fan was of conventional design with a rated capacity of 7500 cfm at 12 inches static pressure.

In-Line Velocity Meter. In the pilot plant it was desired to continuously measure the velocity of the gas in the ductwork to monitor the mass-flow-rate of gas through the system. Two different velocity-measurement approaches were included in the pilot-plant design. First, a full-traverse measuring system from the Air Monitor Corporation was permanently installed in the duct. In the Air Monitor system, an array of pilot tubes are integrated and averaged. Second, ports were included in the ductwork for periodic use of a hot-wire anemometer, as a back-up.

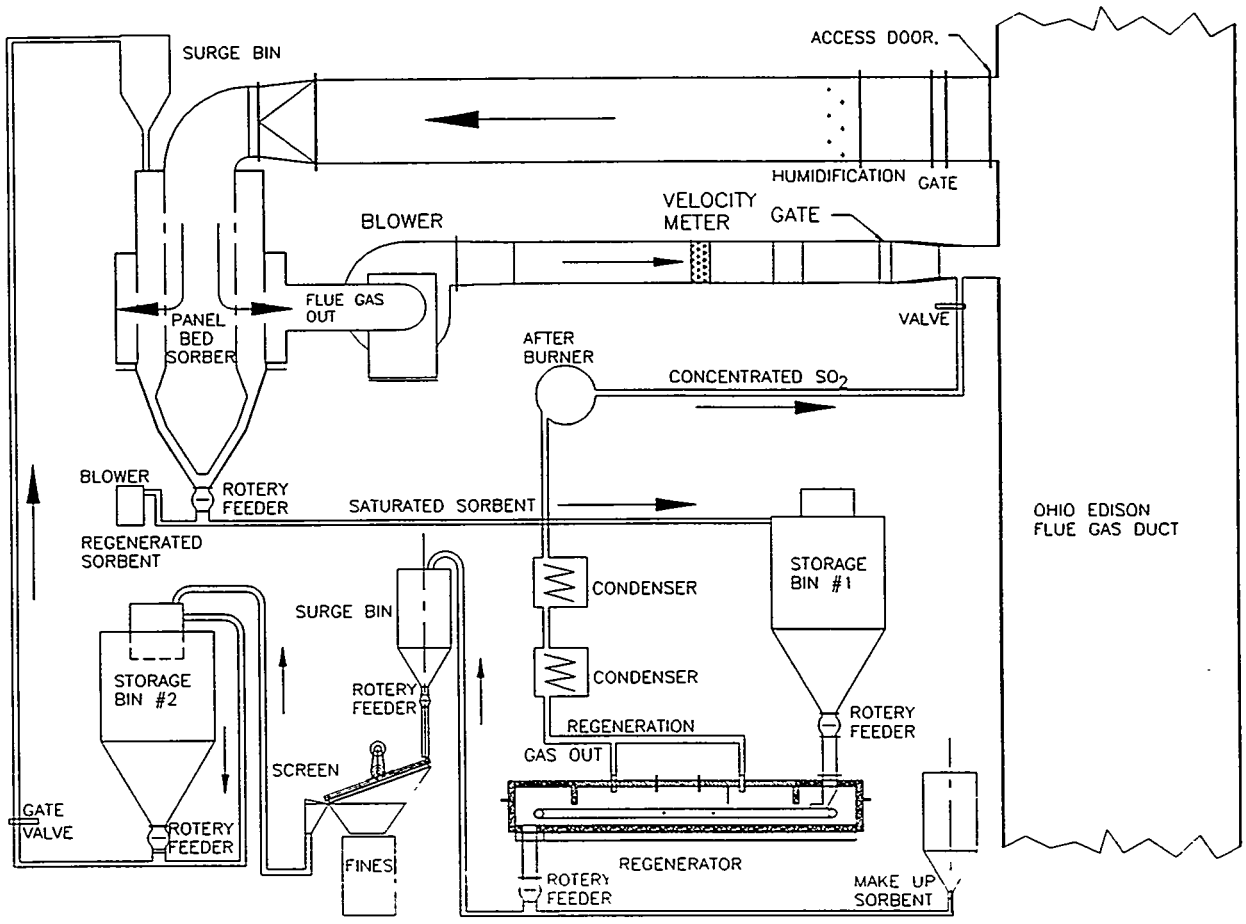


Figure 4.1 Sorbtech/OCDO MagSorbent pilot plant.

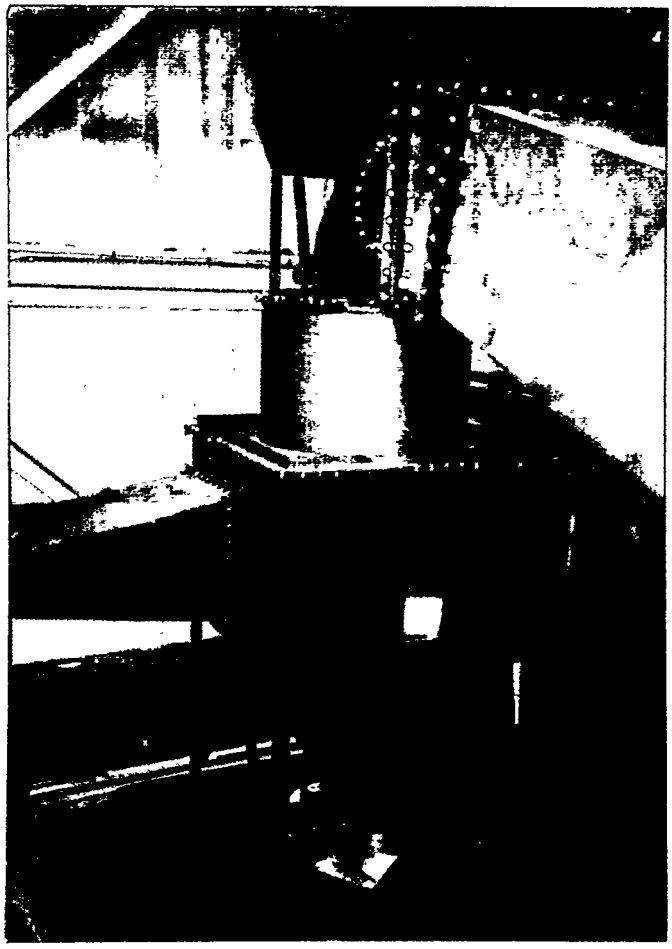


Figure 4.2 Panel-bed sorber
(before insulation installation).

4.1.1 Sorber Design and Construction

The sorber was designed to permit changes in the bed-support structural materials during the pilot plant program without major difficulties. The initial sorber design contained stainless steel screens of approximately 10 mesh to hold the sorbent beds. Auxiliary bed-support structures consisting of Dynapore microscreen, supplied by Michigan Dynamics, Inc. and of stainless steel louvers were also designed and constructed.

The radial-panel-bed sorber was designed and constructed in several parts and was field-assembled. The unit was principally bolted together. A photograph of the assembled sorber and associated ductwork, before they were insulated, appears in Figure 4.2

A cross-section drawing of the sorber is given in Figure 4.3. The overall height of the sorber, including the sorbent-feed hopper at the top, was 18.5 feet. The base dimensions were six feet by six feet. Flue gas entered the sorber from the top through a 2.5-foot diameter chamber. From this chamber, the gas passed horizontally through a 12-inch sorbent panel bed and into an enclosed open chamber outside the bed. The active radial sorbent bed was 4-feet high with a 2.5-foot internal diameter.

Three views of the sorber, in combination with ductwork taking gas from Ohio Edison's main duct and returning it, are provided in the lay-out drawing shown in Figure 4.4. The flue-gas duct was designed and fabricated in 15 separate parts, as shown. The humidifier was installed in Section 4. The sorber was placed between Sections 7 and 9. A special duct section designed to change the direction of the entering flue gas approximately 90 degrees was incorporated into the top of the sorber. Turning vanes were designed, fabricated, and installed inside this section.

The sorber was designed to allow the sorbent to flow smoothly and uniformly through it during operation. Knowledge gained in multiple trials with the cold-flow model were incorporated into the sorber design. Sorbent was supplied to the sorber from the sorbent-feed hopper through three separate 2-inch diameter tubes. Sorbent entering the sorber at the three locations filled an upper chamber of the sorbent forming the radial bed. This radial bed of sorbent then moved uniformly downward through the flue gas exposure zone and into a large collection-hopper at the base of the sorber. From the collection hopper, spent sorbent was extracted from the sorber through a rotary airlock, where it could be pneumatically transported to the regenerator circuit.

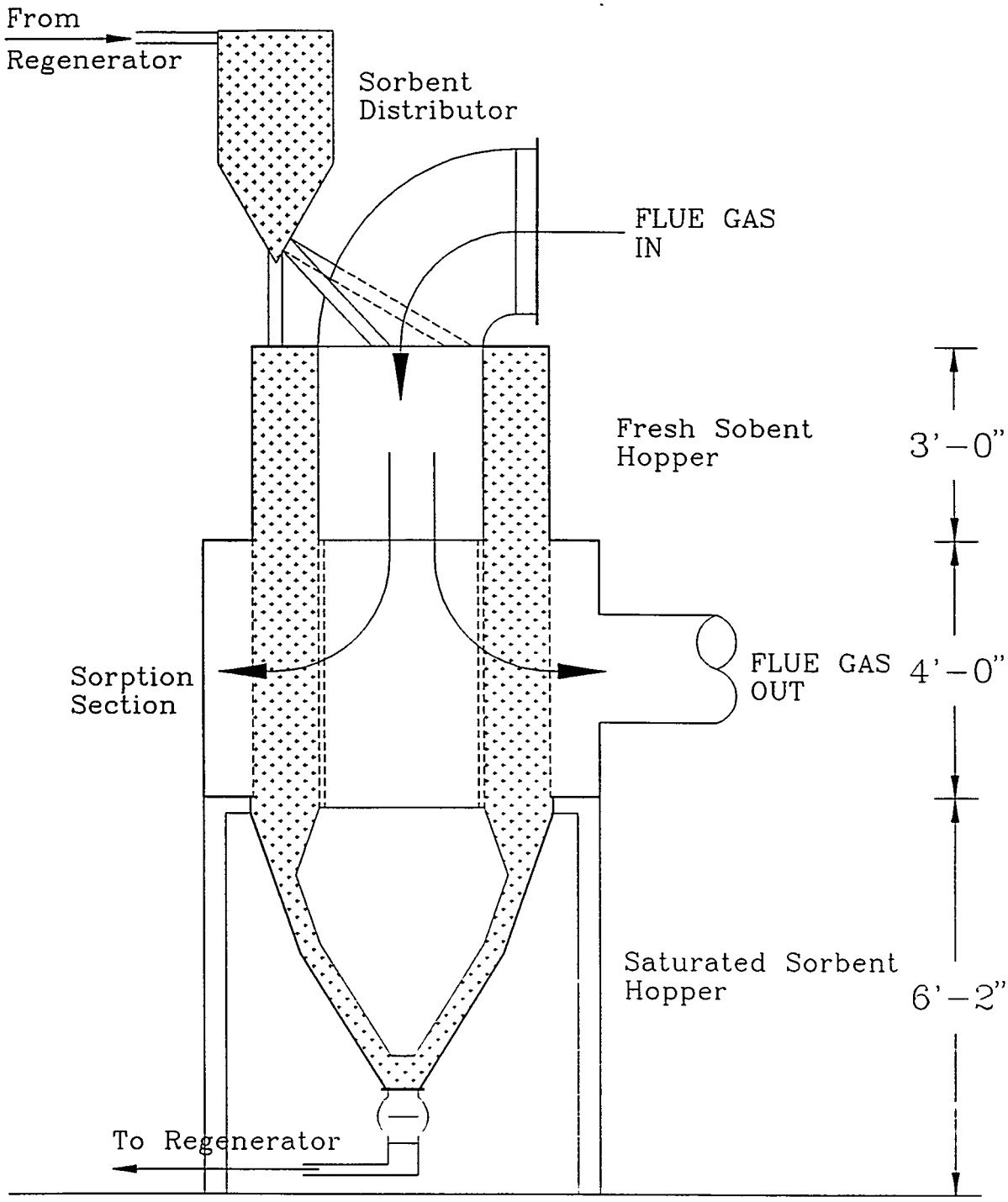


Figure 4.3 Sorber cross-section.

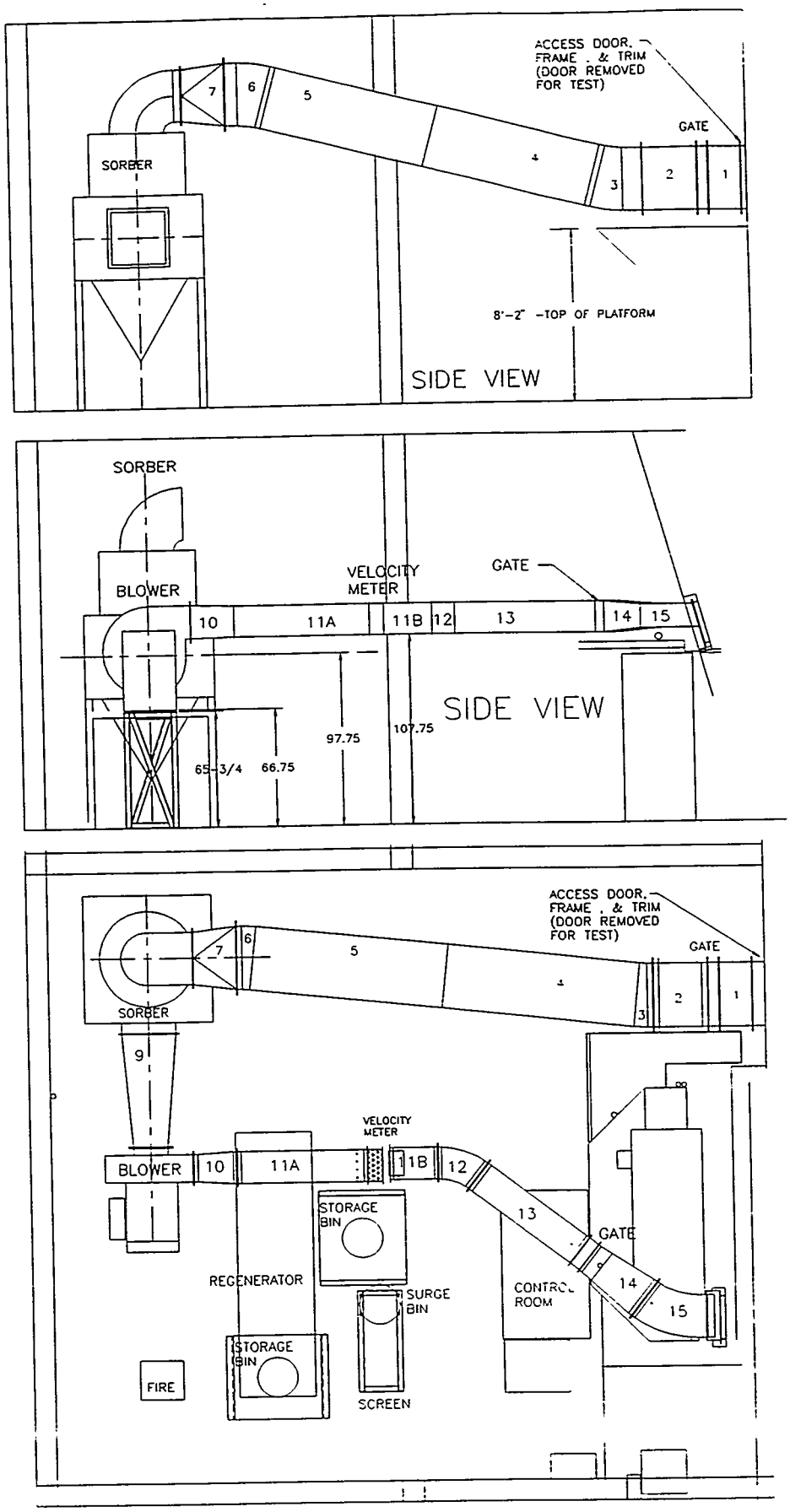


Figure 4.4 Ductwork arrangement.

4.1.2 Humidifier Design and Construction

The humidification system controlled the flue gas's approach to adiabatic saturation. The system consisted of a water-delivery subsystem, a pressurized air system, and an array of nine (9) dual-fluid nozzles in the flue-gas duct, arranged as three rows of three nozzles. The duct section containing the humidifier is shown in Figure 4.5. To provide high residence time for evaporation, this ductwork section was made with a large cross section, slowing the gas velocity to about 10 to 15 fps. Windows were placed in the walls of the duct after the nozzles to allow observation of the nozzles during operation. The nozzles employed were Model SU22-55's, supplied by Spraying Systems, Inc., each designed for 5 to 10 gal/hour of water at about 30 psi water pressure and 4 to 5 cfm of air.

The humidification system was assembled and installed after the sorber and ductwork were in place. The water employed in the system was plant potable water that, on occasion, became muddy when back-flushing occurred in some other areas of the power plant. A filter system was placed in the line leading to the humidifier's water-delivery system to prevent fouling of the nozzles by this muddy water. Plant air was used in the pressurized air system. Again, to prevent fouling of the nozzles and to assist in control, a moisture trap and air filters were placed in the pressurized air line.

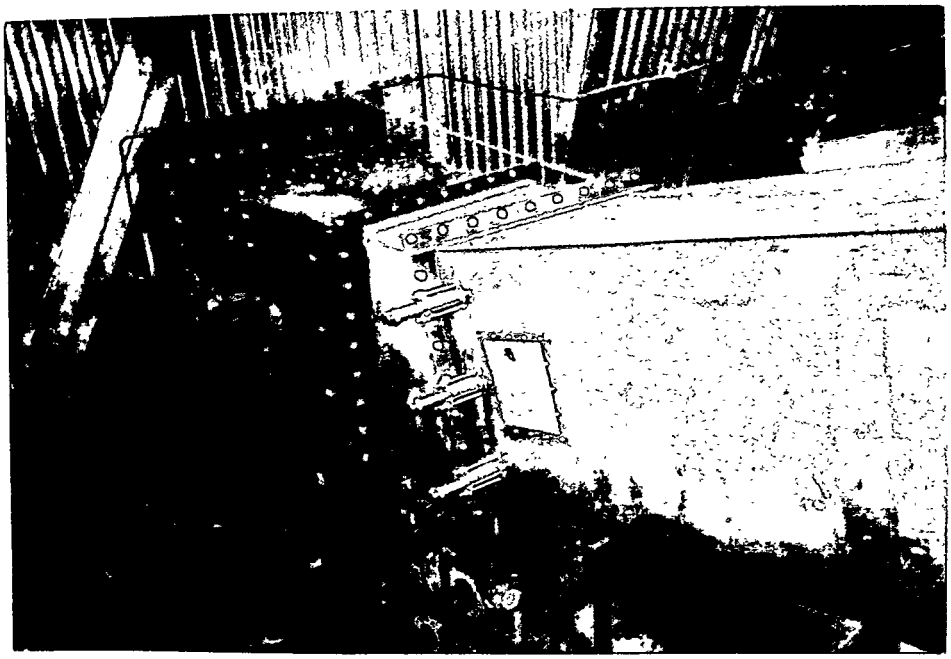


Figure 4.5 Gas inlet and humidification system.

4.1.3 Humidifier and Sorber Start-Up

No significant problems were encountered during the start-up of the humidifier or the sorber. The nozzles in the humidification system produced a fine water spray that rapidly evaporated as it passed along with the hot flue gas. A small amount of wall-wetting occurred, especially on the duct bottom when the gas flow, and so water flow, were highest. This did not present significant operational problems, however, because there was little particulate in the stream. Others have found humidification much easier on larger ducts. All nine spray nozzles performed well during start-up and the desired approach temperatures were achieved. See Table 4.1. Each nozzle appeared to deliver about the same quantity of water. The nozzle directions were adjustable. Several adjustments were made during start-up trials to make the moisture additions uniform across the cross-section of the duct.

The sorber was first started up with no sorbent in the bed. It was then examined with an expanded vermiculite bed, and then, finally, with MagSorbent beds. The same low pressure drops seen in the cold-flow model were observed in the full-scale unit. Because of the natural pressure difference around the system due to Ohio Edison's fan, it became unnecessary to turn on the pilot system booster fan, even when Ohio Edison was operating at full capacity.

Table 4.1 Humidification start-up data.

Power Plant Output: 103 MWe (full power)
Sorber Panel: Vermiculite

	Without Humidification	With Humidification		
Test Number	1	4	2	3
Gas Flow (acfm @ monitor)	6600	7000	6300	7000
(scfm)	4800	5850	5250	6025
(MWe)	2.1	2.5	2.3	2.6
Water Rate/Press. (gpm/psi)	0/0	0.5/41	0.8/45	1.1/45
Air Rate/Press. (scfm/psi)	0/0	n.r./70	80/70	80/60
Approach Before Sorber (F)	156	74	60	44
Dry Bulb Temperatures (F)				
Before Spray	290	n.r.	290	n.r.
Before Sorber	281	194	184	164
At Flow Monitor	235	172	177	155
Drop to Sorber	9	96	106	126
Drop Total	55	118	113	135
Wet Bulb Temperatures (F)				
Before Spray	125	n.r.	124	n.r.
Before Sorber	125	120	124	120
At Flow Monitor	115	113	114	113
Approach At Flow Monitor (F)	120	59	63	44
Panel Pressure Drop (in WG)	n.r.	3.7	n.r.	3.5

n.r. = not recorded

4.2 Regeneration System

The regeneration system that was installed included: (1) a pneumatic conveying system that transported sorbent from the sorber to the regenerator and back; (2) the regenerator; (3) an in-line screening station; (4) storage bins; and (5) a regenerator-gas processing system.

Pneumatic Conveying System. Air was employed to convey sorbent around the regeneration circuit. The pneumatic conveying circuit was constructed with four separate lines:

(1) from the sorber to a storage bin above the regenerator;
(2) from the regenerator to a collection bin above the screening station;
(3) from the screening station to a large general storage bin; and
(4) from the large storage bin to a smaller surge bin above the sorber.

Except for the line leaving the regenerator, all lines were constructed of 2-inch diameter PVC and acrylic tubing.

Regenerator. The regenerator was a key piece of equipment in the system. It was employed to regenerate the MagSorbent that was saturated with acid gases. During regeneration, captured SO_2 and NOx were released and the sorbing properties of the MagSorbent restored. Figure 14 shows the regenerator.

Screening Station. When 10-mesh screens were employed in the sorber, it was desirable that particles smaller than 10-mesh be removed from the sorbent material before the material was delivered to the sorber. Also, it was desirable to remove a pre-selected percentage of the sorbent during each cycle and to replace the removed amount with fresh sorbent. These activities were accomplished at the screening station. The screening station consisted of a simple vibrating screen over which the regenerated sorbent flowed and a splitter that physically separated and removed a pre-selected percentage of the sorbent from the stream. Fresh make-up sorbent could be added to the sorbent stream at the screening station.

Flow-Control Bins. Five carbon steel bins were employed to hold sorbent at different stages of the regeneration circuit. The locations of these bins are shown in Figure 9.

Regeneration-Gas System. The objective of the regeneration-gas system was to carry away gases produced in the regenerator, to treat them, if necessary, and to deliver them eventually back into Edgewater's main flue-gas duct. The regenerator-gas system contained two alternate exhaust lines. One line lead directly from the regenerator to the main flue-gas duct. This line was employed when an air atmosphere was used in the regenerator and the regenerator gas contained no elemental sulfur or H_2S. The second line lead from the regenerator to a sulfur condenser, a water condenser, and a burner before passing to the main flue-gas duct. In the latter system, any elemental sulfur, sulfuric acid mist, and moisture was to be removed from the exhaust gas and any H_2S was oxidized to SO_2.

Figure 4.6 Pilot-plant regenerator.

4.3 Data Collection

The pilot plant at Edgewater was extensively instrumented. Figure 4.7 shows where various temperature (T1-T9), differential pressure (P1-P2), humidity (H1), and flue gas velocity data were collected from during each test run. The locations where flue gas was continuously sampled for the determination of SO_2, NOx and O_2 concentrations are also marked (S1-S3). During each test run this data was electronically recorded by a data acquisition system and, as a precaution, the data and conditions were also periodically recorded manually.

4.3.1 Data Acquisition and Instrumentation

The data acquisition system included a CompuAdd 316s microcomputer and LabTech Notebook/XE software. Interface hardware purchased from Cyber Research included a data acquisition board, solenoid activation board, two data multiplexers, a thermocouple multiplexer, and a solenoid multiplexer.

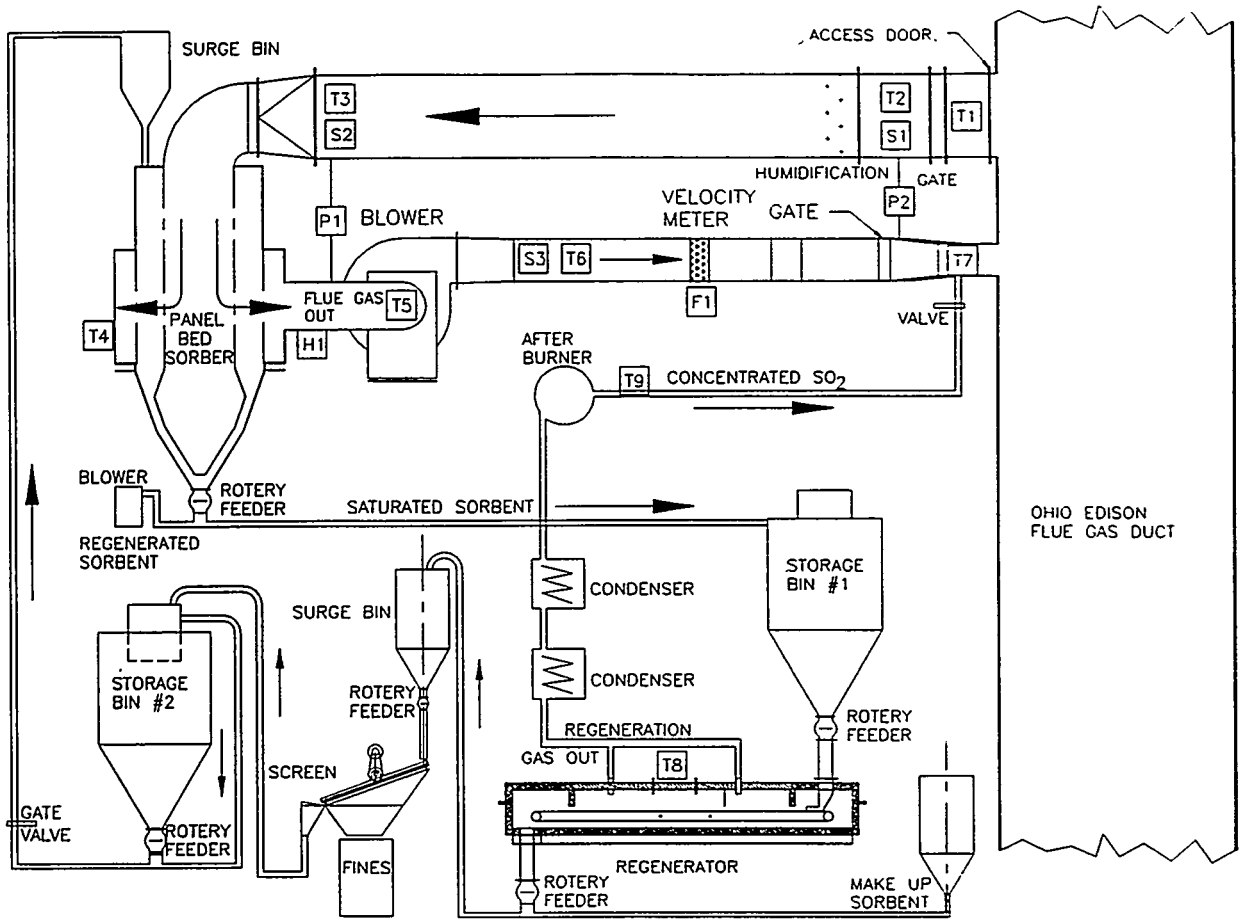
Table 4.2 provides a summary of the measurement devices used to collect data during the tests. Every ten seconds the data acquisition system sampled the dry bulb temperatures, gas flowrate, relative humidity and the SO_2, NOx, and O_2 concentrations and it recorded averages every minute. Wet-bulb temperature and pressure drop measurements were taken and recorded manually. A K-type thermocouple covered with a wetted wick was used to measure the wet-bulb temperature. A water-filled manometer measured the pressure drop both across the sorber and across the whole system.

4.3.2 Sample-Gas Conditioning and Analysis Equipment

Gas samples were continuously drawn from the system at three locations: at the flue gas inlet, after humidification, and after the sorber. Each sample gas was then passed through a glass-wool filter to a heated, stainless-steel sample line, and then, into a gas conditioning system The gas conditioning system removed the moisture from the gas, performed micro-filtration, and delivered the gas at the proper flowrate and pressure to the gas analyzers. The system also provided reference gases and a regulated vacuum source required by the analyzers. It is shown schematically in Figure 4.8.

The gas conditioning system continuously pulled gas through all three sample lines, but gas from only one sample line would be analyzed at any one time. The data acquisition system controlled three solenoid valves, allowing one gas to be analyzed, while the other two sample lines were exhausted back to the duct. A sample gas was analyzed for three minutes, then the solenoid valve would close and the next valve was opened. To allow the lines to flush and the instruments to stabilize, only values for the last two minutes of each sampling were averaged an recorded.

The SO_2 concentrations were determined by infrared spectrophotometry using a Horiba PIR 2000 gas analyzer. The NOx and O_2 concentrations were determined using a Horiba CMA 321 analyzer with a NDIR cross flow modulation gas analyzer for NOx measurement and magnetopneumatic analysis for O_2 measurement. The Horiba instruments were calibrated using zero and span gases before and after each run.



	Temperature		Gas Sampling Lines
T1	Inlet gas	S1	Inlet Gas
T2	Pre-humidification	S2	Post-humidification
T3	Pre-sorber	S3	Outlet gas
T4	Sorbent bed		
T5	Post sorber		Other
T6	Velocity meter	F1	Flow Monitor
T7	Outlet gas	H1	Relative humidity probe
T8	Regenerator		
T9	Post after-burner		

	Pressure
P1	Pressure drop across the sorber
P2	Pressure drop across the system

Figure 4.7 Data acquisition points.

Table 4.2 Data collection summary.

Parameter	Sampling	Instrumentation
Dry-bulb temperatures	7 places in flue gas stream 2 in regeneration gas stream	K-type thermocouples
Wet-bulb temperatures	Manual, at the sorber outlet	K-type thermocouple covered with a wetted wick.
Pressure drop	Across sorber Across the whole system	water-filled manometer
Gas flow rate	In-line	Air Monitor electronic pitot tube array.
Relative humidity	sorber outlet	Vaisala electronic relative humidity probe.
SO_2	3 separate sample lines: Before humidification Before sorber After sorber	Horiba PIR 2000 infrared spectrophotometry analyzer.
NOx	Before humidification Before sorber After sorber	Horiba CMA 231 using a NDIR cross-flow modulation detector.
O_2	Before humidification Before sorber After sorber	Horiba CMA 231 using a magnetopneumatic detector.

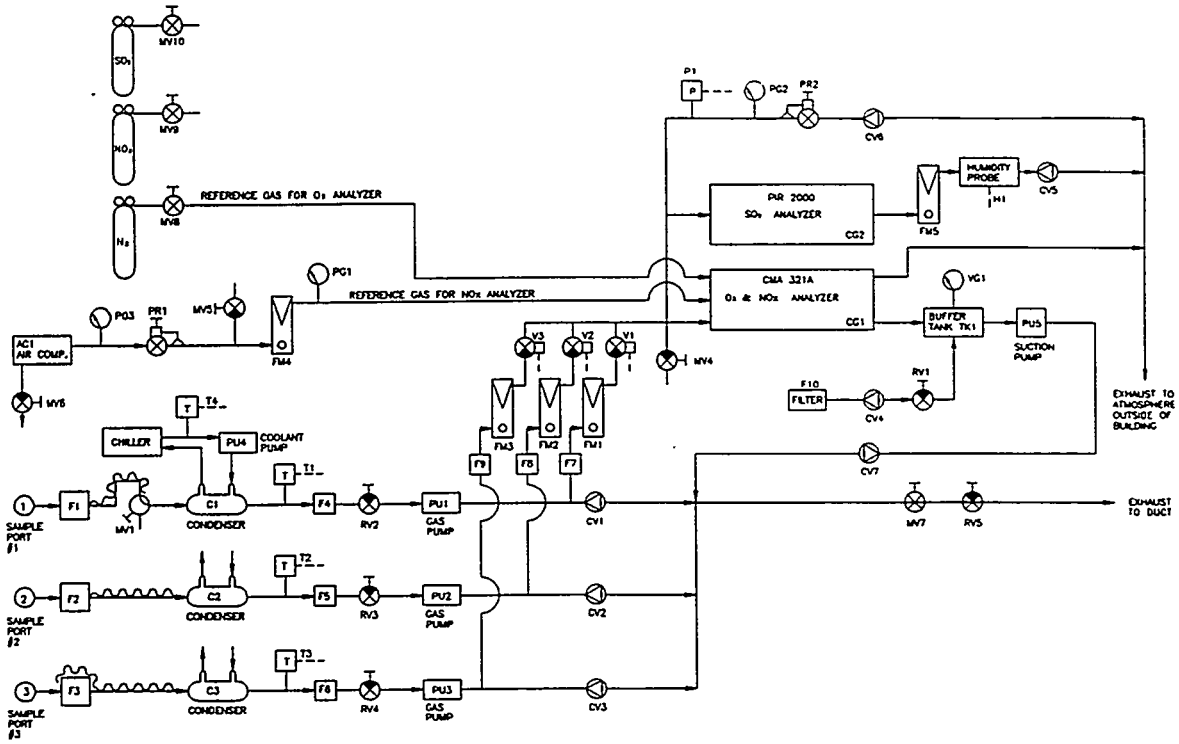


Figure 4.8 Sample-gas analysis system.

A problem occasionally encountered with the gas conditioning system was that a small amount of circulating through the water condensers would be chilled below freezing and a condenser would become clogged with ice. When a condenser became clogged, the flow of gas to the analyzers was interrupted and the analyzers would give obviously erroneous results. The condensers for the number two sample line froze up most frequently due to the higher liquid moisture content in that line. This line removed sample gas from the duct after humidification and before the sorber. The purpose for sampling at this location was to determine if the SO_2 concentration in the flue gas would be reduced when the flue gas was humidified. Once it was demonstrated that the SO_2 concentration was relatively unaffected by humidification, this sample line was disconnected, which allowed for significantly more frequent sampling of the more important inlet and outlet lines.

The oxygen concentrations were measured in order to standardize the SO_2 and NOx inlet and outlet readings. The O_2 values allowed us to correct the SO_2 and NOx readings to account for things like humidification air dilution or sampling line differences, which might indicate artificially high SO_2 removal rates.

5. PARAMETRIC STUDIES

One objective of the project was to learn how various operating parameters affect technology performance. In particular, the test program was designed to explore the affect of:

1. flue-gas temperature and relative humidity;
2. gas flow;
3. sorbent composition; and
4. sorber design variables.

The dependent variables were SO2 and NOx removal and sorbent utilization.

We had only limited flexibility in varying the flue gas chemical conditions. Because of the scale, the SO_2 and NOx levels could not be readily changed. The flue gas entering the pilot plant system usually had a dry bulb temperature of about 300°F and a wet bulb temperature of from 115 to 120 °F. Chemically, the flue gas to the pilot plant varied from:

SO_2	700 - 1100 ppm
NOx	150 - 350 ppm
O_2	6.5 - 10.0 %.

Early in the project, it was discovered that during the start-up of a boiler, large amounts of unburned carbon usually appeared in the flue gas, carbon that was not removed by the electrostatic precipitator (ESP) that appeared before the pilot-plant facilities in the Edgewater system. Also, it was discovered that during times of boiler-tube problems, it was common to see very large quantities of moisture in the flue gas. It was obvious that boiler start-up times and periods with boiler-tube problems should be avoided in the pilot-plant program.

Although the sorber was built for continuous, moving-bed operation, the parametric testing was carried out with individual static beds. Static-bed testing allowed much more information to be collected with each run. Moving-bed operation adds the bed speed as an operating variable. To choose the proper bed speed for a run, we would first need to know the sorbent utilization, which, unfortunately, was one of the dependent variables we were trying to determine. See, for example, the drawings in Figure 5.1. Each rectangle represents a 1-ft by 4-ft cross-section of the radial sorber panel at a particular point in time. In these diagrams, flue gas with SO_2 is passed uniformly through the panel from the right to the left. The test starts with a totally fresh or regenerated bed at time equal to zero.

In the case of a constant-speed moving-bed, fresh sorbent is continuously added to the top of the bed and an equal amount of sorbent is continuously drawn off from the bottom. At 60 minutes, in this example, sorbent originally at level A has moved one-fourth of the way down the sorption zone. Over time, some of the sorbent becomes fully saturated, denoted by the darkened areas. As long as none of the saturated areas reach entirely across the panel, SO_2 removal will remain high and the sorbent bed has not yet "broken through." If the sorbent bed rate is chosen optimally, breakthrough will almost occur at the very bottom of the sorber sorption section, wherein the sorbent going to regeneration would be maximally utilized. This profile would then be maintained continuously, once one bed-height has been transversed.

However, if the sorbent flow rate chosen was too slow, a large part of the bed would already be saturated at that time, allowing large amounts of SO_2 to pass through, significantly dropping high-end SO_2 removal performance. See the next drawing. Conversely, if the bed speed was too fast, high SO_2 removal would be seen in the equilibrium contour, but the overall sorbent utilization would be only a fraction of what it could be. Unfortunately, the optimal bed speed is not known ahead of time, being a function of the sorbent performance that is being tested for. Consequently, if the sorbent was tested in the moving-bed mode, many different runs would be required, each at a different bed speed to find the optimums of overall SO_2 removal and sorbent utilization for each set of other parameters examined.

Testing the radial panels as static beds theoretically solves this problem. In this case, as shown in the drawings, the saturation front moves slowly and uniformly across the sorbent panel cross-section with time. High 90+% SO_2 removals are seen for a long time, until the whole bed becomes utilized and "breaks through" nearly all at once, thereafter removing very little SO_2. This is the pattern that had been seen in earlier, smaller-scale tests. Such a static-bed test produces not just one data point, as in the moving-bed case, but a whole saturation curve of the various combinations of SO_2 removal and sorbent utilizations that are possible under the particular parametric conditions. These combinations of removal rate and utilization are then selectable by choosing a particular bed speed. Moreover, the full bed is uniformly saturated and, when regenerated, can be saturated again for representative multiple-run testing.

Figure 5.2, for example, presents the data from a single static-bed fresh-sorbent run. Conditions were held approximately constant at a flue gas flow of 4000 acfm (1.4 MWe) and a 62°F approach to adiabatic saturation. SO_2 and NOx removal by the radial sorbent panel was measured as a function of time for over 500 minutes. The instantaneous SO_2 removal was very high for the first three hours, then slowly and continuously dropped off. (Note that the slow drop off is not the quick breakthrough expected. This will be explained later. Note also the relationship between SO_2 removal and the relative humidity of the gas.)

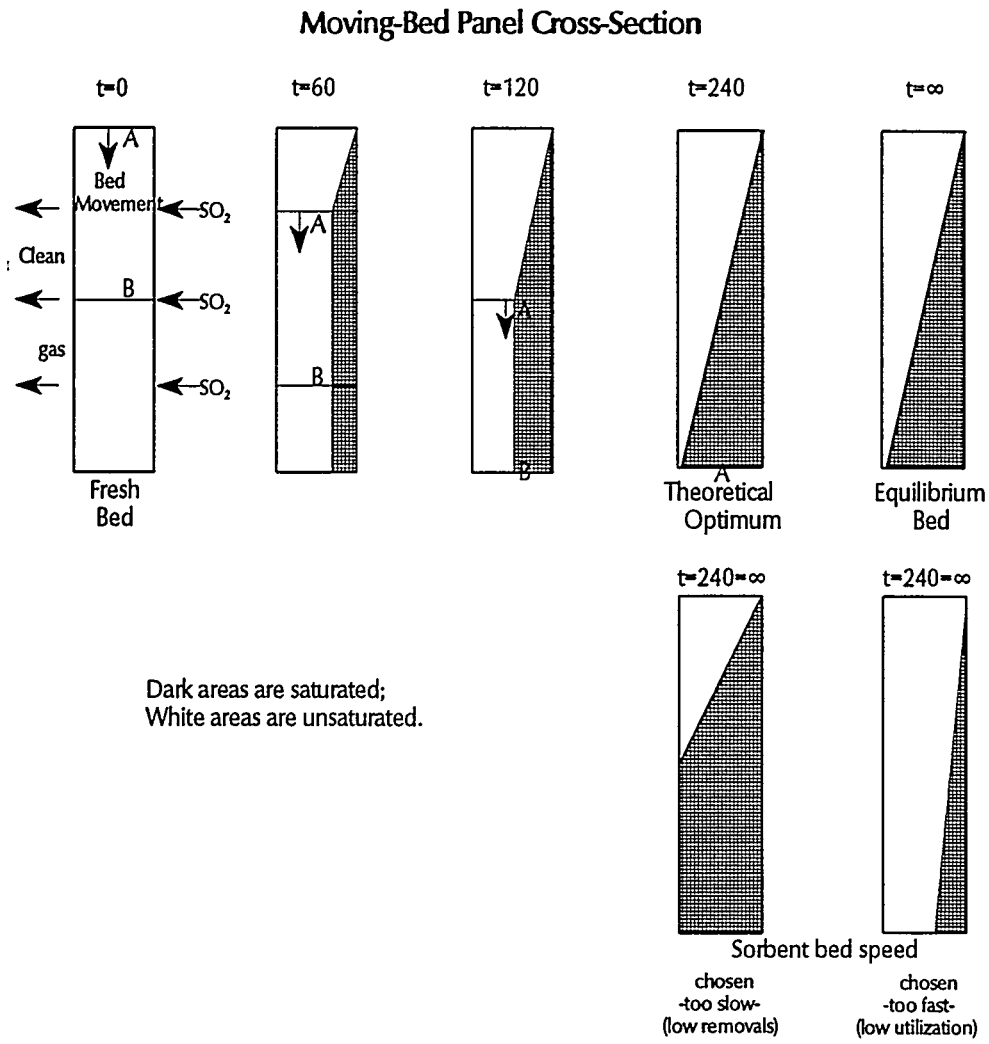


Figure 5.1 Theoretical saturation profile cross-sections of moving and static panels.

To properly interpret the raw static-bed data of Figure 5.2, it must first be converted into a continuous, moving-bed mode. In a steady-state moving bed, SO_2 removal does not vary with time: there is only one SO_2 removal rate and one sorbent utilization. Importantly, the sorbent panel at any particular utilization rate gets credit for all the SO_2 removal that has occurred up to that point. Consequently, we must integrate the instantaneous static-bed SO_2 and NOx removal curves from zero to each time point in order to derive the average removal rates representative of intended moving-panel operation. Additionally, we can convert the time dimension into a measurement of sorbent utilization by dividing the cumulative SO_2 and NOx absorptions by the total moles of reactive species in the given static bed. This normalizes the saturation time to enable comparisons of runs with different flue gas flows and SO_2 and NOx levels. See below.

$$so2cum(t) = \frac{\int_0^t [\epsilon(t)_{SO2} * gasflow(t)]\ dt}{\int_0^t gasflow(t)\ dt}$$

where:	so2cum(t)	=	cumulative (or average) fixed-bed removal rate to time t;
		≈	equiv. to SO_2 removal rate for moving-bed operated at U(t)
	$\epsilon(t)_{SO2}$	=	instantaneous fixed-bed removal rate at time t
	gasflow(t)	=	gas flow at time t in standard units

with similar relationships for NOx. To normalize time to utilization:

$$U(t) = \int_0^t [so2rem(t) + noxrem(t)]\ dt$$

where:

$$so2rem(t) = \epsilon(t)_{SO2} * so2in(t)$$

and:	U(t)	=	cumulative utilization through time t
	M_{MgO}	=	moles of MgO in the panel
	so2rem(t)	=	moles of SO_2 removed by the panel at time t
	so2in (t)	=	moles of SO_2 entering the panel at time t.

The properly transformed data of the earlier-described run is plotted in Figure 5.3. It shows, for example, that under the various operating parameters chosen for the run, we can achieve 97% SO_2 removal from the sorbent panel, and will also see about 40% NOx removal, but we will have to settle for only about 13% sorbent utilization. This would be achieved by a quickly-moving panel. Alternatively, we could slow the sorbent panel down to 90% continuous SO_2 removal, 30% NOx removal, and 23% utilization. Similarly, at 32% utilization we would see about 80% SO_2 removal and 25% NOx removal on a continuous basis. Such curves of cumulative SO_2 and NOx removal versus cumulative sorbent utilization are how the various parametric tests were evaluated.

The data are believed to be accurate to about 2% absolute and very robust. The instruments were calibrated before and after each run. Each data point is an average of several measurements and each is corrected for interferences and any dilution through leakage. Ohio Edison cross-checked our flow and gas analysis at one point and agreement was good. Overall, the results were repeatable and run-to-run correlation was good.

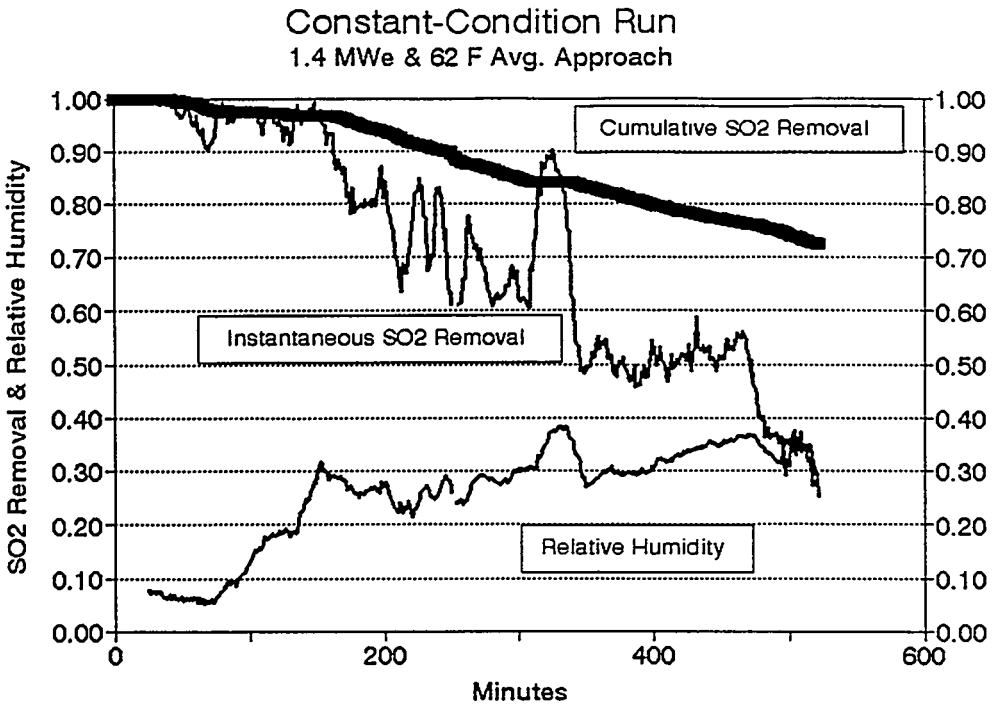


Figure 5.2 SO_2 performance and relative humidity versus time with a static bed.

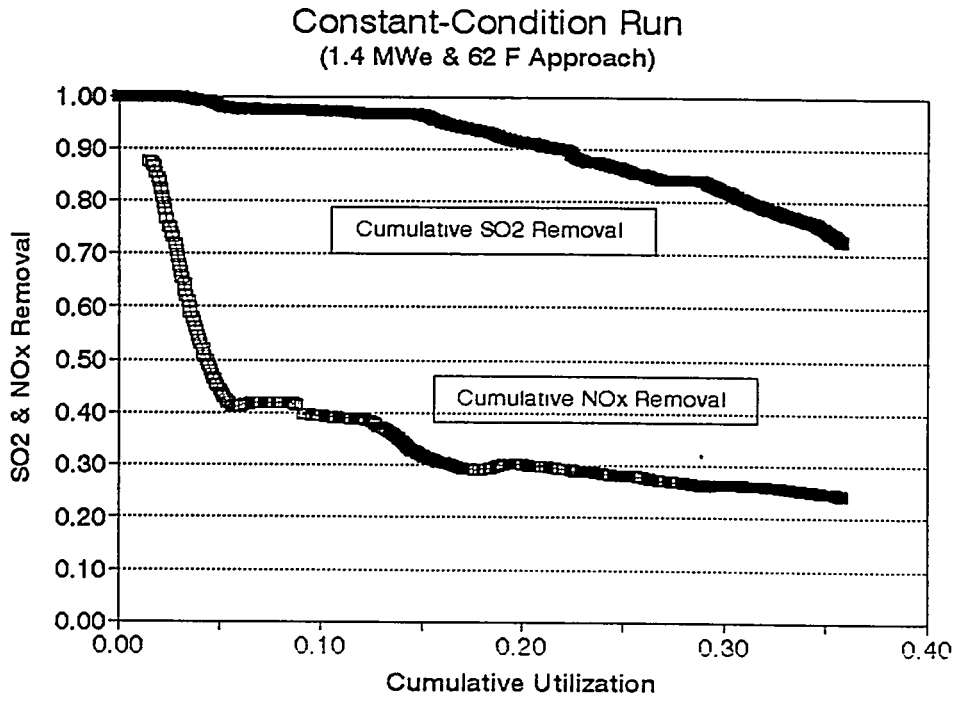


Figure 5.3 Cumulative performance curves derived for moving-bed operation.

5.1 Flue Gas Temperature and Relative Humidity

In earlier work, perhaps the most important parameters affecting sorbent performance were observed to be flue-gas temperature and relative humidity. The relative humidity of a gas, a relative measure of its moisture content, is frequently expressed as how close it is to its adiabatic saturation point, its dew point. This "approach to saturation," measured in degrees Fahrenheit, can be represented by the difference between the wet-bulb and dry-bulb temperatures of the gas. In past research studies, better performance was generally identified with lower gas temperatures and lower, closer approaches to saturation.

Flue gas temperature and moisture level proved easy to control. The temperature of the flue gas could be decreased by introducing humidification water. Simultaneously, the flue gas moisture level was increased by the humidification water additions, and the approach to adiabatic saturation decreased.

5.1.1 SO_2 Removal

During the initial stages of static bed run, when SO_2 removals were high and no part of the radial panel was near breakthrough, the sorbent beds proved relatively insensitive to the approach temperature. As shown in Figure 5.4, 90+% SO_2 removals were achieved over an approach temperature range of 80° to 40°F.

In long-term runs, however, when the beds were at higher levels of utilization, SO_2 performance was significantly effected by the relative moisture of the gas. With data from multiple runs, Figure 5.5 shows how the degree of sorbent utilization achieved at high removal rates is affected by the approach temperature. The sensitivity of SO_2 removal to relative humidity can also be seen in Figure 5.1. Note how the patterns of small changes in the relative humidity directly correspond to small changes in the SO_2 removal rate. In order to achieve high sorbent utilizations with the magnesia-vermiculite sorbents in the panel-bed, it can be concluded that, as with lime-based sorbents, an approach temperature of less than 60°F is necessary, and preferably it is 40°F or less.

Because there was only twenty feet of duct between the humidification sprays and the sorber for the injected water to evaporate, we did not test below a 40°F approach temperature. We were afraid of having liquid water in the sorber or sorbent bed. The trend, however, is clear that much higher SO_2 performance could be expected at closer approaches, as others have shown. During the many hours of operation at approaches of 60°F to 40°F, the bed stayed dry and flowed easily. In one early run, we had a single occurrence where changing utility conditions caused the approach temperature to dip and a part of the bed evidently saw liquid moisture, which caused a hardened sorbent clump to form. Staying at flue gas exit temperatures above 160°F, however, we saw no condensation or sorbent-flow problems during the program.

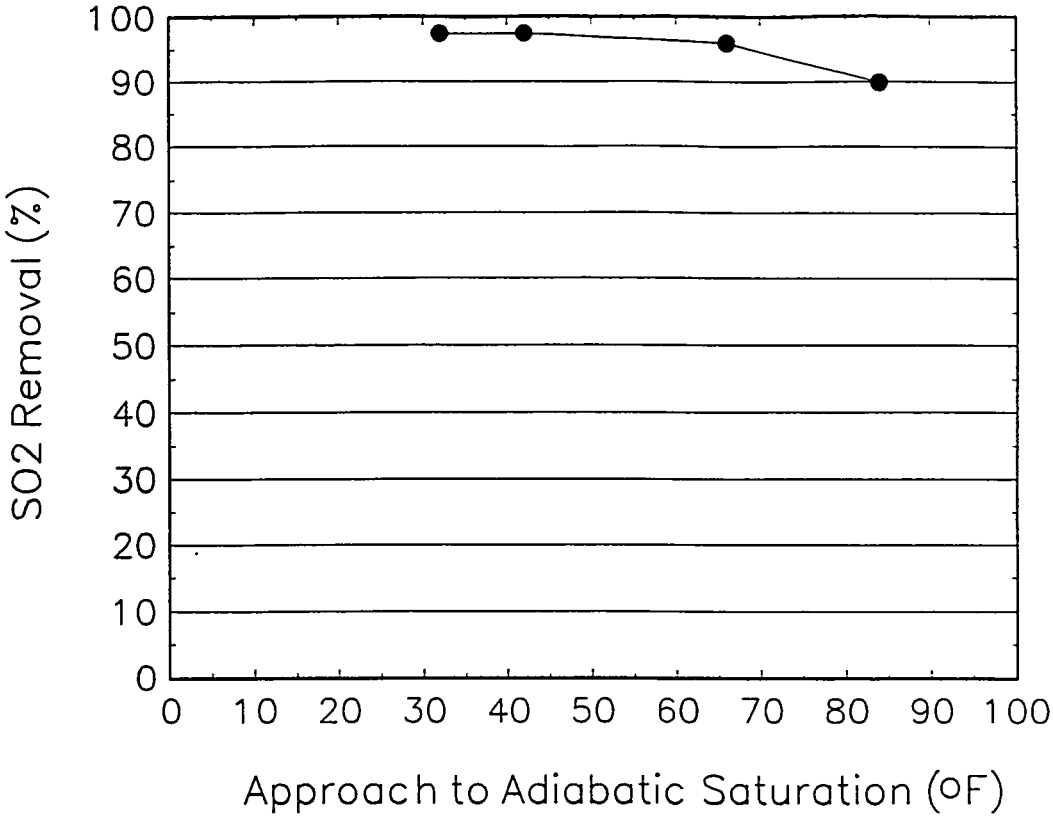


Figure 5.4 SO_2 removal versus approach early in a run.

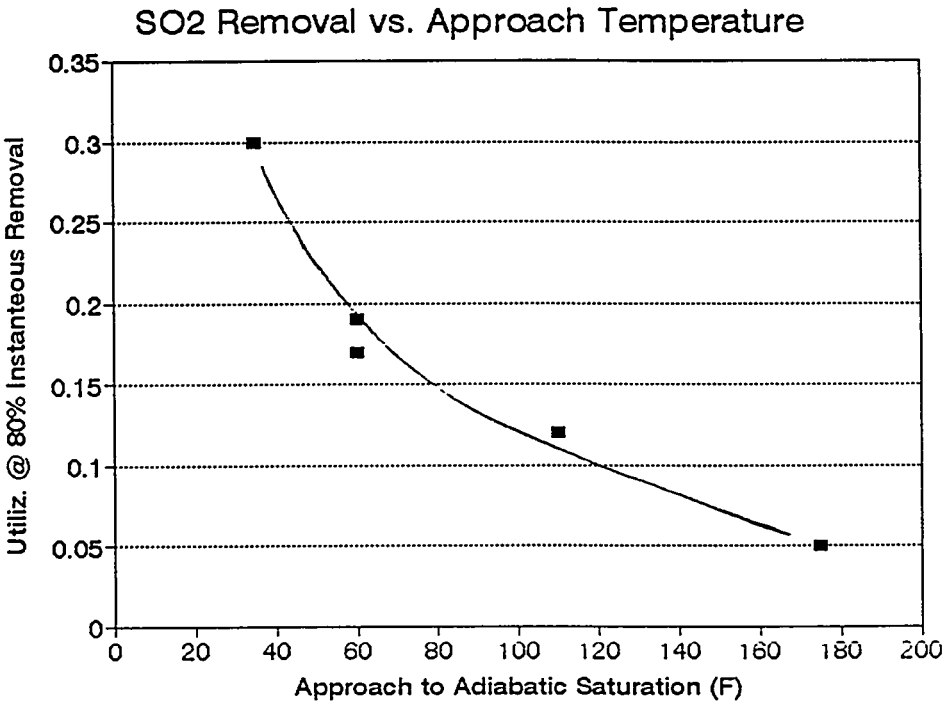


Figure 5.5 SO_2 performance versus approach temperature.

5.1.2 NOx Removal

One potential advantage of the magnesia-vermiculite sorbents is that they remove a not-insignificant amount of NOx simultaneously with the SO_2. NOx removal performance was also observed to vary with flue gas temperatures and moisture level, although differently than did SO_2 removal.

Optimum long-term NOx removal of 40% was achieved at a flue gas temperature of about 180°F, or a 60°F approach. See Figure 5.6. NOx removal was still relatively high at higher temperatures, averaging 25% removal at 275°F. A discontinuity seemed to occur between 180°F and 160°F. At the lowest temperatures and closer approaches that favored maximum SO_2 utilization, continuous NOx removal dipped to about 10%. These removal rates are for runs at the designed sorber gas velocities and residence times; if the flow rate was cut back to 1000 scfm, slightly over 50% NOx removal could be achieved at 230°F.

Unfortunately, the NOx and SO_2 removal mechanisms behaved in an inverse manner with respect to relative humidity. This can be seen in Figure 5.7, the plot of a single run. The instantaneous SO_2 and NOx removal curves moved in clear inverse, mirror-like fashion with respect to small changes in flue gas temperature and relative humidity. Consequently, optimizing the sorber conditions to improve NOx removal degraded SO_2 performance and visa versa.

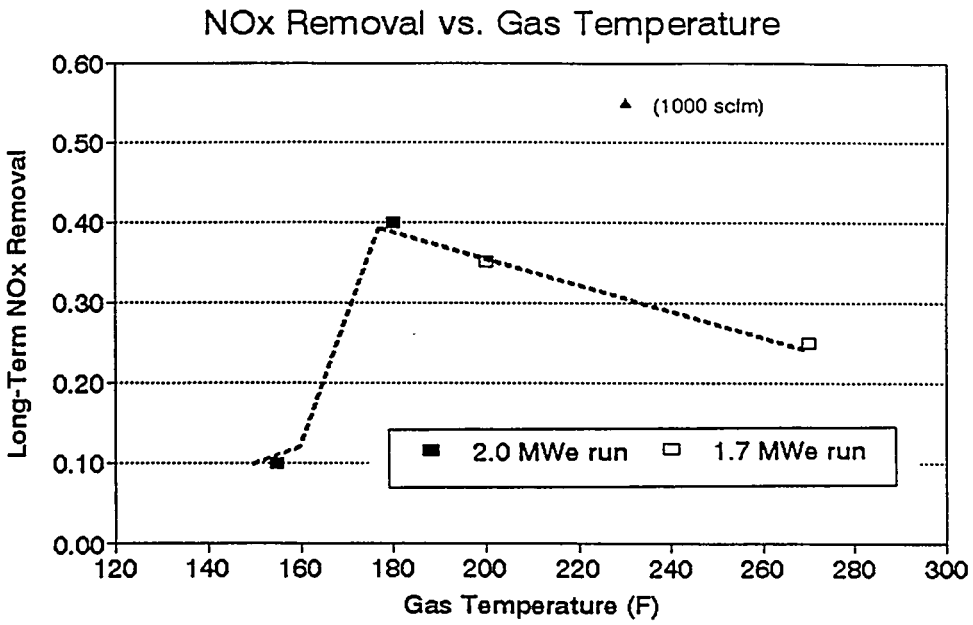


Figure 5.6 NOx removal versus gas temperature.

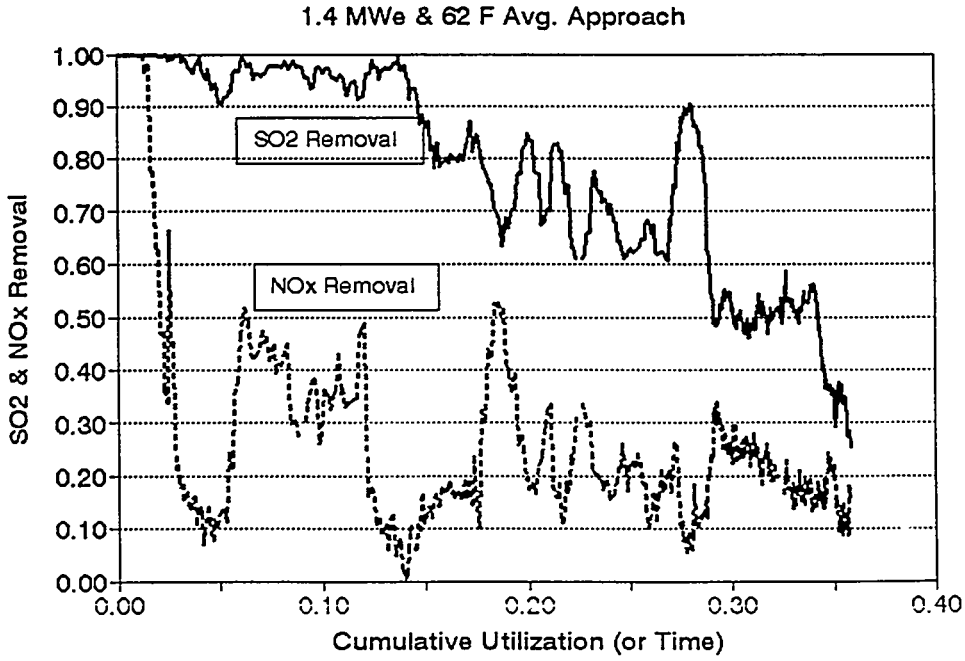


Figure 5.7 Contrast of instantaneous SO_2 and NOx performance.

5.2 Gas Flow

Gas flow rate and velocity proved simple to control. The flow rate was a function of the operating level of the power plant, the gate opening to the pilot plant duct, and the speed of the pilot fan, when it operated. We found that operation of the pilot fan proved unnecessary, as Ohio Edison's fan provided adequate draft. The gas velocity was controlled by adjusting the damper gates that allowed gas into and out of the slip-stream system. The operating level of the power plant influenced the velocities that were possible. Higher pilot plant velocities were achievable when the power plant was operating at high levels.

The capacity of the pilot unit is directly related to the flue gas space velocity and face velocity. The space velocity is the relative volumetric flow of the gas in relation to the volume of the sorbent bed, which can be expressed in bed-volumes-per-hour or per-second. The superficial face velocity of interest is the linear speed of the gas perpendicular to the sorbent bed as it passes through the bed, which can be expressed in terms of actual-feet-per-second at the panel inside or outside surface. The sorber was designed for a capacity of 2-MWe of gas, equivalent to 4600 scfm, or about 6600 acfm at 300F. At a bed temperature of 170F, this translates to a space velocity of 7,500 actual bed-volumes-per-hour and a superficial face velocity at the inside panel of about 3.0 actual feet-per-second. Most tests were run in the designed range of 1.5 to 2.0-MWe.

The flue gas velocity can affect MagSorbent SO_2 and NOx removal performance in two important ways. The first is by affecting the bed residence time. If the gas passes too rapidly through the sorbent bed, there is not enough reaction time for good acid-gas removal. All other things being equal, increasing the flue gas velocity proportionally increases the gas flow, lowering the sorbent reaction time available.

If the gas velocity is too high it can deleteriously affect performance a second way too: by creating channels through the sorbent. Because of the radial nature of the sorbent bed, the velocity of the gases decreased as they passed through the bed. The inside surface area of the bed was 31.4 sq ft; the outside surface area was 56.5 sq ft. At 2-MWe of gas flow, then, the panel gas velocities are 1.6 fps (entering) and 3.0 (leaving). In cold-flow model tests, it was observed that the sorbent begins to fluidize at velocities above 3 fps. Therefore, with gas flows above 2-MWe (4600 scfm, or 6600 acfm at 300F), one can expect some fluidized sorbent at the entrance surface of the beds and channelling to occur. With channelling, high amounts of gas pass through open channels in the bed and see no sorbent, resulting in low net removal rates. Non-uniform velocity distributions would exacerbate this problem.

The gas flow rate is also important by affecting the pressure drop across the sorbent panel bed. Increasing the velocity of the flue gas results in increased pressure drop. High pressure drops may mean additional fan power may be required to draw the flue gas through the sorbent bed.

5.2.1 Gas Velocity and SO_2 Performance

It was observed that during the initial hour of sorbent runs, when the sorbent bed was essentially fresh, changes in flue gas velocity did not markedly affect SO_2 removal. However, once the sorbent bed became partially saturated, this was not the case and changing the flue gas velocity greatly affected SO_2-removal efficiency.

The run described in Figure 5.8 on air-regenerated material provides an example. At the beginning of this test, when the system was operated at about 1.7-MWe, the panel was removing about 95% SO_2. The gates were then opened to allow 2.8-MWe of gas to the sorber. This raised the superficial gas velocity at the panel inside surface to an average of 4.2 fps. The SO_2 removal rate dropped to about 40%, probably due to "holes" in the bed and channelling of the gas. The gas volume was then raised to 4.0-MWe (or 6 fps)--double the sorber's design flow--and the SO_2 removal rate dropped even further, to 20%. But when the gas flow was dropped back to 1.7-MWe, the SO_2 removal rate jumped back up to 95%.

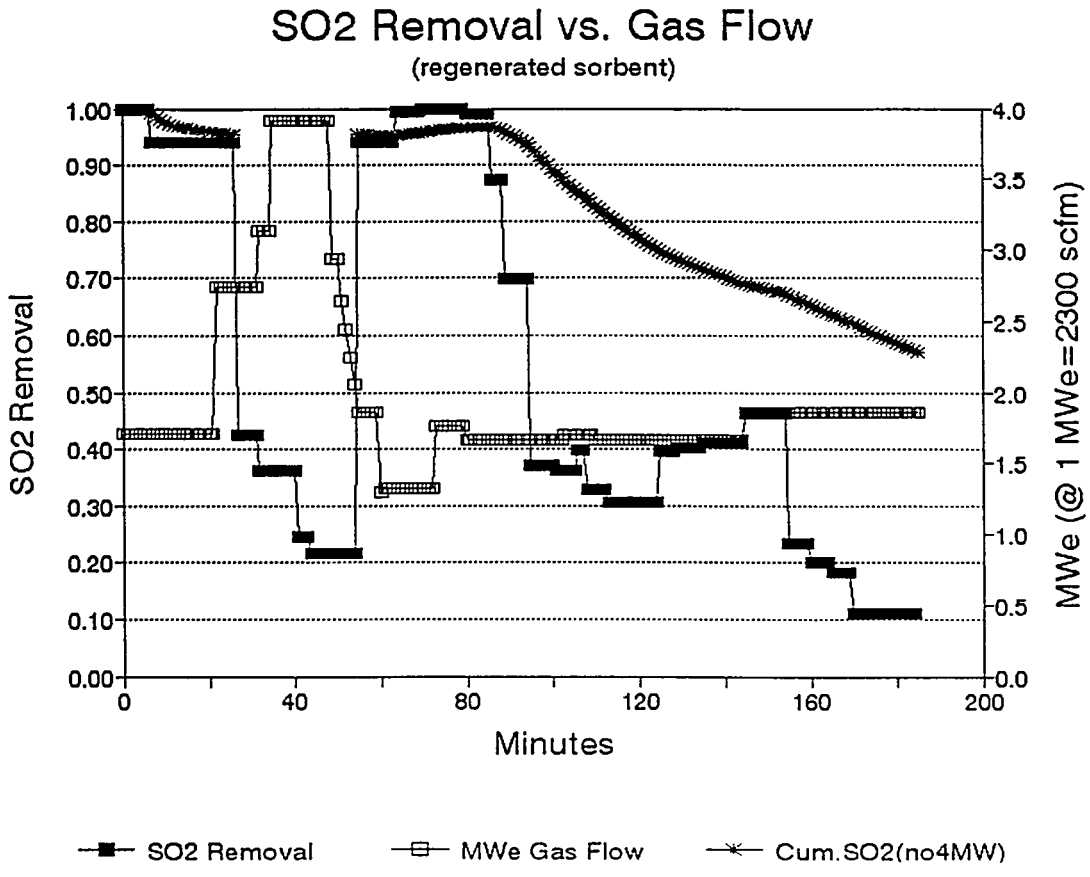


Figure 5.8 SO_2 removal versus gas flow.

5.2.2 Pressure Drop

In pilot-plant tests, the pressure drops across the radial panel bed for the MgO-vermiculite sorbents were approximately the same as those observed in cold flow model tests in the laboratory. See Figure 5.9 for pressure drop as a function of the capacity of the unit for the 50/50 MgO-vermiculite sorbent.

For the same flue gas velocity, however, the pressure drop across the 12-inch panel bed varied with the bed composition and with the number of times the sorbent was regenerated. Pressure drops measured for different bed materials with an approximately 2 fps (1.5 MWe) flue gas are shown in Figure 5.10. The pressure drop for a bed of fresh MgO-vermiculite sorbent was about the same as that for a bed of fresh MgO-perlite. On the other hand, beds of regenerated sorbent demonstrated somewhat larger pressure drops than fresh sorbent, and the pressure drop appeared to increase with increased number of regenerations, at least through two regenerations. Increased levels of fines present in the regenerated sorbents are believed responsible for the increased pressure drops.

Overall, the low pressure drops across the panel were a pleasant surprise. With louvers and a one-foot-thick panel, we anticipate a larger unit to exhibit sorber pressure drops in the range of 4 to 6 inches WG.

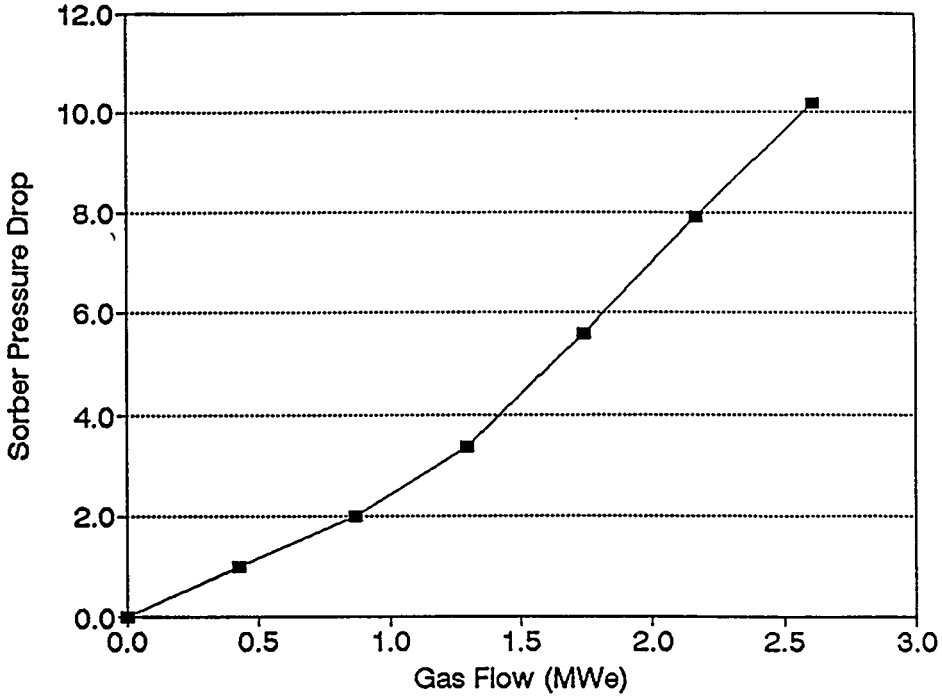


Figure 5.9 Sorber pressure drop as a function of flue-gas flow.

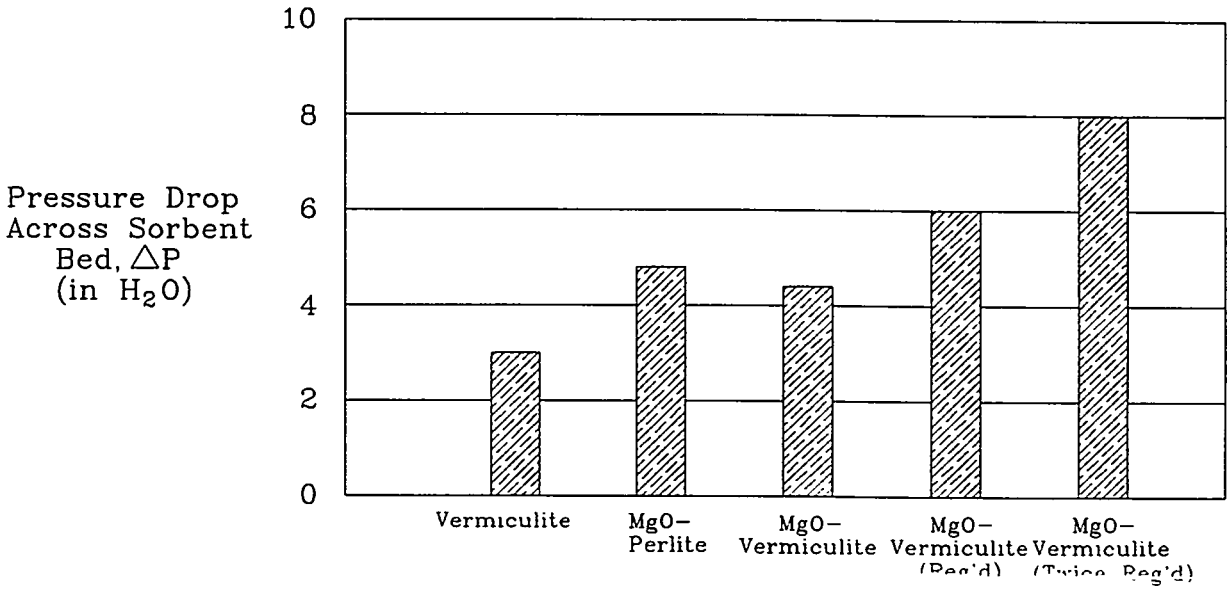


Figure 5.10 Relative pressure drop of different sorbents at approx. 1.5 MWe.

5.2.3 Radial Gas-Flow Distribution

A major problem was discovered when gas velocity profiles were measured along the height and circumference of the sorber during runs. It was expected that gas flow through the sorbent bed would be relatively uniform. However, this proved not to be the case. A typical distribution of gas flows through the bed is shown in Figure 5.11. Radially, gases flowed preferentially through east and west surfaces of the bed. The sorber exit duct was located on the west side of the sorber, so preferential flow here might be expected. However, preferred flow also occurred in the opposite direction, at the back of the sorber, which was initially counterintuitive. The distribution of flows did not vary significantly with the level of overall flow, as can be seen in Figure 5.13. High, medium, and low gas flows resulted in similar flow patterns.

Gas flows also varied from the top to the bottom of the sorbent panel bed. Generally, gas flows were the highest at center height and were lowest at the top of the bed. Irregular flow along the height of the bed is not as serious a problem as irregular flow along the circumference of the bed, because in a moving bed the sorbent bed moves continuously downward and the SO_2 mass-flows, and consequent sorbent utilizations, average out.

Radially-irregular flow of flue gas through the sorbent bed, however, will result in a premature SO_2 breakthrough, especially if high net SO_2 removal rates (e.g. 90%) are required. With premature breakthroughs, poor sorbent utilization rates can be expected. Those parts of the bed that see high gas flows saturate much quicker than the others and begin leaving high amounts of SO_2 through, while the other bed sections are underutilized. Figure 5.12 shows the cumulative utilization curve for a typical 60/40 MagSorbent test run as well as a curve for what one might expect if the flue gases passed uniformly through the bed, resulting in a sharper breakthrough. If high SO2 removal is required, the difference in utilizations at 90% removal of these curves greatly affects the economics of the new technology.

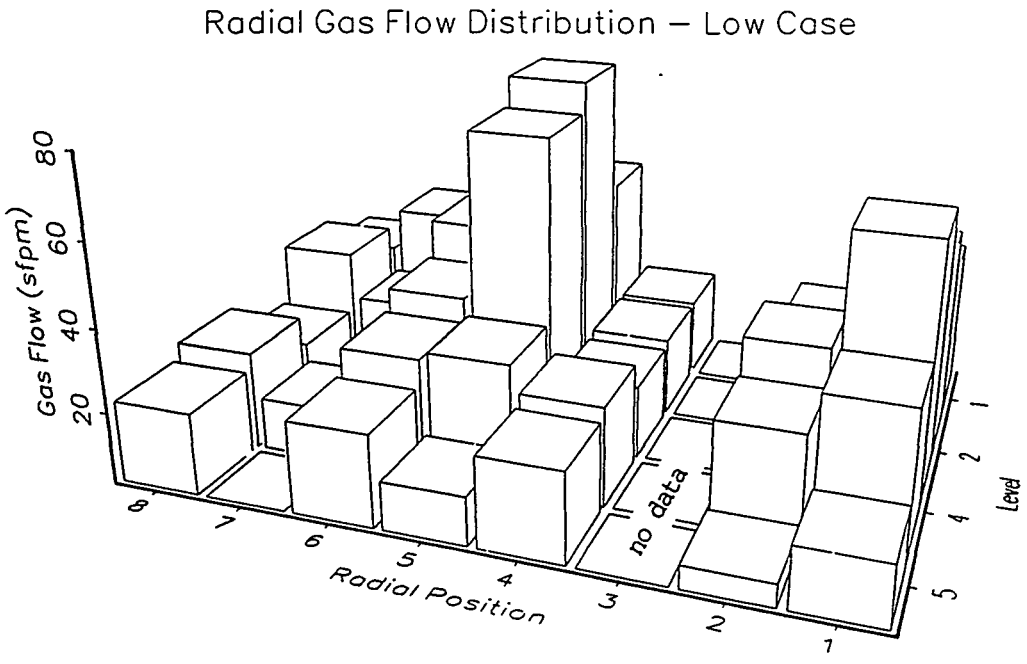


Figure 5.11 Flue gas distribution through the radial bed.

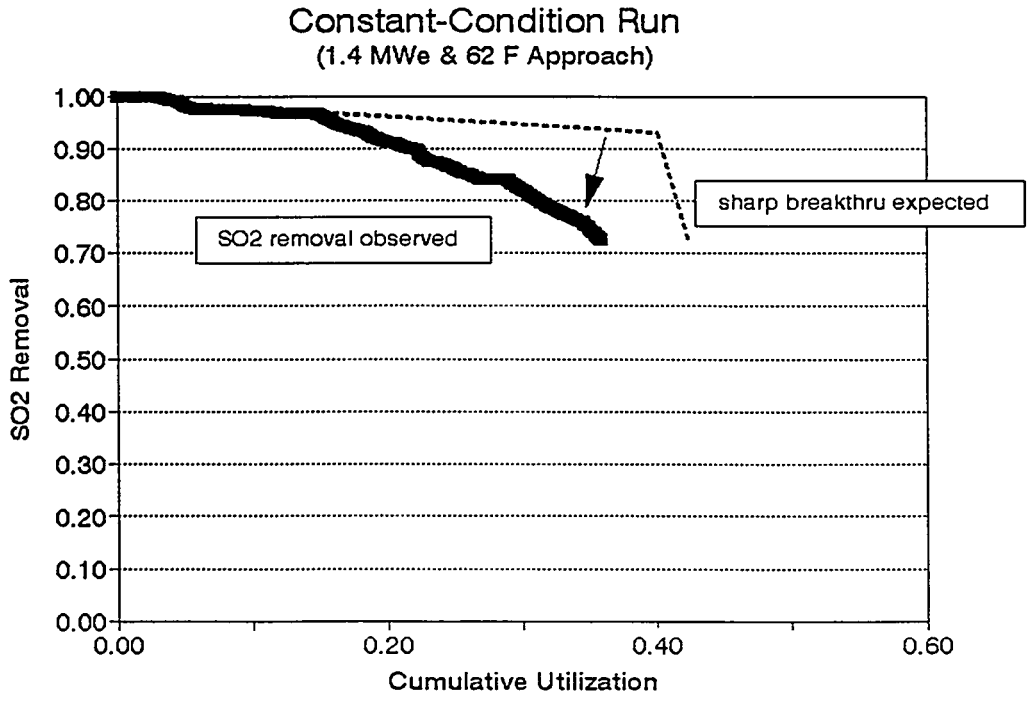


Figure 5.12 Decreased high-end SO_2 performance due to flow maldistribution.

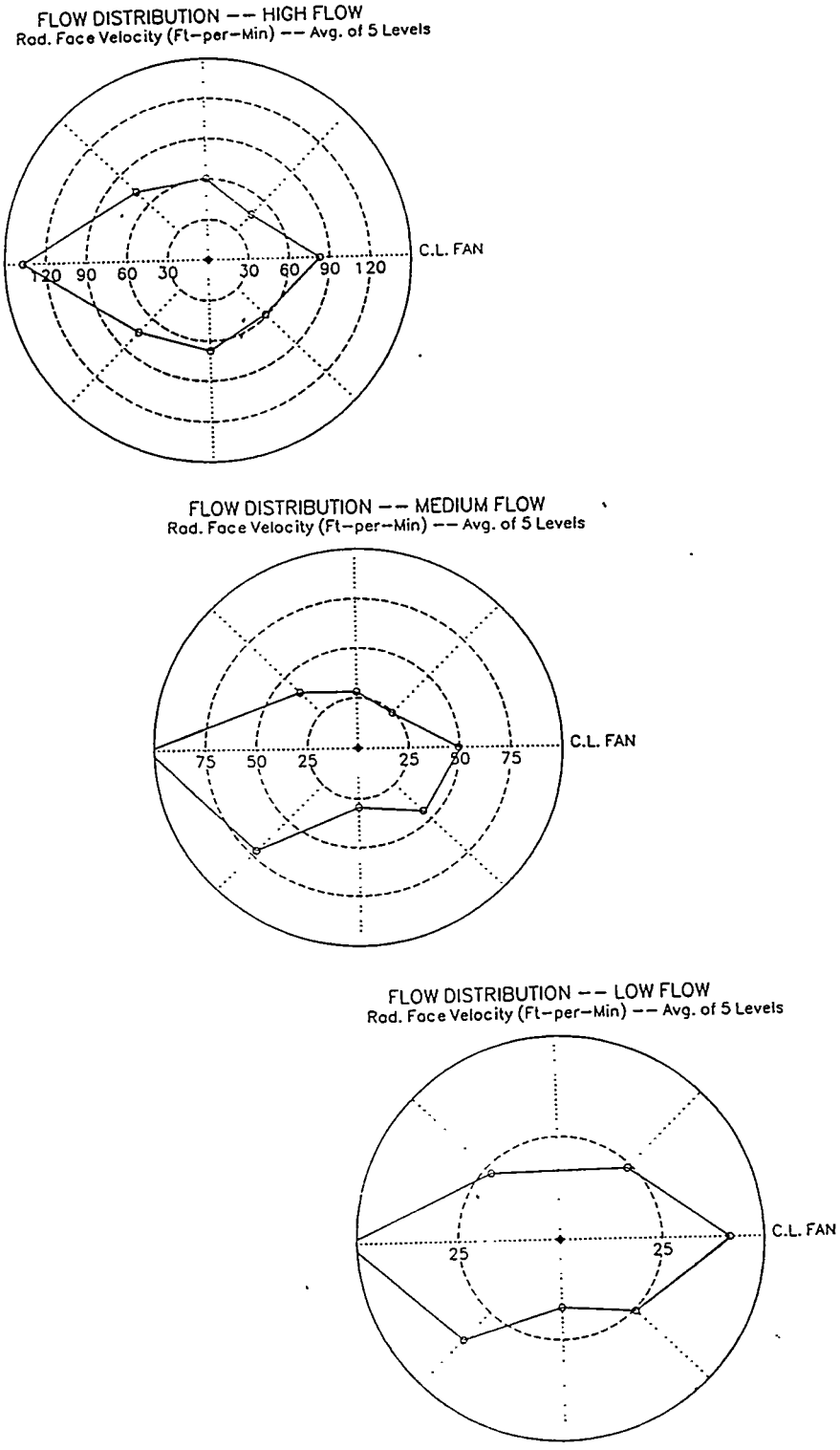


Figure 5.13 Flow maldistribution at different flow rates.

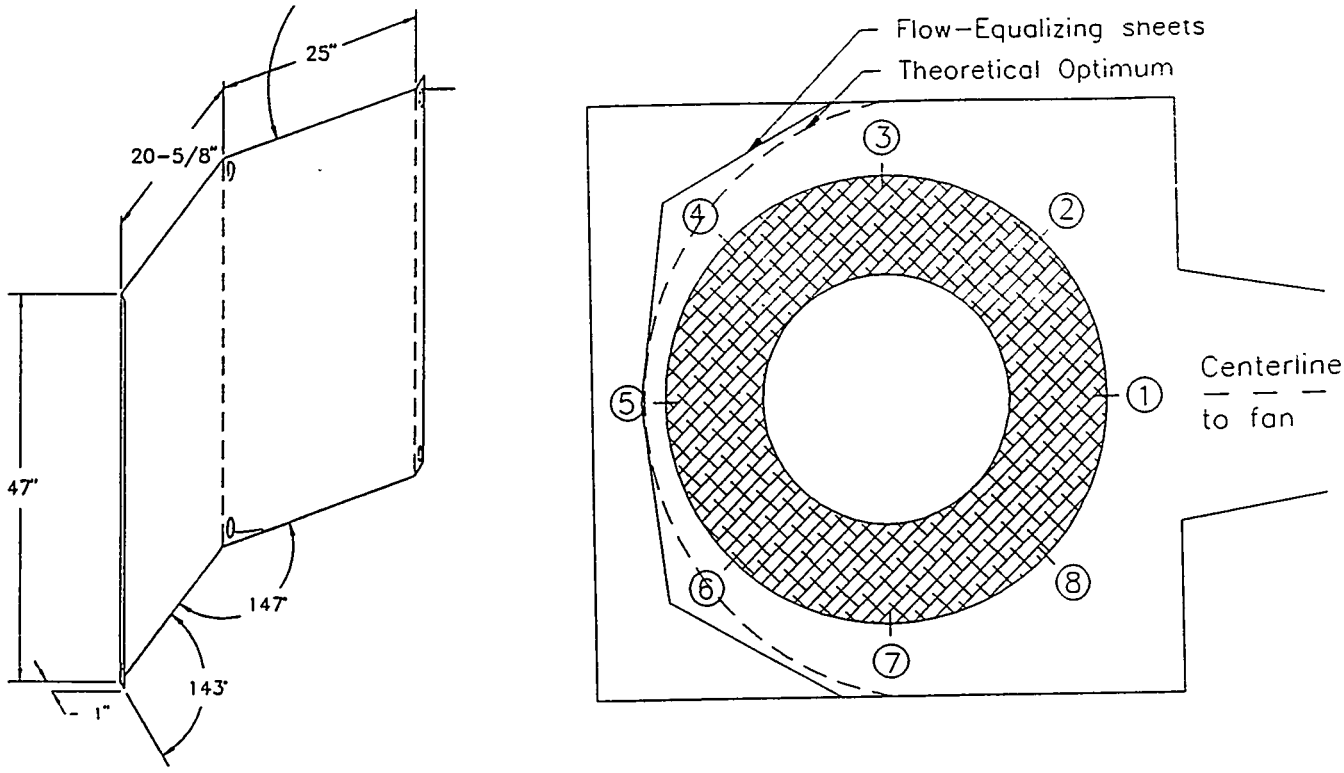


Figure 5.14 Gas diverter plates and their placement in the sorber.

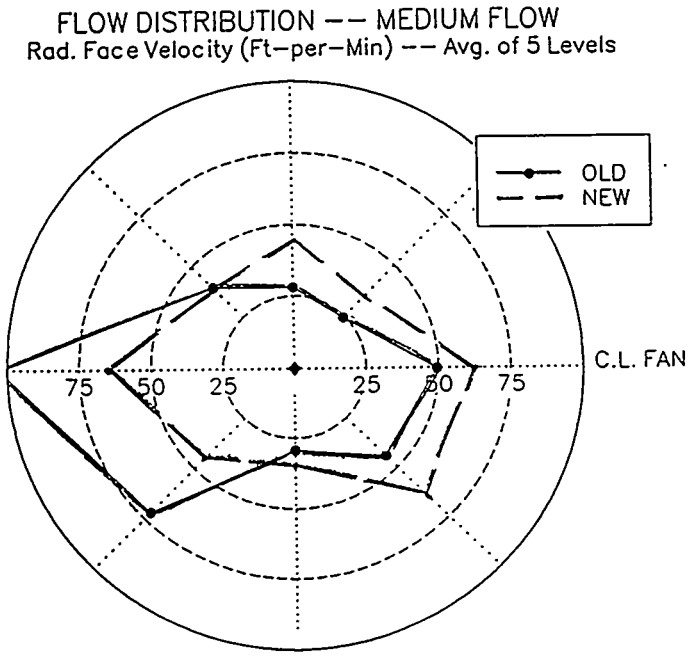


Figure 5.15 Change in flow pattern with gas diverter plates.

In efforts to solve the problem of irregular flow around the circumference of the sorber, a mathematical study of flow distributions was carried out. A way to model the gas flow in the sorber was developed. It was discovered that the highly-uneven radial gas flow distribution was a result of the particular outside geometry chosen for the sorber. Because all of the gas exited to the fan on one side only, all of the gas passing through the back half of the sorber had to crowd through two nine-inch passes on the sides. These squeezed sections caused much less gas to pass radially through the bed in these areas, perpendicular to the exiting flows.

Consequently, a series of plate restrictions were designed to restrict gas flows in the rear of the sorber, where excess gas and sulfur flows were most pronounced. Metal plates were then fabricated and installed, as shown in Figure 5.14. With the new plates, the flow distribution problem was lessened, as shown in Figure 5.15, but not totally solved. To cure the irregular radial flow problem, the sorber would have to be redesigned to allow flue gas to be removed more uniformly around the panel, exiting the bottom radially, for example, rather than on just one side. Because of time and budget constraints, such a change could not be made during the project. However, one of the objectives of the project was to discover such design factors and with the new modelling ability, we now feel comfortable that the sorber chamber can be designed to provide more even flows, and so much higher SO_2 utilization performance.

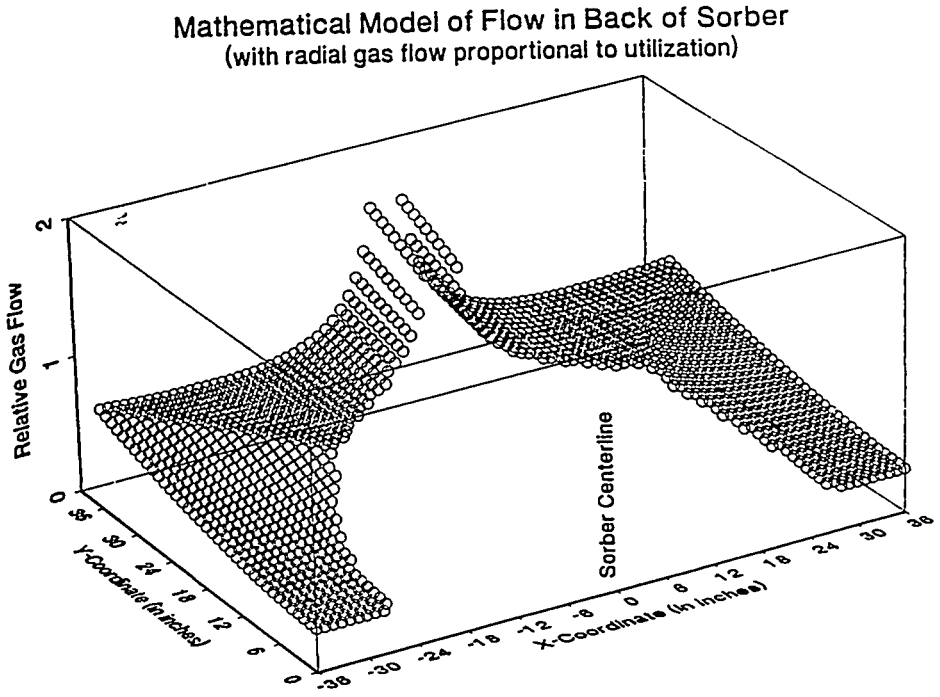


Figure 5.16 Plot of mathematical model of sorbent flow.

5.3 Sorbent Composition

Different sorbent compositions were examined in parametric studies. These included:

A. 50/50 MgO-vermiculite (higher-grade MgO from Elastomag)
B. 50/50 MgO-vermiculite (lower-grade MgO from Premier)
C. 45/55 MgO-vermiculite (Premier)
D. 40/60 MgO-perlite

In preparing the two 50/50 MgO-vermiculite materials, the same weight proportions of MgO and vermiculite were used, but because the Elastomag MgO was significantly purer than the Premier MgO, the two materials had different overall compositions. For simplicity sake, all sorbent utilizations were calculated on an as-received basis, assuming that the magnesiums were 100% pure. However, chemical analysis of starting material and of freshly prepared sorbents showed that the actual compositions of the above materials were:

A. 49.5 wt% MgO–50.0 wt% vermiculite–0.5 wt% Inerts ($MgCO_3$, $CaCO_3$, etc.)
B. 40.2 wt% MgO–50.0 wt% vermiculite–9.8 wt% Inerts
C. 37.2 wt% MgO–55.0 wt% vermiculite–12.8 wt% Inerts
D. 32.6 wt% MgO–60.0 wt% perlite–7.4 wt% Inerts

Slight differences in SO_2 and NOx removal performance were noted for the different material compositions. The 50/50 MgO-vermiculite sorbent with Elastomag MgO performed the best, on both an absolute and a relative basis. The Premier MgO performed almost as well, especially on a relative basis, where its lower purity and lower cost are factored in. There was little difference in the performance of the 50/50 and 45/50 sorbent runs, making the higher-loaded 50/50 formula preferable on economic grounds.

Because granular perlite accepts a somewhat lower loading than vermiculite, the perlite sorbent was made to only a nominal 40 wt% MgO. Its SO2 performance was a little less than the vermiculite runs, as can be seen in Figure 5.17, but acceptable in light of the maldistributed gas flow. Its NOx performance, however, was lower. The lowest performing material was a batch of regenerated MgO-vermiculite sorbent that was pre-hydrated with water, turning some of the MgO to Mg(OH)2.

In the general handling of the sorbents, and in net particulates capture, significant differences were seen. The MgO-perlite material, by far, performed poorest in this area. The sorbents were conveyed to the sorber pneumatically. During pneumatic conveying, an unsatisfactory portion of the MgO-perlite sorbent degraded, as the individual particles were propelled along the transfer duct and into the storage hopper and into the sorber itself. This resulted in the creation of more than 5 wt% percent fines. The three MgO-vermiculite materials, on the other hand, performed satisfactorily in handling, with the significantly-smaller number of fines generated in handling being in about direct proportion to the percentages of MgO in the sorbents.

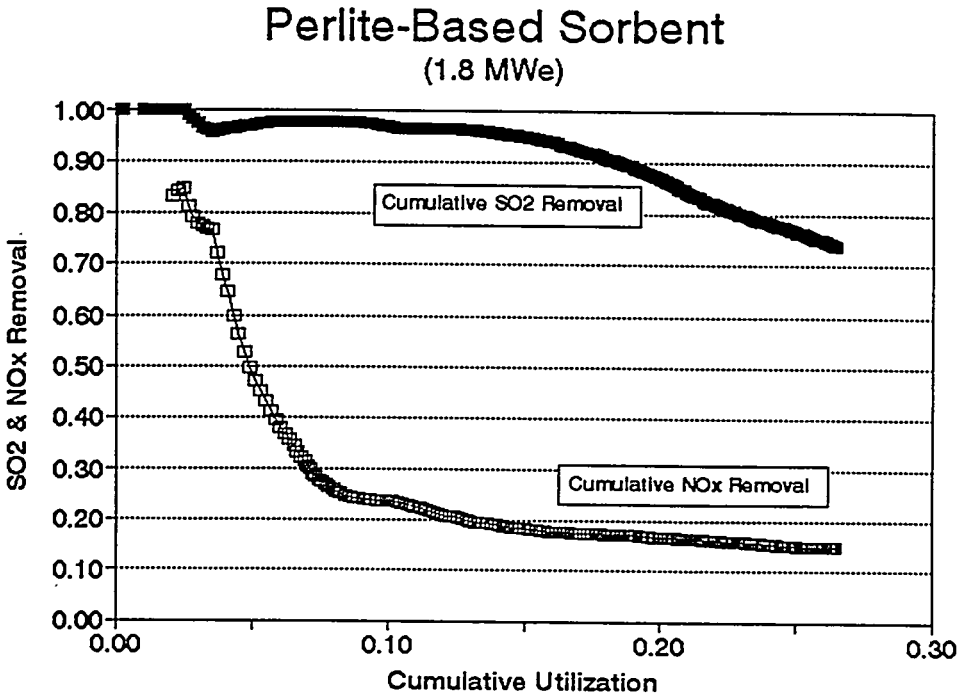


Figure 5.17 Perlite sorbent run.

5.4 Design Parameters

5.4.1 Panel Design

The major sorber design variable examined in parametric studies was the nature of the materials employed in supporting the sorbent beds. Three different bed-materials' support schemes were evaluated. They were:

1. screens;
2. microscreens; and
3. louvers.

In all past work, steel screens were employed to support sorbent panel beds. Generally speaking, these screens performed satisfactorily, as long as they were constructed of stainless steel and possessed a mesh size small enough to hold back the smallest sorbent particles. A common size employed was 10 mesh. Some disadvantages with these screens, however, included the passage of some fines through the screens, the lack of rigidity over long spans, and relatively high pressure drops at the back screen surfaces.

Microscreens are a new product that was introduced recently by Michigan Dynamics (now owned by Fuji Filter Manufacturing Company). They are constructed in two or three layers that are bonded together, with one layer having a very small pore size. Although the individual pore size in a microscreen is very small, there is significant open area. The second and/or third layer provides support and rigidity to the structure. The pore size of microscreens is so small that most fines will not pass through them.

Louvers are a series of parallel plates, usually constructed of metal. The louvers are normally installed at a small vertical angle with small spaces between them. As such, they are able to hold back material while allowing gas to pass through, as long as the bed material does not become fluidized. A number of commercial facilities employ louvers to hold beds of particulate materials. Advantages of louvers include their rigidity and robustness.

Type 304 stainless steel screens were evaluated initially. After about a dozen start-up and parametric runs, the screens were examined and heavy corrosion was noted. After another several runs, the screens failed in two locations and repairs were made.

Near the end of parametric testing, the outside stainless steel screens were replaced with microscreens. The stainless steel screens at that point were in poor shape. Several runs were then performed with the microscreens. The microscreens were found to support the sorbent bed well and to prevent or reduce fines from entering the exiting flue gas, but to add increased pressure drop to the overall system. Very fine particles were observed to fill the pores of the microscreen as sorbent was processed. Clogging became an increasing problem with time. Gas flow was retarded and pressure drops exceeding 15 in W.G. were observed. The screens could be cleaned by hand, but eventually clogging would reoccur. The microscreens, which were supposed to be of a corrosion-resistant steel showed some early signs of corrosion, although not as severe as the coarse screens.

Both the inside stainless steel screen and the outside microscreen were then replaced with stainless steel louvers, and parametric testing continued. The louvers performed surprisingly well. Particle blow-out through the outside louvers that was expected did not occur, although gas flows below 6000 ACFM (2-MWe) were maintained at all times. There was some particle blow-out through the inside louvers, where some fluidization of the bed is suspected. The louvers showed some signs of oxidation, but because the louvers were constructed of relatively heavy plate, the useful lifetime of a louvered installation would probably be long. As a safety precaution, a screen was placed over the outside louver. After several runs, no sorbent particles, except a few fines, were found in the space between the louver and the screen.

5.4.2 Regeneration

The function of the regenerator is to drive off from the sorbents the sorbed SO_2 and NOx captured in the sorber and to restore the capturing properties to the sorbents. As mentioned earlier, the regenerator was designed to operate with an air environment or with a reducing gas (methane) environment. However, because it was found to be impossible to seal the regenerator vessel, methane environments were not used for safety reasons. Instead, it was decided to have methane regenerations performed by an outside contractor.

A series of experiments were performed to determine the optimum temperatures and exposure times needed to achieve satisfactory regeneration in air. Earlier research indicated that good regeneration could be attained in air at a temperature of 600°C with an exposure time of 15 minutes or longer.

These results were confirmed in pilot-plant regenerator tests, although an exposure time at temperature of no less than 20-30 minutes was found optimum. The slightly longer furnace residence time was found necessary because sorbent on the conveyor belt passing through the furnace had a maximum thickness of about 1.5 inches, which was slightly larger than was employed previously. A suitable flow rate of sorbent through the regenerator kiln was found to be about 4.0 cu ft per hr. This meant that for the continuous operation of the sorber and regenerator together, the system could be approximately balanced with the storage hoppers that were present in the system.

6. CYCLING AND LONG-TERM RUNS

Ohio Edison's Edgewater power plant was not operating the majority of the time during the last eight months of the project because of low power demand. It was during this time that the cycling runs and long-term run were planned. Because of the irregular operating schedule, it became necessary to plan test runs well in advance and to be ready to perform the runs immediately upon learning that the plant was operating. Also, it became expedient to combine test runs so that some of the long-term and cycling run objectives could be accomplished at the same time.

Initially, it was planned to test regenerations in both oxidizing (air) and reducing (methane) environments. In a number of early runs at Edgewater, the sorbents were regenerated in air before being resorbed. The regenerator circuit was then installed with methane injection, sulfur condensors, and an after-burner for methane regeneration. However, in shaking down the regenerator for methane, we discovered that the equipment selected was problematical for this purpose. With our particular design, small amounts of oxygen could conceivable enter the regenerator and create a potentially dangerous situation. After consultations with natural gas engineers at the East Ohio Gas Company, as well as consultations with Ohio Edison and OCDO, it was decided that it was too risky to attempt methane regeneration with the existing equipment. While the probability of an accident was very small, the potential magnitude of any accident could have been significant. For safety reasons, then, it was decided to only regenerate at Edgewater in air and to test regeneration in methane at an outside facility.

Further, while the project was in this stage, the decision was made by the Ohio Edison Company to close down the entire Edgewater power plant. This further limited our options on the last runs.

Consequently, to achieve the project's cycling and long-term objectives, the following schedule was adopted:

1. A Continuous Run of 40-hours, during which time sorbent was continuously cycled through the sorber and regenerator about three times, where regenerations were performed in air.

2. Additional Cycling Runs consisting of an outside regeneration in methane, a fourth resorption, a regeneration in air, and a fifth sorption, with the sorption and regeneration steps performed on alternating days.

3. Additional cycling of these materials in smaller-scale laboratory runs, where the sorbent was again recycled through the sorption and regeneration steps, but where the regenerations were performed in a methane environment.

In the end, Sorbtech was able to accomplish nearly all of what was planned and the project was only marginally affected.

6.1 Continuous Run

The principal purposes of the 40-hour continuous run with regeneration in air were to test the continuous cycling of the various pilot-plant-system components and to collect life-cycle data on the sorbent. The continuous run was performed with lower-grade 45/55 MagSorbent. During the run, the sorbent was continuously recycled between the sorber and the regenerator. All regeneration was performed in air. SO_2 removal data collected during the run are summarized in Figure 6.1. The sorbent and regeneration flow are tracked in Figure 6.2. Observations and highlights of the test run included the following:

1. The run was carried out with no major equipment or operational problems. We did have problems with one gas sample line during the test, but the sorption and regeneration equipment performed as planned.

2. Start-up and subsequent shut-down of the equipment were simple and uneventful.

3. As in earlier runs, the SO_2 and NOx removals were initially high, greater than 90 percent, but then became somewhat less as the sorbent bed became saturated.

4. As expected, with the sorbent bed moving continuously downward, a near-equilibrium condition was achieved after several hours. SO_2 removal levels decrease somewhat, while NOx removal increased. At that time, SO_2 and NOx removals became fairly constant at specific approach temperatures.

5. After regenerated material cycled back to the sorber, the sorbent's SO_2 removal rate dropped to approximately 60 percent. The increasing amounts of $MgSO_4$ present in the recycled sorbents due to regenerating in air is believed to be primarily responsible for this lower removal rate, lower than expected. Effective regeneration in methane would be expected to break down this sulfate.

6. The approach temperature significantly affected the SO_2 removal rate. Closer approach temperatures gave more favorable removals. An approach temperature of approximately 40°F was maintained for most of the test.

7. The power plant varied its operating conditions widely during the 40-hour period. This resulted in wide swings in exhaust gas compositions and temperatures. The robust nature of the sorption system handled these swings well. The swings in power plant conditions, however, did affect the humidification system. It was necessary to change water flows to the humidification system at irregular intervals to maintain the desired approach temperatures.

8. Approximately three complete sorption-regeneration cycles with sorbent were performed during the 40-hour period.

9. Regenerating with excess air resulted in a regenerator exhaust gas containing about 1.0 percent SO_2. Regeneration in air also resulted in some sulfur retained in the sorbent, in the form of $MgSO_4$.

10. Sorbent attrition in recycling was not excessive. An average of about 3 to 4 wt% of the sorbent was reduced to particles <0.10 inch in size (defined as fines) during each cycle. This rate remained constant through three cycles, which were removed through screening. The fines made up of only a small fraction of material removed from the system during each cycle.

11. Sorbent flow through the sorber was nearly balanced with sorbent flow through the regenerator. The average sorbent flow rate through both units was approximately 4.5 cubic feet per hour.

12. The louver panel design with added screens performed very well. It supported the sorbent bed adequately and no particles of any significant size were observed in the sorber outside chamber after 40 hours of operation.

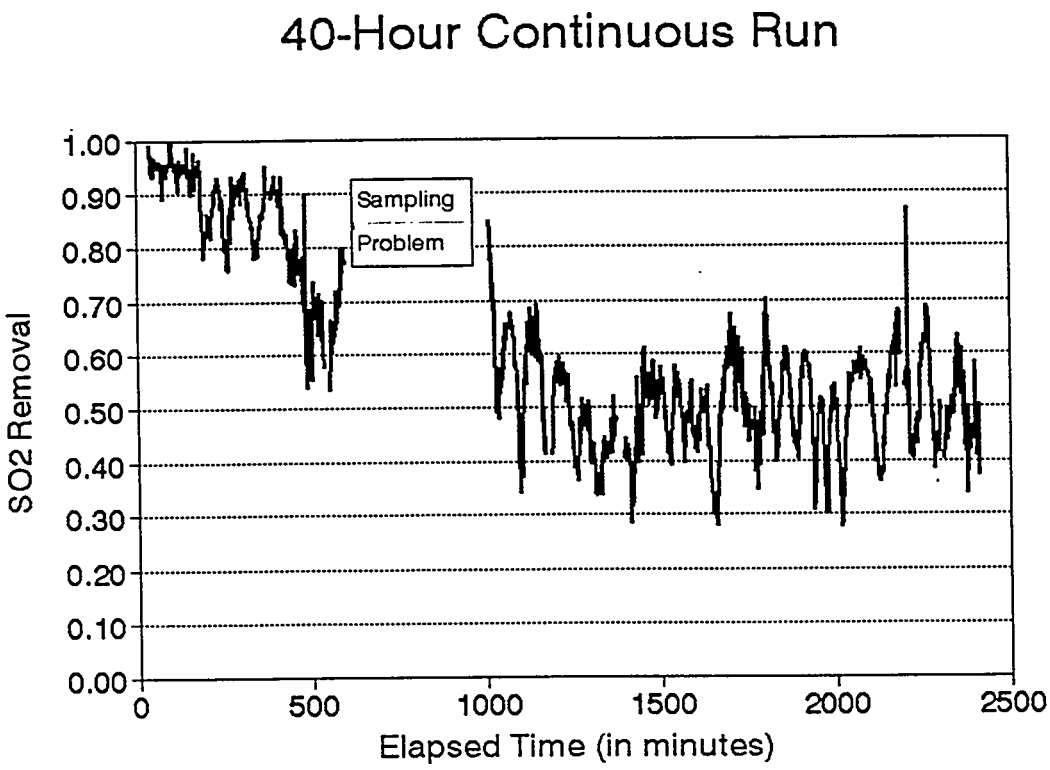


Figure 6.1 SO_2 removals observed during the long-term run with air regeneration.

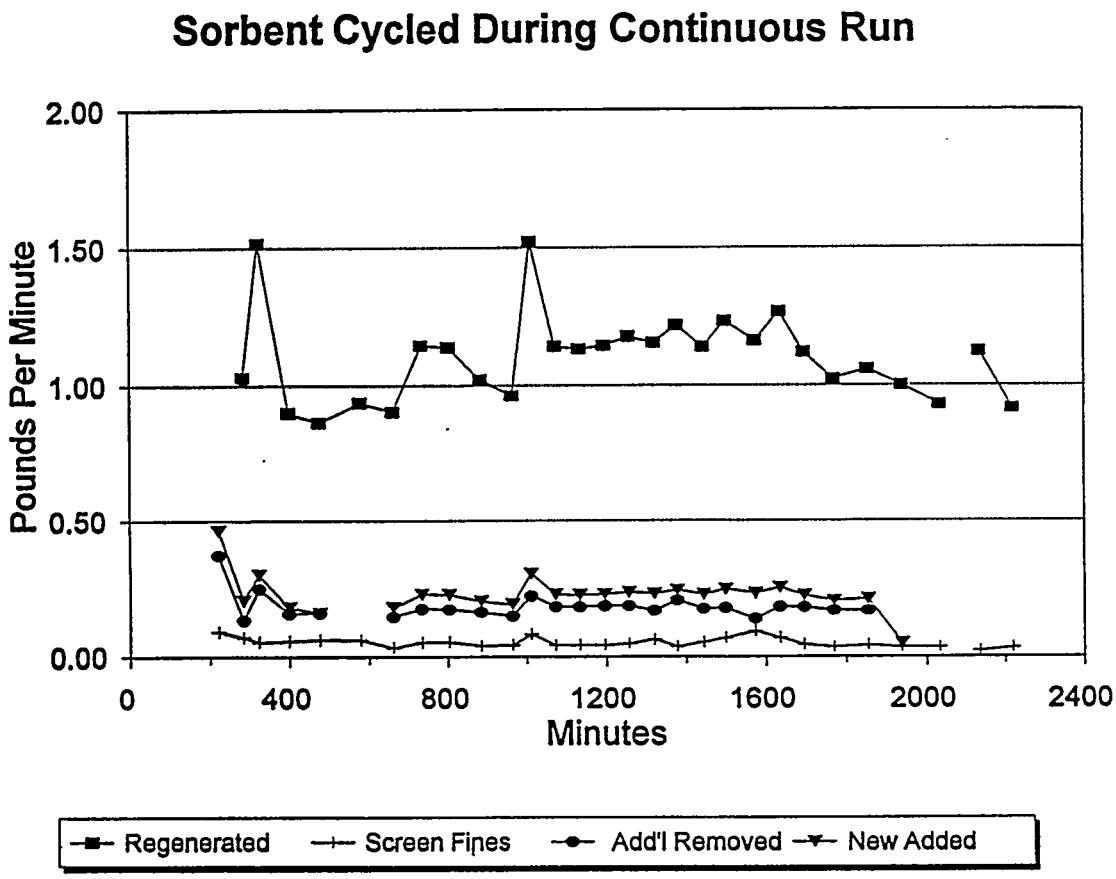


Figure 6.2 Sorbent flow during 40-hour run.

6.2 Further Cycling Studies

Having completed about two regenerations and three sorptions, spent sorbent from the 40-hour continuous run was delivered to Thermal Treatment Center, Inc. (TTCI) Cleveland, Ohio for regeneration in a reducing atmosphere of reformed methane (a combination of H_2 and CO). At TTCI, the sorbent was regenerated on a batch basis at approximately 700°C for about 30 minutes. Unfortunately, TTCI regenerated the sorbent in very thick beds and Sorbtech was uneasy as to the quality of this regeneration.

The sorbent was then returned to the Edgewater pilot plant and saturated in a fourth sorption cycle. This material was then regenerated again, in air, at Edgewater and sorbed for a fifth time. The two sorption cycles were about five hours long. The SO_2 and NOx removal data collected during these fourth and fifth cycles are shown in Figure 6.3.

The performance of the TTCI reduced-atmosphere regeneration run and the later air-regenerated sorption run were very similar. This conflicts with a good deal of data obtained before the project where methane regeneration more effectively broke down the magnesium sulfate fraction in the saturated sorbents and provided significantly improved performance in repeated sorptions. It suggests that TTCI's methane regeneration was not well performed.

Consequently, the multiply-regenerated materials were then extended through six additional sorption-regeneration cycles in the laboratory with the regeneration carefully performed with methane. The results of these runs are summarized in Table 6.1. These small-scale runs performed in the laboratory included no make-up fresh sorbent additions, as would be the case in a commercial facility. Yet it can be seen that the SO_2 removal performance and utilizations of these runs were indeed very high and remained so.

A comparison of the laboratory sorbent performance of the material regenerated in methane with that of fresh sorbent and cycled sorbent regenerated in air is given in Table 6.2. Clearly, the methane-regenerated material performs much better than the air-regenerated material, and more closely duplicates the performance of the fresh sorbent. Consequently, work is being pursued to more-effectively scale up the methane regeneration of the sorbents to larger-scaie equipment, which will be required to make the MagSorbent technology commercial.

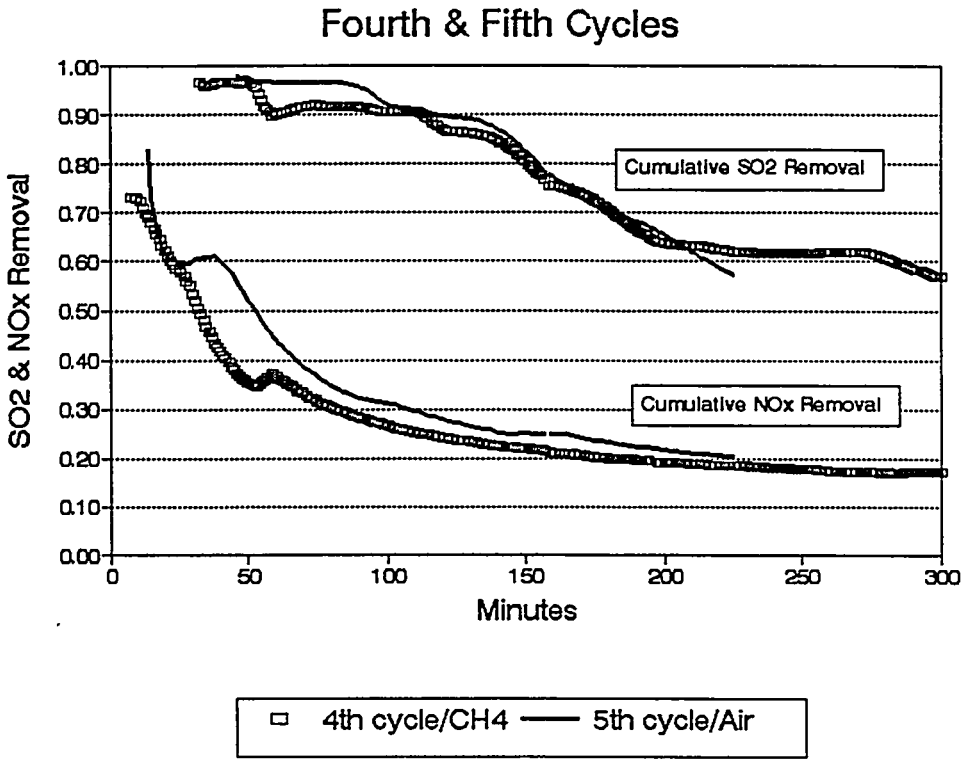


Figure 6.3 SO_2 performance curves for fourth and fifth cycle runs.

Table 6.1 Sorbent performance after regenerations in reducing-gas environments.

Sorbent: 45 wt% MgO - 55 wt% Vermiculite from cycling runs

Sorption Cycle	5	6	7	8	9	10
Regeneration No.	4	5	6	7	8	9
Regeneration Atmos.	CH_4	CH_4	CH_4	CH_4	CH_4	CH_4
Sample wt. (g)	10.09	10.03	10.00	10.16	10.20	10.11
SO_2 in Gas (ppm)	2137	2175	2070	2016	2190	2230
Gas Flow (lpm)	4	4	4	4	4	4
			Average Percentage SO_2 Removal			
Time Period (Min)						
1-10	99.6	99.5	98.7	98.2	95.3	95.3
11-20	98.8	96.2	91.9	93.6	72.0	83.1
21-30	97.1	89.8	83.3	89.1	73.6	79.7
31-40	95.7	79.1	75.5	84.5	71.9	70.8
41-50	93.0	69.6	77.7	71.5	62.5	61.3
51-60	87.8	62.3	73.6	59.3	52.9	40.5
61-70	83.0	53.4	65.3	52.2	35.1	38.8
71-80	83.0	65.7	48.8	41.0	32.4	49.7
81-90	78.2	64.3	56.4	42.8	41.2	51.7
1-30	98.5	95.2	91.3	93.7	80.3	86.0
1-60	95.3	82.8	83.4	82.7	71.4	71.8
1-90	90.7	75.6	74.6	70.3	59.6	63.4
			Sorbent Utilization (Moles SO_2 Sorbed as % of Moles MgO Available)			
1-90	28.7	24.0	23.8	22.0	18.7	20.0
1-140	40.2	33.1	31.6	29.3	26.7	26.7

Table 6.2 Regeneration in air versus methane.

Sorbent: 45 wt% MgO - 55 wt% Vermiculite

Sorption Cycle	1	6	6
Regeneration No.	Fresh	5	5
Regeneration Atmosphere	–	CH_4	Air
Sample wt.	10.01	10.03	10.01
SO_2 in Gas	2200	2175	2200
Gas Flow (lpm)	4	4	4
	Average Percentage SO_2 Removal		
Time Period (Min)			
1-10	100.0	99.5	96.4
11-20	97.0	96.2	83.4
21-30	90.5	89.8	61.1
31-40	80.7	79.1	61.7
41-50	82.2	69.6	78.5
51-60	84.8	62.3	61.4
61-70	79.5	53.4	48.6
71-80	73.8	65.7	37.1
81-90	67.3	64.3	45.4
1-30	95.8	95.2	80.3
1-60	89.2	82.8	73.7
1-90	84.0	75.6	63.7
	Sorbent Utilization (Moles SO_2 Sorbed as % of Moles MgO Available)		
1-90	26.7	24.0	15.1
1-120	33.3	29.8	18.9
1-140	38.0	33.1	20.2

6.3 Particulate Removal

One advantage of the MagSorbent approach is that the panel bed also acts as a physical filter medium for fine particulates that pass through the electrostatic precipitator (ESP). From visual examinations of the duct before and after the sorber, it was clear that the sorbent beds were performing well as particulate filters. This was particularly true during boiler start-ups and upset conditions when large quantities of unburnt carbon and ash passed through the ESP. These were effectively collected by the sorbent bed.

Attention was given near the end of the program to collect fine particulate samples before and after the sorber to quantify the net amounts of particulate removal occurring during SO_2 removal runs. Isokinetic sampling methods were employed to collect particulate samples simultaneously before humidification and after the sorber bed. See Table 6.4 below. The data show that sorbent beds of even multiply-regenerated sorbent can demonstrate significant particulate removals, achieving the 80% net removal objective of the project. As PM_{10} regulations tighten, the fine particulate scavenging ability of such a panel-bed can be a major advantage.

Table 6.4 Particulate removal.

	Particulate Load (mg/Nm^3)		
Sorbent Bed	Sorber Inlet	Sorber Outlet	Net Particulate Capture (%)
Reducing-Gas-Regenerated Material - 5th Cycle	57	10	82.2
Air-Regenerated Material - 6th Cycle	(57)	6.1	89.3

6.4 Materials Performance

6.4.1 Pilot-Plant Materials

Most pilot-plant components stood up well during the program. A summary of materials' performance is given in Table A1 in Appendix I. Stainless steel components, with the exception of screen material, performed satisfactorily. The few non-ferrous metal components used in the pilot-plant design corroded badly.

6.4.2 Exposure Panels

A materials study was performed to obtain information that may be useful in designing commercial facilities employing the new technology or any similar FGD technology. In this study, racks of different materials were prepared and were exposed inside pilot-plant equipment during the test program. The racks were fabricated and coupons were assembled on the racks by Haynes International, (Kokomo, Indiana). Haynes supplied all the metal alloys; plastic materials were supplied by Dow Chemical (Derakane) and Ashland Chemical (Hetron). Paul Crook of Haynes performed the corrosion evaluations.

Two separate test racks were employed. Test Rack A was placed into the stainless steel duct between the humidifier and the sorber; Test Rack B was placed inside the sorber, near the exit gas duct. Each rack comprised coupons of the following materials:

1. 316L Stainless Steel
2. 317L Stainless Steel
3. 904L Stainless Steel
4. FERRALIUM 255 Alloy
5. HASTELLOY G-30 Alloy
6. HASTELLOY H-9M Alloy
7. HASTELLOY C-22 Alloy
8. ULTIMET Alloy
9. Fiberglass - Reinforced Derakane Plastic
10. Fiberglass - Reinforced Hetron Plastic

Differences in material corrosion were marked. Of the materials tested, the HASTELLOY C-22 alloy (both base metal and weldment), the ULTIMET alloy, and the Fiber-Reinforced Plastics performed best. These materials are recommended for materials of construction, particularly FRP for the humidification section. Details of the various materials' performances can be found in Appendix A.

7. WASTES AND BY-PRODUCTS

While compliance with the rules of the Clean Air Act Amendments of 1990 will ease the acid rain problem, it will also create a significant new waste disposal problem. Literally tens of millions of tons of new flue gas desulfurization (FGD) wastes will be produced with the new wet scrubbing systems currently being installed, these wastes will require disposal. Historically, the U.S. has done a poor job at preventing pollution by introducing minimum-waste or waste-free processes.

A central feature of this project's technology is that the amount of waste materials that is produced is small to none. The MagSorbent technology results in useful by-products, instead of wastes. The SO_2 originally sorbed from the flue gas stream can be directly converted into valuable elemental sulfur. The spent sorbent materials can be used as beneficial soil amendments or pelletized into slow-release agricultural fertilizers.

7.1 Elemental Sulfur

Elemental sulfur is produced in the system directly when a reducing environment is employed in regeneration. Elemental sulfur is a particularly attractive by-product because it is essentially inert, can be easily stored, and is normally in high demand. Sulfur is the second-most-traded solid commodity, behind coal. By-product sulfur can typically be sold for about $50+/ton.

Prior to the project, Sorbtech observed typically about 25 to 35 percent of the liberated SO_2 was converted directly to elemental sulfur during regeneration, with the rest evolving as SO_2. Consequently, in a separate project co-supported by the Ohio Coal Development Office, the U.S. Environmental Protection Agency, and Sorbtech, three approaches were studied to improve the direct elemental sulfur yields. Two of these approaches, recycling the regeneration gas and use of a new catalyst developed by Research Triangle Institute, resulted in significantly higher elemental sulfur yields, but problems remained.

It was then discovered that MgO-vermiculite materials, in addition to being good sorbents for SO_2, were themselves catalysts for the direct conversion of SO_2 to elemental sulfur in the presence of CO or hydrogen. Consequently, Sorbtech researchers examined the passage of SO_2 and regenerator off-gases through multiple beds of MgO-vermiculite. Using this approach they found that they could achieve elemental sulfur yields approaching 100 percent with no residual SO_2 in the gas stream. Work in this area is continuing, with support from the U.S. Department of Energy and by the U.S. Environmental Protection Agency.

7.2 Spent Sorbent By-Products

After a number of sorption-regeneration cycles, the sorbents begin to appreciably degrade physically. This happened after about 10 to 15 cycles in earlier laboratory tests and after about 5 to 8 cycles in the pilot-plant runs. When this occurs, the materials are removed from the system and replaced with fresh sorbent. Additional sorbent is also removed after regeneration to make room for a constant supplement of fresh sorbent. This results in a small by-product stream that must be disposed of. This spent sorbent, which consists of vermiculite and magnesia, can then be put to use as valuable by-products, particularly as environmentally-friendly soil conditioners and slow-release fertilizers.

The exhausted MagSorbent materials differ from other FGD wastes in five important ways:

1) They have already been used multiple times, so there is only a small fraction to consider;
2) They have been liberated of their sulfur species through regeneration;
3) They contain substantial amounts of vermiculite, a premium soil amendment material, along with their magnesia, a liming ingredient;
4) They contain little or no deleterious fly ash, with its associated heavy metals; and
5) They are already granular and, if desired, easy to pelletize.

By itself, the spent sorbent stream has the properties of a beneficial soil additive. Many U.S. soils are poorly-constituted for their desired use. For example, some topsoils are too dense for robust plant growth. Compacted and exhausted by continuous farming, water runs off from their surfaces and air has difficulty permeating to the plant roots. When soils have too much clay, they lack the capillary porosity needed for productive use. Unlike other advanced coal technology wastes, waste MagSorbent contains a large amount of a premium horticultural growth medium: exfoliated vermiculite. These sponge-like mineral supports make up one-half of the sorbent's mass and over half of their volume. Added to these soils, the low-density vermiculite of the spent sorbents significantly increases their root-zone porosity, effectively aerating the soil and boosting their biological productivity.

Other soils are too sandy. Excess water consumption is a major problem in regions with these soils. Water permeates through the soils too quickly, requiring high levels of irrigation. With drought conditions, many plants die. Some golf courses in the U.S., for example, actually import manufactured soil amendments from Japan to help hold water in their turf grass soiis. Lower-value agricultural lands, of course, cannot afford such a luxury. When applied to sandy soils, the vermiculite in the spent sorbent materials acts as a sponge, holding in water. This is why vermiculite is frequently added to horticultural soils and is used in greenhouse mixes.

Still other soils are too acidic. In fact, most soils in the Eastern U.S. are considered too acidic and periodic liming is recommended for the best ornamental or agricultural results. The magnesia in the spent materials is an excellent liming agent. If desired, the release rate of its alkalinity can be substantially lowered by pelletizing.

By pelletizing or agglomerating the spent sorbent materials with added fertilizer or pesticide compounds, an even higher-value product can be created. The exhausted sorbent materials look to be an excellent and inexpensive source of substrate for slow-release agricultural and turf grass products. Pelletized with nitrogen-containing urea, for example, such wastes have shown promise to slowly make nitrogen available to plants or grasses. The substrate of vermiculite and magnesia of the exhausted sorbents is not dissimilar from some compositions being commercially marketed today. As a timed-release substrate, they can lessen the overall amount of fertilizer or pesticide chemicals required while decreasing surface water runoff and groundwater pollution.

Figure 7.1 Trial pellets were made from dry FGD waste and vermiculite. The left sample was extruded, the right sample was agglomerated. The plant was grown in a potting soil containing MagSorbent.

Water pollution from agricultural activity is increasingly being recognized as a major environmental problem. Each year forty million tons of chemical fertilizers are spread in the U.S., but only a fraction is effectively taken up by the targeted plants. Applied as liquids or easily-leached prills, large amounts of fertilizer chemicals, particularly nitrogen from urea or fertilizer nitrite, are frequently inefficiently utilized, quickly leaching from their intended placement and causing surface water pollution and groundwater contamination. Similarly, agricultural pesticide use has similarly become a major pollution concern. Every day an average of over 1,000,000 kilograms of insecticides, herbicides, and fungicides are introduced into U.S. agricultural and turfgrass environments. Less than 0.1% of this actually reaches the targeted pests. The other 99.9% enters the environment, contaminating our soil, water, and air resources. Parts of the upcoming Clean Water Act reauthorization are expected to focus on these fertilizer and pesticide issues.

One of the primary factors influencing the rate at which fertilizers and pesticides enter the environment is their physical formulation. Liquid agricultural and turf grass chemicals, in particular, are easily leached or volatilized. Spreadable granular formulations, on the other hand, are usually the more long-lasting. Granular formations, however, require the added expense of substrate materials. Because the spent sorbents are waste materials, it may be possible to create slow-release products from them at only a fraction of the cost of virgin materials, thus opening up new markets and replacing easily-leachable formulations with slow-release varieties.

Fresh exfoliated vermiculite has long been used as a soil amendment and inert carrier for herbicides in turfgrass products. The O.M. Scott & Sons Co., the producer of TurfBuilder,™ is the largest consumer of vermiculite from some mines. This popular, granularized turf grass product sells for $1,000 per ton or more. Thus, the targeted uses are relatively high-value, with products currently serving these markets costing from $200 to $1000+ per ton. If $40-80 per ton of value can be extracted to pay for the spent MagSorbent materials, the economics of the new technology would look increasingly promising for utilities and their ratepayers.

Due to OCDO program constraints, actual processing and agricultural testing of the spent sorbent by-products were not included in the project statement of work. Sorbent Technologies is, however, pursuing demonstrations of this technology elsewhere.

Because the MagSorbents were exposed to coal-burning boiler flue gases, there is the concern that heavy metals might appear in the by-product wastes after exposure, particularly after multiple recycles. For this reason, EP-Tox leachate tests were performed on various spent MagSorbent samples by the analytical laboratory of Premier Services Corporation. The results of these tests are summarized in Table 7.1. As can be seen in these results, no significant levels of toxic heavy metals were detected and the materials appear to present no leachability concerns.

Table 7.1 EP-Tox leachate tests.

Constituent	EP Toxicity Regulation Level (mg/liter)	Fresh MagSorbent (mg/l)	MagSorbent Exposed for 6 hours (mg/l)	MagSorbent Regenerated 4 times (mg/l)
Aluminum	–	22	15	–
Cadmium	1.0	ND	ND	ND
Chromium	5.0	ND	ND	ND
Copper	–	ND	60	–
Iron	–	185	170	–
Lead	5.0	ND	ND	ND
Mercury	0.2	ND	ND	–
Nitrates	–	ND	650	–
Nitrites	–	<1	<1	–
Selenium	–	–	–	ND
Zinc	–	ND	4	–

ND = None Detected

Revised extraction procedure for toxicity (EP-Tox) tests performed by the analytical laboratory of Premier Refractories & Chemicals, Bettsville, Ohio.

8. ECONOMICS

The project helped to establish a better base from which to estimate the economics of a full-scale application of the regenerable MagSorbent concept. On the following tables, such an estimate is carried out. This economic model considers a retrofit installation at a large 510-MW plant burning a 2.5%-sulfur Ohio coal. See Table 8.1 for power plant and pollution control parameters. The calculations are based on MagSorbent performance of 90% SO_2 removal, 30% NOx removal, and 80% removal of residual particulates.

8.1 Capital Costs

In line with the standard economic analysis methodology of the DOE's Clean Coal program, the various air pollution control plant sections were broken down and capital costs estimated. See Table 8.2. Sorbent production is assumed here to be done at the power plant and the scale of this facility is based on the calculated sorbent requirements. The two most expensive capital cost areas are the panel-bed sorber units and the regeneration and sulfur recovery sections. The size of the sorber units are based on the face velocities demonstrated in the project. The $16 million equipment cost for the regeneration and sulfur recovery facilities is the estimate with the least certainty; that process is still being optimized.

At a greenfield site, the various equipment requirements are estimated to total about $43 million for our model plant. As a retrofit it would cost about 20% more. Including all the typical add-on costs such as general facilities, engineering, contingencies, etc., total capital costs for the 510-MW facility come to about $67 million, or $132/kW. Based on a 20-year life, this translates to a capital cost charge of about $120 per ton of SO_2 removed.

Table 8.1 MagSorbent installation at a 510-MW Ohio plant.

Power Plant Parameters		
Power Plant Size	510	MW
Capacity Factor	70%	
Coal Btus	12,400	Btu/lb
Coal Sulfur	2.5%	
Flue Gas	1100	K scfm
Tons Coal Used per Year (@ 2K T/MW)	952	K tpy
Pollution Control Performance		
SO2 Removal	90%	
NOx Removal	30%	
Net Additional Particulate Removal	80%	
Net SO2 Produced (@ 95% Coal S)	3.80	lb SO2/MM Btu
Tons SO2 Produced	45	K tons SO2/yr
Tons SO2 Removed	41	K tons SO2/yr
Tons SO2 Emitted	5	K tons SO2/yr
SO2 Emitted	0.38	lb SO2/MM Btu
NOx Produced	1.20	lb NO2/MM Btu
NOx Removed	4.3	K tons NO2/yr
NOx Emitted	0.84	lb NO2/MM Btu
ESP Fugitive Particulate	0.10	lb /MM Btu
Net Particulate Emitted	0.02	lb /MM Btu
Sorbent Usage Summary		
Average MagSorbent Life	6	cycles
Average MagSorbent Utilization	30%	
Tons Fresh MagSorbent per Year	30.3	K tpy MS
Total Variable Cost	$353	/ton SO2
Total Variable Cost	$14.4	Million/yr

Table 8.2 Capital costs.

MagSorbent Production Requirements	30.3	K tpy MS
Oversizing	15%	
MagSorbent Production Plant Size	34.8	K tpy MS
Shifts per Day	2	/day
Equipment Cost Per Ton of Annual Capacity	$90	/T MS
Cost of Production Plant	$3.1	Million

Section	Capital Cost Item	Millions
100	Sorbent Production, Storage, & Handling	$4.0
200	SO2-NOx-Part. Radial Panel-Bed Sorber Units	12.0
300	Flue Gas Ducting, Humidification, & Fans	8.0
400	Sorbent Regeneration & S2 Recovery Section	16.0
500	Sorbent By-Product Processing & Handling	3.0
>	Total New Plant & Equipment Cost	$43.0
	Multiplier: Retrofit	1.20
>	Total Retrofit Plant & Equipment Cost	$51.6
	Multiplier: Add-ons (including Gen.Fac., Eng'g Fees, AFDC, Inventory, Conting.)	1.30
>	Total Capital Cost (Millions)	$67.1

Capital Cost Summary

Plant & Equipment Cost	$84	/ kW
Retrofitted Cost	$101	/ kW
Total Capital Cost	$132	/ kW
Total Capital Cost	$67	M
Capital Recovery Lifetime	20	years
Real Discount Rate	4.0%	
Annual Capital Recovery Rate	7.4%	
Annual Capital Recovery Cost	$4.94	M
Capital Cost Per Ton of SO2 Removed	$121	/ton SO2

Table 8.3 Operating costs.

Sorbent Production Cost Elements	Mat'l $/T	Frt.	Total $/T	Wt.%	Wt.$
Mined Magnesia (94%)	$220	$40	$260	0.50	$130
Vermiculite Ore (Med.Gr.)	$160	$40	$200	0.50	$100
Raw Materials Costs / T MagSorbent				1.00	$230
Other Variable Costs (Processing)					$30
Cost / T MagSorbent					$260

SO2 Removal Efficiency (@ Average Utilization)	90%	
MgO Purity	94%	
Tons SO2 Removed per Ton MagSorbent (@100% Utiliz.)	0.75	T SO2/T MS
Regeneration Cost ($/Ton Original MagSorbent)	$30	/T MS
Other Variable Costs (Fan Power, Labor, Misc.)	$40	/T SO2
Spent Sorbent By-Product Credit	$20	/T MS

Average Variable Cost Per Ton of SO2 Removed

Number of Cycles	Cycle SO2 Utiliz.	Average SO2 Utiliz.	T SO2 per T Sorb.	Sorbent Cost $/T SO2	Regen. Cost $/T SO2	Other Costs $/T SO2	Avg.Total Var.Costs $/T SO2
1	40%	40%	0.30	$804	$100	$40	$944
2	35%	38%	0.28	$429	$107	$40	$576
3	30%	35%	0.26	$306	$115	$40	$461
4	30%	34%	0.25	$238	$119	$40	$397
5	25%	32%	0.24	$201	$126	$40	$367
6	20%	30%	0.22	$179	$134	$40	$353
7	20%	29%	0.21	$161	$141	$40	$341
8	15%	27%	0.20	$150	$150	$40	$339

Sulfur Recovery

Sulfur Values (@ 50% of market)	$50	/ton S2
Sulfur Recovery Operating Costs (Assumed)	$50	/ton S2
Net Sulfur Income	$0	/ton S2

(The direct sulfur recovery process is still under development and costs are largely unclear. Here we assume that sulfur revenues only cover recovery expenses, providing no net income.)

Table 8.4 Cost attributions.

Attributing All Costs to SO2 Removal		
Annual Capital Cost	$5	Million
Annual Variable Costs	$14	Million
Annual Total Cost	$19	Million
Total Cost Per Ton of Coal	$20	/ton coal
SO2 Removal Rate	90	%
Annual Tons SO2 Removed	41	K tons SO2/yr
Capital Cost	$121	/ton SO2
Variable Operating Cost	$353	/ton SO2
Total Cost Per Ton Of SO2 Removed	$474	/ton SO2
NOx Removal Rate	30	%
Total Cost Per Ton Of NOx Removed	$0	/ton NO2
Residual Particulate Removal Rate	80	%
Total Cost Per Ton Of Particulate Removed	$0	/ton partic.
Attributing Costs to both SO2 and NOx		
Annual Tons SO2 Removed	41	K tons SO2/yr
Annual Tons NOx Removed	4	K tons NO2/yr
If NOx removal costs 2.5 times SO2:		
Total Cost Per Ton Of SO2 Removed	$375	/ton SO2
Total Cost Per Ton Of NOx Removed	$938	/ton NO2
Total Cost Per Ton Of Particulate Removed	$0	/ton partic.

8.2 Operating Costs

The major operating costs in this process are the sorbent and regeneration costs. The cost of a ton of the MagSorbent is derived on the top of Table 8.3. The magnesia and vermiculite raw materials are relatively inexpensive.

The variable operating costs are largely a function of the sorbent utilizations achieved. These have been adjusted downward based on the project results. The operating costs are a function of the original sorbent costs, the regeneration costs, and other costs (primarily power costs for pressure drop and humidification air). The variable costs decrease depending on how many times the sorbents are used, but the costs level off after about six to eight cycles. In this model it is assumed that the elemental sulfur revenues simply cover the recovery costs. A small credit is taken for the value of the spent sorbent by-product materials.

Adding the annual capital contribution costs to the operating costs provides the total costs of the MagSorbent system. See Table 8.4. Because the process removes SO_2 and NOx (and residual particulates) simultaneously, it is confusing to attribute all the costs to SO_2 control and calculate them on only a per-ton-of-SO_2-removed basis. If it is assumed that NOx removal is about 2.5 times as expensive as SO_2 removal, the MagSorbent cost efficiency can be calculated as \$375 per-ton-of-SO_2 removed and \$938 per-ton-of-NO_2 removed.

8.3 Continuing Work and Commercialization

For a dry, waste-free SO_2/NOx system, the economics of the MagSorbent continue to look promising and there is room for added improvement. Consequently, Sorbent Technologies is continuing to develop the technology, particularly in the areas of optimizing the regeneration process, scaling up the sorption, and demonstrating the value of the spent sorbent materials.

The project pointed out weaknesses in our regeneration equipment selection and the possibilities of improved regeneration performance. Based on the results achieved so far, the U.S. Environmental Protection Agency and the Dept. of Energy have sponsored two additional sulfur-recovery projects at Sorbtech for $280,000 and a demonstration proposal is currently pending for over $500,000. The goal is to achieve essentially complete conversion to elemental sulfur in one step.

As long as U.S. utilities are allowed to simply landfill their flue gas desulfurization wastes, once-through FGD process will always be at a competitive advantage over regenerable processes. This is not the case in Europe and Japan, however, where land is more valuable and water pollution and waste disposal regulations are much more stringent. While the U.S. will follow in this direction in the future, commercial interest in regenerable processes is currently much stronger overseas. Consequently, Sorbent Technologies has pursued a next-step commercial scale-up of the technology in Europe. Working with a European utility technology supplier, Sorbtech has made presentations seeking commercial demonstrations to boiler owners in Europe. A Swiss energy foundation, NEFF, recently awarded a Sorbtech associate a grant to further study the technology and install an industrial-scale unit if appropriate.

An important environmental link in the MagSorbent technology which has not yet been demonstrated is the utility of the spent sorbent stream as a soil conditioner or slow-release fertilizer substrate. The vermiculite in this stream is still valuable and, when easily pelletized, can retain air and water in soils and slow the release rate of included fertilizer chemicals or pesticides to reduce agricultural or turf-grass water pollution. Sorbtech has been actively seeking support for the development work and field studies needed to establish the efficacy of such process by-products and so to close the loop on the "sustainable" MagSorbent technology.

9. FINAL BUDGET SUMMATION

The original project budget totalled $720,000. The final project cost totalled $754,188, only slightly higher than initially projected. Sorbent Technologies Corp. contributed cash to cover the entire additional $34,000 in added costs.

Table 9.1 breaks down the total project budget by major category, delineating the contributions by the Ohio Coal Development Office (OCDO) and Sorbent Technologies Corporation. The Ohio Edison Company contributed its site and miscellaneous utilities at no cost to the project.

Sorbent Technologies takes great pride in the fact that this pilot plant project was completed for only a fraction of the cost of other similar projects. A great deal of valuable information and experience was gained for an OCDO contribution of only $360,000. On the following page is Table 9.2, detailing the project costs and the expenditures of OCDO funds by line item.

Table 9.1 Project budget.

Category	Original Project Budget	Final Project Cost	OCDO Contribution	Sorbtech Contribution
Personnel	$ 286,400	$ 305,117	$ 145,037	$ 160,080
Fringe Benefits	77,300	82,382	39,160	43,222
Travel	14,000	11,831	5,415	6,416
Equipment	79,500	78,946	39,239	39,707
Supplies	20,000	20,008	10,004	10,004
Contractual	62,400	63,681	29,772	33,909
Total Direct Charges	$ 539,600	$ 561,965	$ 268,627	$ 293,338
Indirect Charges	180,400	192,223	91,373	100,850
Total	$ 720,000	$ 754,188	$ 360,000	$ 394,188
Percent			47.7%	52.3%

Table 9.2 Line item breakdown.

Personnel	MHr	Avg. Rate	Labor Cost	Total OCDO Labor Cost	
Project Manager	3412	$25.15	$ 85,807	$ 40,788	
Engineers	7640	21.32	162,918	77,443	
Technicians	5059	9.19	46,501	22,104	
Secretarial and Other	1219.5	8.11	9,891	4,702	
	17330.5		$305,117	$145,037	(49.3%)

	Total Costs	OCDO Costs	
Contractual & Other Directs			
Fabrication Services	$ 33,622	$ 15,719	
Other Outside Services	$ 20,825	$ 9,736	
L.D. Telephone, Copying & Misc.	$ 9,234	$ 4,317	
	$ 63,681	$ 29,772	(46.7%)
Equipment			
Pilot Plant Equipment	$ 72,631	$ 36,100	
Laboratory & Misc. Equipment	$ 6,315	3,139	
	$ 78,946	$ 39,239	(49.7%)
Supplies			
Gases	$ 4,352	$ 2,176	
Sorbent Materials	$ 1,661	$ 831	
Laboratory Supplies & Chemicals	$ 2,205	$ 1,102	
Direct Project Materials	$ 2,132	$ 1,066	
Miscellaneous	$ 9,658	$ 4,829	
	$ 20,008	$ 10,004	(50.0%)
Travel			
Travel Expenses	$ 11,831	$ 5,415	(45.8%)

10. CONCLUSIONS

The pilot plant test program demonstrated that SO_2 removals in the 90% range could be regularly attained with granular magnesia-vermiculite sorbents in a thin, radial panel-bed sorber at megawatt scales. Simultaneous NOx removals in the 20 to 30% range were also demonstrated. It was shown that much of the sorption ability of the new sorbents could also be recovered by thermal regeneration. The integrated nature of the process was demonstrated in a 40-hour continuous run.

Sorbent utilizations at high removal rates, however, were generally less than originally expected, ranging from about 35% to 15%. The outside design of the sorber and consequent irregular gas flow and saturation of the sorbent bed was at least partially responsible for these lower utilizations. Moreover, for run with regenerated sorbents, the inability to safely use methane as the regeneration atmosphere in the fan building, and the consequent sulfate build-up in the sorbent, also significantly contributed to lower removals and utilizations. However, it is believed that both of these design problems can be solved in further work and scale-up, which would improve the economics of the process.

The levels of SO_2 and NOx removal were found to be sensitive to the approach temperature at higher utilizations. The runs were generally performed at conservative 50F approach temperatures; going closer would have generally resulted in higher SO_2 removals and larger utilizations. The levels of SO_2 and NOx removal were also found to be sensitive to the face velocity of the gas through the panel. Once past a critical velocity, it is believed that channels begin appearing the panel and some untreated gases pass through. Happily, the panel and system pressure drops were low and less than expected.

The radial panel-bed also performed well as a polishing filter for the fine particulate that passed through the Edgewater ESP, as well as for the coarse particulate that the bed saw during cold start-ups of the power plant. The net 80% particulate-removal goal was achieved even with regenerated sorbent. The vermiculite-based sorbents handled well and little attrition was seen with regeneration. The perlite-based sorbents were less successful in this respect.

The waste streams from the process, spent vermiculite sorbent and high-concentration SO_2 or elemental sulfur, both possessed the qualities of potentially high-value by-products. The technology still appears to be a no-waste process. The overall economics of the technology continue to look promising, with total retrofit costs of around $400 per-to-of-$SO_2$ removed and $900 per-ton-of-NOx removed. As there are still areas of possible improvement, Sorbent Technologies is continuing to develop this technology and pursuing scaled-up commercial demonstrations.

11. BIBLIOGRAPHY

To translate the results of this project to the marketplace and further the commercialization of this technology, a number of papers and presentations were made to industry. These include:

1. Sorbent Technologies Corp. MagSorbent Project Dedication Event, Ohio Edison Edgewater Generating Station in Lorain, Ohio, November 26, 1991.

2. Nelson, S., "The Economics of MagSorbent Dry Scrubbing," Comparative Economics of Clean Coal Technologies Conference, Washington DC, March 1990.

3. Van Stone, D. & S. Nelson Sr., "Sorbtech's Regenerable MagSorbent Proof-of-Concept Demonstration Program," 9th Annual Pittsburgh Coal Conference, October 1992.

4. Bolli, R. & S. Nelson, "Wastefree SO_2/NOx Control at Ohio Edison's Edgewater Plant with a Regenerable Magnesia-Based Sorbent," Power-Gen '92, Orlando FL, November 1992.

5. Nelson, S., "Supported Sorbents," Joint EPA/DOE/EPRI 1993 SO_2 Control Symposium, Boston, MA, August 1993.

Numerous industry publications have also reported on the project, the latest being:

6. Livengood, C.D. & J. Markussen, "FG Technologies for Combined Control of SO_2 and NOx," Power Engineering Magazine, January 1994.

Appendix A: Materials Performance

Pilot-Plant Materials

Most pilot-plant components stood up well during the program. A summary of materials' performances is given in Table A.1. Stainless steel components, with the exception of screen material, performed satisfactorily. The few non-ferrous metal components used corroded badly.

Exposure Panels

A materials study was performed to obtain information that may be useful in designing commercial facilities employing the new technology. In this study, racks of different materials were prepared and were exposed inside pilot-plant equipment during the test program. The racks were fabricated and coupons were assembled on the racks by Haynes International, (Kokomo, Indiana). Haynes supplied all the metal alloys; plastic materials were supplied by Dow Chemical (Derakane) and Ashland Chemical (Hetron). Paul Crook of Haynes performed the corrosion evaluations.

Two separate test racks were employed. Test Rack A was placed into the stainless steel duct between the humidifier and the sorber; Test Rack B was placed inside the sorber, near the exit gas duct. Each rack comprised coupons of the following materials:

1. 316L Stainless Steel
2. 317L Stainless Steel
3. 904L Stainless Steel
4. FERRALIUM 255 Alloy
5. HASTELLOY G-30 Alloy
6. HASTELLOY H-9M Alloy
7. HASTELLOY C-22 Alloy
8. ULTIMET Alloy
9. Fiberglass - Reinforced Derakane Plastic
10. Fiberglass - Reinforced Hetron Plastic

The two racks were exposed to a pre-test period of about 37 hours total, an intermittent test period totalling about 108 hours, and idle time between tests and during shake-down runs consisting of over 10,000 hours. The pre-test period involved a gas flow averaging 6400 cfm. Of the 37 hours of pre-testing, 6.5 hours were at about 40 percent humidity, and the balance of the time was at approximately 13 percent. Both racks were exposed to 800 to 1000 ppm SO_2 and about 300 ppm NOx (average) during the pre-test period.

During the 108-hour main test-period, the average relative humidity was approximately 40 percent. During the main test period, Rack A was exposed to averages of 1300 ppm SO_2 and 270 ppm NOx at an average temperature of 190°F, and Rack B was exposed to averages of 580 ppm SO_2 and 140 ppm NOx at an average temperature of 165°F. Rack B became coated with MgO dust during the first 22.5 hours of the main test period. Thereafter, the dust loading of the gas exiting the sorber was very near zero and no additional dust occurred on the coupons. During the idle time, the racks were exposed to an atmosphere containing 0 to 1500 ppm SO_2 and 0 to 400 ppm NOx at room temperature..

Table A.1 Pilot plant materials performance.

Item	Construction Material	Condition During and After Program
Duct to the Sorber	Type 304 Stainless Steel	Good condition, generally.
Duct after the Sorber	Carbon Steel	Good condition, generally.
Humidifier Components	Brass, Stainless Steel	Brass components failed during the program and were replaced with stainless steel. Stainless steel components were attacked, but stood up satisfactorily.
Sorber	Carbon Steel, Stainless Steel	All components were attacked corrosively. Stainless steel screen failed two areas. Most other components were in fair condition after the program.
Velocity Meter Flow-Straightener	Aluminum	Very heavily attacked and partially disintegrated.
Gate Valves	Carbon Steel	Good condition, generally.
Window Ports in Duct	Lexan Plastic	Weakened and failed. Replaced by tempered glass, which performed well.
Regenerator	Refractory Firebrick, Black Iron (pipe), Stainless Steel	Kiln components in good condition; iron gas-exit pipe severely corroded.

The corrosion rates and comments on the condition of the individual materials after the exposures are presented in Table A2 for Rack A and Table A3 for Rack B. Corrosion rates are presented for the main test period alone (i.e., assuming all the corrosion took place during the main test period), for the main test plus pre-test period, and for the total service time (assuming the idle environment was also corrosive, which the condition of other components in the system indicated was the case). On the basis of the materials evaluations before and after the test program, it was clear that:

1. Differences in material corrosion were marked. Of the materials tested, the HASTELLOY C-22 alloy (both base metal and weldment), the ULTIMET alloy, and the Fiber-Reinforced Plastics performed best. These materials are recommended for materials of construction, particularly FRP for the humidification section.

2. The environment between the humidifier and sorber was significantly more severe than the environment after the sorber. Although no materials showed massive corrosion, both environments resulted in a pitting attack on most metallic materials.

3. The plastic materials gained weight during exposure; all metals lost weight. A small degree of degradation of the plastic materials occurred, particularly of those materials exposed after the humidifier.

Table A.2 Corrosion rates and conditions of samples from test rack A.

Alloy	Condition	Corrosion Rates (mpy) Severe Exposure Based on 108 hrs	Heavy Exposure Based on 145 hrs	Total Exposure Based on Over 10,000 hrs
316L Stainless Steel	Uniform Attack Base Metal & Weld Metal Pitting	89.6	766.7	0.8
317L Stainless Steel	Uniform Attack Base Metal & Weld Metal Pitting	73.9	55.1	0.7
904L Stainless Steel	Uniform Attack Base Metal & Weld Metal Pitting	85.5	63.7	0.8
FERRALIUM 255 Alloy	Uniform Attack Base Metal & Weld Metal Pitting	101.0	75.9	0.9
HASTELLOY G-30 Alloy	Uniform Attack Base Metal & Weld Metal Pitting Slight Crevice Attack (around support holes)	27.0	20.1	0.2
HASTELLOY H-9M Alloy	Uniform Attack Base Metal & Weld Metal Pitting Slight Crevice Attack	4.7	3.5	<0.1
HASTELLOY C-22 Alloy	Uniform Attack Very Slight Crevice Attack	0.5	0.3	<0.1
ULTIMET Alloy	Uniform Attack Weld Metal Pitting Very Slight Crevice Attack	2.2	1.6	<0.1
Derakane FRP	Discolored Small Weight Gain Interlayer Damage (Edges)	Nil	Nil	Nil
Hetron FRP	Discolored Small Weight Gain Interlayer Damage (Edges)	Nil	Nil	Nil

Table A.3 Corrosion rates and conditions of samples from test rack B.

Alloy	Condition	Corrosion Rates (mpy) Severe Exposure Based on 108 hrs	Heavy Exposure Based on 145 hrs	Total Exposure Based on Over 10,000 hrs
316L Stainless Steel	Uniform Attack Base Metal & Weld Metal Pitting	22.2	16.5	0.2
317L Stainless Steel	Uniform Attack Base Metal & Weld Metal Pitting	20.1	15.0	0.1
904 Stainless Steel	Uniform Attack Base Metal & Weld Metal Pitting Slight Crevice Attack (around support holes)	17.3	12.9	0.1
FERRALIUM 255 Alloy	Uniform Attack Base Metal & Weld Metal Pitting	15.7	11.6	0.1
HASTELLOY G-30 Alloy	Uniform Attack Slight Base Metal & Weld Metal Pitting Slight Crevice Attack	2.40	1.8	<0.1
HASTELLOY H-9M Alloy	Uniform Attack Slight Weld Metal Pitting	0.3	0.2	<0.1
HASTELLOY C-22 Alloy	Uniform Attack	0.2	0.2	<0.1
ULTIMET Alloy	Uniform Attack	0.3	0.2	<0.1
Derakane FRP	Discolored Small Weight Gain	Nil	Nil	Nil
Hetron FRP	Discolored Small Weight Gain	Nil	Nil	Nil