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Supported-Sorbent Injection

Final Report

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Sorbent Technologies Corporation**

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Supported-Sorbent Injection

Sorbent Technologies Corporation

Executive Summary

- A. A new retrofitable, wastefree acid-rain control concept was pilot-tested at Ohio Edison's high-sulfur coal-fired R.E. Burger generating station at the 2-MWe level. During the project, moistened "supported" sorbents, made from a combination of lime and vermiculite or perlite, were injected into a humidified 6,500-acfm flue-gas slipstream. After the sorbents reacted with the sulfur dioxide in the flue gas, they were removed from ductwork with a cyclone and baghouse.

The \$1.0 million project was co-funded by Sorbent Technologies Corporation, the Ohio Edison Company, and the Ohio Coal Development Office.

- B. The project included a preliminary bench-scale testing phase, construction of the pilot plant, parametric studies, numerous series of recycle tests, and a long-term run. The project proceeded as anticipated and achieved its expected results.

This duct injection technology successfully demonstrated SO₂-removal rates of 80 to 90% using reasonable stoichiometric injection ratios (2:1 Ca:S) and approach temperatures (20-25F). Under similar conditions, dry injection of hydrated lime alone typically only achieves 40 to 50% SO₂ removal. During the testing, no difficulties were encountered with deposits in the ductwork or with particulate control, which have been problems in tests of other duct-injection schemes.

- C. Results from this pilot demonstration seem sufficient for the design and construction of a permanent 10 to 30 MWe installation of the technology.
- D. Two technology configurations were tested during the project:
- 1) installation before an electrostatic precipitator (ESP), and
 - 2) installation after the ESP, with an added high-velocity baghouse.

In the first instance, the estimated capital cost is \$ 69/kW, based on the project results, with operating costs of \$ 465/ton of SO₂ removed. In the second configuration, the respective estimated costs are \$ 101/kW and \$ 639/T SO₂. These are for the difficult case of a 100 MW plant with 10 years of remaining life, a 50% operating factor, and wastefree operation.

- E. Central to the supported-sorbent concept is the beneficial use of the novel saturated sorbents. Once saturated, they contain liming values for acidic soils, sulfur values for plant growth, micronutrients from any included fly ash, and the structural, aeration, and water-holding qualities of the mineral supports. They can be added to soils in a raw form or pelletized, for slow-release properties. In greenhouse trials by the Ohio Agricultural Research and Development Center, agricultural by-products made from the Burger-saturated materials performed at least as well as currently-commercial products.

Figure E.1 Schematic of the wastefree, retrofit supported-sorbent injection process.

- F. This technology was specifically designed for coal-fired plants with a tough control profile: retrofit situations at older, smaller, plants. It looks to be most cost-effective for combustion gas streams in the 10-to-100 MWe range, like those from industrial, institutional, and small power plant boilers. Ohio has over one hundred such plants, with at least one in almost every county.
- G. Based on the promising results achieved, a small full-scale demonstration of the technology is recommended.

1. Introduction

1.1 Problem Statement

Much of Ohio's electrical generation comes from power plants that are over thirty years old and not base-loaded. It is difficult and expensive to retrofit acid rain controls on such plants. Over the last few years, a number of dry sorbent injection processes have received attention as possible low-capital-cost flue gas desulfurization (FGD) technologies for such units. The initial promise of these sorbent duct-injection technologies was that they could be easy and inexpensive to retrofit onto existing boilers. Consequently, they would be particularly appropriate for older plants, smaller plants, and non-base-loaded plants, where the high capital costs of other technologies could not be effectively amortized over many tons of SO_2 removed.

Unfortunately, however, weak performance has plagued the dry lime injection schemes, with SO_2 removals of typically around 40 to 50% at reasonable lime-to- SO_2 stoichiometric ratios (e.g. $\text{Ca:S} = 2.0$). See the Department of Energy data below, photocopied from Duct Injection for SO_2 Design Handbook, Volume 1 (1994). Moreover, particulate-control problems have occurred in these trials. By adding tons of very-fine sorbent particles to the flue gas streams, the plants' particulate removal requirements were significantly increased and a particulate compliance problem was sometimes observed. Finally, the wastes from these demonstrations also proved to be a problem. The very fine lime materials, mixed-in with electrostatic precipitator (ESP) fly ash, required costly disposal, rather than being put to beneficial reuse.

Figure 1-3

Source: Beverly DITF, Meradosia, EPRI, Coolside (no recycle, no additive)

Page 1-12

Figure 1.1 SO_2 removal results of previous dry duct-injection demonstrations.

A new concept, called supported-sorbent, or "Fluesorbent," was specifically developed to address these problems. Based on a new sorbent material, the technology results in 85+ % SO_2 removal, net particulate reductions, and a valuable agricultural by-product instead of wastes. The process is shown schematically in Figure E.1. A 6,500 acfm, 2-MWe Fluesorbent pilot plant was recently constructed at Ohio Edison's R.E. Burger station to demonstrate the process. This report describes the technology and the results from the Burger demonstration project.

1.2 Project Objectives

The primary objective of the project was to demonstrate the new supported-sorbent technology and to gather the operating data and performance experience necessary for the design of a full-scale utility installation of this new retrofit acid rain control technology.

The specific technical objectives of this 6,500 acfm, 2-MWe pilot-plant project were to sufficiently demonstrate:

- the production of lime-based supported-sorbents,
- the satisfactory design and operation of a system for the duct-injection of the moist sorbent materials to achieve in-duct SO₂ removal, and
- the recovery of the saturated sorbent materials for by-product testing,

such that a utility-scale demonstration installation of the technology is warranted.

The project includes both parametric tests injecting the sorbents in a once-through mode, as well as longer-term testing in a recycle mode.

1.3 Project Team and Co-Sponsors

The project team involved in the pilot-scale testing of the new sorbent consisted of Sorbent Technologies Corporation and the Ohio Edison Company. The Ohio Coal Development Office (OCDO) of the Ohio Department of Development, an important sponsor, provided approximately 50 percent of the overall project funding. Mr. Richard Chu was the OCDO project officer. OCDO supports the research and development of coal-related technologies that encourage the use of Ohio coal. Sorbent Technologies, 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, Sorbent Technologies' research and engineering facilities in Twinsburg, Ohio and Ohio Edison Company's R.E. Burger power plant near Shadyside, 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 project consulting. The Electric Power Research Institute donated a COHPAC microbaghouse for use during the project. Under contract, the Ohio Agricultural Research and Development Center of the Ohio State University carried out the greenhouse testing.

1.4 Description of the New Technology

Fundamental to the new technology are composite sorbents called "Fluesorbents." These granular sorbents contain a hydrated lime coated onto the large internal surface areas of inexpensive mineral supports, such as exfoliated vermiculite or expanded perlite. See Figures 1.2 and 1.3. Because of the mineral supports' unique sponge-like characteristics, the sorbents can carry with them the high amount of moisture needed for optimum acid-gas removal.

Sulfur dioxide removal rates are enhanced by recycling the Fluesorbents a number of times through the gas stream. The Fluesorbents are very large relative to typical FGD powders, about 10,000 times the mass of individual hydrated-lime injectants. Consequently, they are easy to mechanically remove from the gas stream and particulate problems do not result, even with the increased loading that recycling entails. For example, the sorbent can be injected at a $\text{Ca}:\text{SO}_2$ stoichiometry of 10:1, but be recycled an average of five times, yielding a net stoichiometry of 2:1. To ensure that particulate emissions are reduced, rather than increased, Fluesorbent injection can be optionally accompanied with a microbaghouse.

Unlike other coal technology wastes, saturated Fluesorbents contain a large amount of a premium horticultural growth medium, the sponge-like exfoliated vermiculite or perlite. Both of these materials are commonly used in greenhouse soils. By halving lime consumption by doubling the utilization rate, these mineral supports pay for themselves in the FGD application. But more importantly, because of the vermiculite or perlite supports, saturated Fluesorbents are not wastes, but are rather feedstocks for valuable soil-amendment by-products. Once saturated with SO_2 , it appears that they can be advantageously applied to agricultural or turf lands either directly by themselves or pelletized. Initial greenhouse tests have been promising. A U.S. patent, No. 5,627,133, was recently issued to Sorbent Technologies covering such by-products.

Vermiculite is an alteration mineral, a magnesium silicate. Perlite is a form of obsidian, a volcanic glass. These industrial minerals possess the unusual property of expanding tenfold in volume when heated. Internal water turns to steam and they pop like popcorn, yielding a high surface area support for incorporating the lime. A fine, waste grade of exfoliated vermiculite is used in Fluesorbents, or a similarly fine grade of popped perlite. Raw material prices vary, but are in the range of \$50 to \$70 per ton. Geographically, vermiculite is readily available in the Eastern U.S.; perlite is more available in the West. Both are common in numerous regions around the world.

Fluesorbents are easily produced. The vermiculite or perlite ore is thermally expanded in the traditional, automated manner. This expanded base allows for a very high loading of reactive species, hydrated lime, with a resulting sorbent composition of about 60-wt% $\text{Ca}(\text{OH})_2$. The material is then moistened before injection. A key to Fluesorbent FGD performance is their moisture-carrying-capacity. Because their mineral supports are like sponges, the sorbents can be heavily loaded with water, up to 35 wt%, yet remain free-flowing and dry to the touch. Thus, they carry their water with them, right along with the widely-exposed lime. On a high-sulfur gas stream, very little humidification water is needed because most of the water needed to cool the gas to a reasonable approach-to-saturation temperature is injected with the sorbents.

Figure 1.2 Fluesorbent and uncoated vermiculite. Moist, yet free-flowing, the supported sorbents on the left are fine enough to be entrained in a gas stream, yet coarse enough to be easily removed once saturated.

Figure 1.3 Photomicrograph of supported sorbent. The fine lime imbedded in exfoliated vermiculite. The white line on the left is 100μ long. The sorbent is 60 wt% $\text{Ca}(\text{OH})_2$ on a dry basis, with an average particle size of about 200μ . Photo by Cornell University.

Fluesorbents can be used in either of two modes: with an added microbaghouse or as a simple retrofit.

If the existing particulate removal device is a marginal performer, then a microbaghouse is added to the circuit, such as the Electric Power Research Institute's COHPAC (COmpact Hybrid PArticulate Control) pulse-jet device. These units can operate with acceptable pressure drops at air-to-cloth ratios of 12 to 16 acfm/ft², rather than 2 to 4 acfm/ft², and their size and cost are proportionally reduced. Operating in this mode, Fluesorbent is injected into ductwork after the original particulate device, scalped out before the new baghouse, remoistened upon recycle, and with make-up sorbent, reinjected a few times. Fly ash and sorbent do not mix. This design has higher capital costs because of the added baghouse, but it allows for improved particulate reductions, higher SO₂ performance, and a cleaner agricultural by-product. Any existing fly ash sales would be unaffected, which is not the case with most other retrofit FGD technologies. The added microbaghouse could also remove extra fine-particulate air toxics.

On the other hand, if the existing particulate removal device works well, a simple retrofit configuration is possible. Capital costs are very low, because little construction is necessary. Existing ductwork and particulate collection is used, although the fly ash handling system would need to be upgraded or a mechanical collector inserted before the ESP. In this mode, the Fluesorbent is injected into the ash-laden stream ahead of the existing ESP, scalped out at the ESP entrance, remoistened, and recycled back to the injection point with some make-up sorbent. A stoichiometric amount of saturated Fluesorbent is continuously drawn off, along with the fly ash.

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

1. Capital costs are lower than with comparable technologies.
2. The technology is readily retrofitable.
3. No wastes are generated requiring disposal.
4. Useful by-products are produced.
5. Relatively high SO₂ removals can be attained.
6. Excess fine particulates, including air toxics, can also be removed if a microbaghouse is added.

2. Preliminary Testing

2.1 Bench-Scale System

In order to establish the design and test parameters for the Burger pilot plant, a 100-acfm bench-scale screening test system was designed, built, and installed at Sorbent Technologies' facilities. This allowed the pre-testing of various process parameters while the project was initially delayed waiting for Babcock & Wilcox to leave the pilot plant site.

2.1.1 System design

In this preliminary testing, the trial supported sorbents were metered into hot, simulated flue gas traversing 80 feet of pipe ductwork and the SO₂ removal rates were recorded. The system was designed similarly to, but twice the size of, equipment used at the U.S. Environmental Protection Agency's laboratories in Research Triangle Park, N.C. that earlier had demonstrated promising results with the sorbents. The laboratory system consisted of six separate sub-systems: sorbent preparation; flue gas production; humidification and SO₂ spiking; sorbent injection; gas sampling and data collection; and sorbent collection. These are shown in Figures 2.1 and 2.2.

2.1.2 Subsystems

Sorbent Preparation. The sorbents were prepared from commercial hydrated lime, -200 mesh in size, supplied by the Dravo Lime Company from its Black River facility. Expanded #5 grade vermiculite, -30 mesh, an inexpensive waste grade, was supplied by the Virginia Vermiculite Corporation. Expanded perlite of a similar size was supplied for the perlite run by PVP Inc. of North Bloomfield, Ohio.

To make the sorbents, the hydrated lime and exfoliated vermiculite were mixed together in a twin-shell V-blender and a measured quantity of water was added. The materials were then further mixed and the resulting moist sorbents were screened to break apart any agglomerations. Each batch was approximately 20 lbs. For the majority of the tests performed, the sorbent was 35% moisture by final weight. This value was experimentally determined as near the top moisture loading the sorbent could hold and still be dry to the touch and free-flowing.

Flue Gas Production. Flue gas in the laboratory was produced by combusting bottled propane gas with a controlled amount of excess air dilution in a burner chamber. Through careful control and regulation of the air-to-fuel ratio, constant combustion temperatures of about 550 °F were maintained. The rest of the system duct and equipment heated to steady-state conditions in approximately one hour. Use of actual combustion gas provided some carbon dioxide in the gas stream for carbonation to compete with sorbent sulfation.

Humidification and SO₂ Spiking. The combustion gas and dilution air did not naturally contain enough water to simulate a utility flue gas, so a humidification vessel was installed. Normally, utility humidification would be done by in-duct sprays, but the 3-in. (7.5-cm.) diameter duct was too narrow. Consequently, a dual-fluid air atomizing nozzle in a packed drum was utilized to produce fine water droplets. These evaporated into the gas, cooling it and providing the proper humidity. Wet-bulb temperatures ranged from 116 to 120 °F, as in a coal-fired flue gas. To further simulate the flue gas of a coal-fired boiler, bottled SO₂ was added and mixed into the flue gas after it was humidified. The SO₂ inlet rate was controlled by a mass flow controller.

Figure 2.1 Schematic of the laboratory duct-injection test system.

Figure 2.2 The 100-acfm laboratory duct-injection test system. The system begins with a burner at the bottom left and ends with the exhaust fan at bottom right. Most of the 3-in-diameter ductwork circles the ceiling.

Sorbent Injection. The sorbent was introduced into the duct moistened. The sorbent was not actually injected in these small-scale trials – it was metered in with a screw at about 50 g/min for a Ca:SO₂ stoichiometry of 2.0. Proportionately more was fed during the recycle runs. This subsystem consists of a feed hopper and a variable speed screw feeder supplied by AccuRate Inc. Different size helixes were utilized for different sorbent composition and target feed rates.

Prior to the start of every test run, a known mass of sorbent was placed in the feed hopper and the screw feeder was calibrated at the negative pressure expected during the run. The negative-pressure calibrations resulted in better control of the feed rate. Even with this adjustment, however, the feed rates were often slightly different than planned. A careful materials balance after every run made it possible to calculate the actual average Ca:SO₂ ratio utilized during a run. Care was taken to ensure as uniform a feed rate as possible.

Ductwork. The laboratory system was designed for about 130 Nm³/hr of gas flow, or 2,200 lpm. The "duct" was constructed of insulated, galvanized steel pipe, with an inside diameter of 7 centimeters. To achieve a total length of 35 m, it was necessary to change the flow direction through seven 90° elbows. The sorbent was introduced into the gas in an upward duct section. The ducting then circled the ceiling for about 27 m before descending into a small cyclone and passing to a baghouse. The gas speed averaged about 11 actual meters-per-second, with a residence time of 2.4 seconds between sorbent injection and the cyclone.

Sorbent Collection. Sorbents were separated from the flue gas by a scalping cyclone and back-up baghouse. In this manner, the baghouse receives a much smaller load and its finer fraction can be removed separately. The cyclone was a commercial unit supplied by Kice Industries, Inc. The small two-bag "microbaghouse" was custom-made and patterned after a high air-to-cloth-ratio "COHPAC" baghouse recently developed by the Electric Power Research Institute (EPRI). Sorbtech has acquired a license to the new COHPAC technology. The sorbents captured by the cyclone and the fines found in the baghouse were both very quickly dried in the duct from 35 wt% down to a very-dry 2 to 4 wt% residual moisture.

Gas Sampling and Data Collection. In addition to the masses and moistures of sorbent that were determined before and after each run, data on gas temperatures, pressure drops, flow rates, and gas compositions were monitored and recorded. Data were collected manually. Dry-bulb gas-temperature measurements were made at five to nine duct locations and wet-bulb gas-temperature measurements were made at one or two locations. Pressure drop measurements were made both across the baghouse and across the total system. Flow rates were determined using an in-line orifice plate. The gas flow was kept constant during each run by adjusting a variable-speed controller on the exhaust fan at the end of the system.

The sulfur dioxide and oxygen concentrations of the flue gas were recorded for three locations during the majority of runs. Heated sample lines continuously drew sample gases from before sorbent injection, before the cyclone, and after the baghouse. The gas analysis system was manually toggled back and forth between these three lines. In the later project runs, SO₂ and O₂ levels at up to eight different locations down the duct length were recorded, producing a time and distance profile. An Horiba PIR-2000 non-dispersion infrared analyzer was used for the SO₂ analyses and an Horiba CMA 321 magnetopneumatic analyzer was used to measure oxygen levels. Measurements of oxygen were taken in parallel with SO₂ to detect and correct for any degree of air leakage into the system during the test runs. A sample-gas conditioning system dropped the temperature and condensing water from the three sample gases before they passed through the analyzers.

2.2 Bench-Scale Results

A test program using this bench-scale system helped determine the sorbent preparation procedures, raw material source selections, equipment design, and operating conditions that were to be employed in the larger pilot-plant system. Below is a matrix of over 40 different bench-scale tests that were performed. A table listing all of these results can be found in Appendix A. The standard sorbent consisted of 60 dry wt% lime and 40 dry wt% vermiculite, with 33 total wt% moisture. The standard test conditions consisted of SO₂ at 1800 ppm, a final gas temperature of about 150F, an approach to adiabatic saturation (T_{app}) of 30F, and a Ca:SO₂ stoichiometric injection ratio (SR) of 2. The standard gas flow was 2200 lpm with a sorbent feed rate of about 50 g/min.

Table 2.1 Parameters tested at the bench-scale.

<u>Sorbent Composition and Operating Conditions Tests</u>	
baseline/control: lime only	SR = 1.5, 2, 3, 6
injection parametrics: standard sorbent	SR = 1.5, 2, 2.5
standard sorbent	T _{app} = 10, 15, 20, 30F
standard sorbent	SO ₂ = 600, 1200 ppm
sorbent variations: 30 wt% lime	T _{app} = 15, 30F
vermiculite < 100μ	SR = 1.25, 1.67, 2
vermiculite > 300μ	SR = 2, 6
heat-treated	SR = 1.25, 2, 3
perlite base	T _{app} = 30, 50F
different moisture levels: 15 wt% moisture	SR = 2.5
20 wt% moisture	SR = 2.5, 7, 10
25 wt% moisture	SR = 2.5
35 wt% moisture	SR = 2.5, 5
<u>Sorbent Recycle Tests</u>	
standard sorbent series	SR = 6, 3, 2, 1.5
standard sorbent series	SR = 10, 5, 3.33, 2.5, 2
perlite sorbent series	SR = 8, 6, 4, 2

2.2.1 Sorbent composition and operating condition tests

Lime standards. Plain hydrated lime, without the vermiculite supports, was tested as a comparative baseline. These tests had the poorest performance, even though these runs had the lowest average approach-temperature histories. Injected into gas already humidified down to a temperature of 160 F, for example, lime at an SR of 1.5 yielded only 7% SO₂ removal. An SR of 3.4 only yielded 30% SO₂ removal.

Stoichiometric ratio. Over the course of the project, the injected lime-to-SO₂ SRs of the standard sorbents were tested ranging from 1.2 in the once-through mode to 10 in the recycle runs. As expected, SO₂ removal performance increased with increasing SR. Once-through Ca:SO₂ stoichiometries of only 2 did not result in 80 to 90% SO₂ removal rates. In order to achieve such high levels in the pilot plant, injecting at higher rates is specified, but recycling the sorbents (reinjecting them) so that lime consumption stays low. Because the supported sorbents are very large and easy to remove from the gas stream, it is feasible to recycle them numerous times, resulting in a high equilibrium amount of reactant in the duct.

Approach temperature. With one or two exceptions, the bench-scale data covered a range of final adiabatic approach temperatures of 60 F to 20 F. The closer approach temperatures improved the removal rates considerably. A 20 F to 30 F design approach temperature is specified for the pilot plant.

SO₂ level. On the bench-scale unit, six runs were performed at 600 ppm SO₂, one at 1200 ppm, and twenty-four at 1800 ppm. Other duct-injection processes have reported results varying with the SO₂ level. However, over the range of common concentrations explored, the level of SO₂ in the flue gas did not itself appear to affect supported-sorbent performance.

Sorbent size. Different sorbents were made from a fine, < 100 μ fraction of vermiculite and a coarse, > 300 μ fraction. Over a range of SRs and approaches, the data from both runs seemed indistinguishable from that of otherwise similar runs. Within this range of vermiculite sorbents, sorbent size does not appear to be a major factor affecting performance.

Sorbent lime loading. Two tests used supported sorbent with a 30 wt% lime loading on the vermiculite, rather than 60 wt%. Thus, about 30 grams of lime on 40 grams of vermiculite were injected per minute, rather than 30 grams of lime on 20 grams of vermiculite. The resulting performance was not noticeably improved. Because it is most economical to load as much lime on the supports as is physically possible, i.e. 60 wt%, this is the loading rate specified for the pilot tests. Also, in a few other tests, the sorbents were heat-treated before moistening. This did not seem to appreciably affect SO₂ removal performance and, so, is not recommended.

Perlite. In a couple once-through tests, fine expanded perlite was used instead of vermiculite. This inexpensive mineral can also be used as a sorbent support. The resulting performance at similar injection stoichiometries was only slightly less than with vermiculite supports. The lime loading and moisture content were not individually optimized for perlite for these tests. Because the perlite results were comparable to those of vermiculite, it was recommended to expand the investigations of perlite as an alternate support material in the pilot testing program.

Sorbent moisture level. A minimum moisture level of 10 to 15% is needed with supported sorbents to originally bind the lime to the vermiculite interstices. However, if the sorbent moisture level becomes too high, sorbent handling and injection becomes problematical. If the moisture level exceeds 40%, the material begins to lose its free-flowing properties.

A series of runs on the standard vermiculite supported-sorbents was performed to determine their optimum moisture level for SO_2 removal. See the results in Figure 2.3. (The test at the 25 wt% moisture level missed its target stoichiometry. At the same injection ratio as the others, a slightly higher removal rate could be expected.) The results indicated a direct relationship between initial sorbent moisture content and gas-phase sulfation. The optimum initial moisture level for these sorbents appears to be at about 35 wt% water.

Carbonation. An undesirable carbonation reaction inevitably competes with the desired sulfation reaction in the sorbents. To begin to examine this phenomenon, duplicate saturated samples from the perlite recycle series were sent to the Leco Corporation for carbonation analysis. The results appear in Figure 2.4. The sulfation and carbonation reactions appear to proceed differently. Unlike the sulfited fraction, which grows with each new reinjection, the carbonate content of the sorbents levels off at about 15% of the theoretical calcium utilization. The carbonate fraction may even decrease a bit in later runs as the remoistening step puts carbonate into solution temporarily, leading to additional sulfation. Fortunately, carbonation does not appear to significantly decrease the desulfurization abilities of the Fluesorbents.

2.2.2 Recycle runs

Supported sorbents are made for recycle. Their large size means that even a large loading in the duct can be easily separated from the flue gas. Consequently, they can be injected, collected, remoistened, and injected again until a large amount of their reactivity is utilized. Remoistening the sorbents acts to reactivate the unutilized $\text{Ca}(\text{OH})_2$ and any CaCO_3 , as well as provide the gas with evaporative cooling.

By recycling most of the partially-saturated sorbent back into the duct, the gas is exposed to a greater amount of reactive material, and greater SO_2 -removal results.

Three recycle series were tested in the apparatus. In one series, a batch of standard Fluesorbents was initially injected at an SR of 10:1 into a gas stream with 600 ppm SO_2 . Fully 97% of the SO_2 was removed. The partially-saturated sorbents were then collected, remoistened, and injected a second time. They removed 86% of the SO_2 from the new gas, for an average of 91% of the total gases. The materials were recycled three more times for a total of five cycles and a net SR of 2:1 (i.e. 10/5). The average SO_2 -removal over all the cycles was 70%.

Another recycle series of four runs was carried out with standard supported sorbents at an initial SR of 6 and a series of four runs with perlite-based sorbents was performed with an initial SR of 8. Table 2.2 summarizes these recycle results.

Figure 2.3 SO₂ removal rate as a function of sorbent moisture.

Figure 2.4 Cumulative carbonation and sulfation of recycled perlite sorbent.

Table 2.2 Bench-scale recycle results.

	Initial SR	Average SR	Avg. Approach	Avg. SO ₂ Removal
lime/vermiculite	10	2.5	35F	0.60
	10	2.0	34F	0.70
lime/vermiculite	6	2.0	28F	0.62
	6	1.5	28F	0.59
perlite/vermiculite	8	2.7	33F	0.85
	8	2.0	33F	0.62

2.2.3 Heat and mass transfer model

The fluid-particle behavior and mass-transfer characteristics of the large, injected Fluesorbents are very different than that of fine powders or liquid slurries. In order to develop a better understanding of Fluesorbent injection, Sorbent Technologies applied for and was awarded a grant by the National Science Foundation to model the process (NSF SBIR Phase I Award Number III-9360087).

In this NSF project, outside of the scope of the OCDO project, a model of in-duct Fluesorbent sulfation was constructed from heat and mass transfer principles. This model is detailed in Appendix B.

The model constructed from heat and mass transfer principles proved to be quite robust in describing the chemical sulfation of the relatively large, evaporating Fluesorbent particles. In simple form, the model reduced to:

$$X = -\ln(1 - \epsilon_{SO_2}) = C \left(\frac{SR}{(\Delta T)_{lm}} \right)$$

where:

- X = the number of SO₂ mass transfer units;
- ϵ_{SO_2} = in-duct SO₂ removal rate;
- C = proportionality constant, empirically about = 10;
- SR = stoichiometric lime-to-SO₂ injection ratio; and
- $(\Delta T)_{lm}$ = log-mean approach temperature of injected sorbent.

When applied to the model, the empirical data from the bench-scale duct-injection apparatus followed this framework closely. See Appendix B. The stoichiometric lime-to-SO₂ injection ratio, SR, and the log-mean approach temperature of injected sorbent, $(\Delta T)_{lm}$, proved to be the determinative variables. Also, as the model predicted, the results of the parametric tests showed little sensitivity to flue gas SO₂ concentration or the use of recycle material.

3. Pilot-Plant Demonstration

3.1 Pilot-Plant Site

The original site offered by the Ohio Edison Company for the project pilot plant was their Edgewater station, located in Lorain, Ohio. After the original pilot-plant drawings for this facility were prepared, but before purchase orders for equipment were placed, Ohio Edison announced that it was mothballing the Edgewater plant. As a replacement, Ohio Edison offered to host the project at its R.E. Burger station in Belmont County, located near Shadyside, Ohio. A site in the fan building was selected. Babcock & Wilcox was already at this location with their SNRB demonstration and Sorbent Technologies had to wait for a time until they finished and abandoned the site.

Ohio Edison's base-loaded R.E. Burger station burns local Ohio high-sulfur bituminous coal. The flue gas typically contains about 1800 ppm SO_2 . The Sorbent Technologies test facility was designed to be able to take a 4500-scfm slipstream of flue gas from either of two of the plant's 156-MW boilers trains, after the electrostatic precipitators (ESPs).

Figure 3.1 Ohio Edison's R.E. Burger power plant, the project's location.

3.2 Pilot-Plant Systems

Based on the earlier preliminary test results, a 6,500-acfm, 2-MW pilot-plant test facility was designed, constructed, and installed at Ohio Edison's Burger station. The Fluesorbent pilot demonstration facility included sorbent production and injection, flue-gas humidification, a run of insulated fiberglass-reinforced plastic (FRP) ductwork where the SO_2 removal takes place, a cyclone, the EPRI COHPAC microbaghouse, a measurement venturi, an I.D. booster fan, heat-traced sample-gas lines, various gas-analysis instrumentation, and a computerized data-acquisition and control system. See Figure 3.2 for a schematic of the facility. An optional fly ash injection system was included so that the simple retrofit mode could also be simulated.

The facility had eight subsystems:

1. Sorbent Production	5. Particulate Removal
2. Sorbent Injection	6. Fly Ash Injection
3. Ductwork	7. Sampling and Gas Analysis
4. Humidification System	8. Data Acquisition and Control

Figure 3.2 Schematic diagram of the pilot plant.

3.2.1 Sorbent production

Supported-sorbent production equipment was designed, constructed, and installed at the Burger site. This equipment was also capable of preparing recycled sorbents for reinjection. While the original plans called for only a 2 ton-per-day facility, the actual unit was upgraded to an 8 tons-per-shift capacity, or 1.0 ton of sorbent per hour.

The sorbent raw materials, lime and expanded vermiculite or perlite, were delivered, stored, and handled in supersacks. This made accounting for the various different test runs and saturation cycles easier. Each supersack contained approximately 160 cu.ft. of material. A supersack of saturated sorbent weighed approximately 1,000 lbs.

A skid-mounted sorbent production unit produced Fluesorbent on-site and fed it directly to the pilot plant ductwork. The supersacks were first loaded into two process bins on the production skid. The hydrated lime and either vermiculite or perlite were then fed from bins by volumetric feeders to the production system based on the SO_2 level of the gas stream and the $\text{Ca}:\text{SO}_2$ injection ratio desired. The materials were dry-mixed in a screw conveyor at a 60:40 weight ratio, moistened with a spray to about 25 wt% water, and fed through an airlock to the pneumatic sorbent injection system. When operating in the recycle mode, the materials collected from the cyclone and the baghouse were also fed to the bins and through the volumetric feeders to the mixing, moistening, and injection operations.

Calcitic lime from Dravo Corporation's Black River plant was the baseline hydrate used; additional sorbent tests included a dolomitic lime from Genlime Corporation and a calcitic lime from Chemical Lime Company. The various quantities of different sorbents produced over the course of the project are listed in Table 3.1.

Figure 3.3 Sorbent production skid.

Table 3.1 Amounts of sorbents produced and recycled.

	Sorbent	Produced Fresh	Recycled thru Unit
Shakedown runs	vermiculite/calclitic lime	3,000 lb.	
Parametric runs	vermiculite/calclitic lime	4,000 lb.	
	perlite/calclitic lime	1,000 lb.	
	vermiculite/dolomitic lime	4,000 lb.	
	vermiculite/magnesia	1,000 lb.	
Recycle runs	vermiculite/calclitic lime	6,000 lb.	25,000 lb.
	perlite-based calclitic lime	6,000 lb.	25,000 lb.
Long-term run	vermiculite/calclitic lime	18,000 lb.	75,000 lb.

3.2.2 Sorbent injection

Fluesorbent from the production skid was pneumatically conveyed to a single sorbent injection port and injected into the ductwork. The sorbent quickly dispersed across the entire duct cross-section. A view port allowed observation of the flow patterns of the sorbent leaving the nozzle. A number of different ports were constructed to allow the injection to be tried at different locations with different resulting residence times.

3.2.3 Ductwork

A key capital-cost advantage of the Fluesorbent technology is that no additional FGD vessels are required; the SO₂ removal takes place in existing ductwork. At Burger, 18-inch diameter steel duct took the project slip stream off from inlet gates on the exhaust sections of two Burger I.D. fans after the ESP. The intake flue gas temperature averaged 300°F and contained from 1200 to 2400 ppm of SO₂. A straight run of 100 feet of 18-inch diameter fiberglass reinforced plastic (FRP) duct eight feet off the ground was constructed and used for the injection tests. The flue gas velocity averaged about 50 ft/sec and the sorbent residence time averaged 1.3 seconds. Figure 3.4 shows a horizontal test section of the duct, with humidification in the foreground and the sorbent injection farther downstream. Ductwork also connected the cyclone, microbaghouse, venturi flowmeter, and booster fan before returning the cleaned flue gas back into the Ohio Edison's header to the stack. A flow-control damper at the outlet of the booster fan allowed remote adjustments of the gas flow from the project control room.

3.2.4 Humidification system

A humidification port was located at the beginning of the FRP duct. A single dual-fluid humidification nozzle 30 feet upstream of sorbent injection nozzle was used to supplement the sorbent moisture and help achieve the desired approach temperature. Approximately 20 percent of the total water was added through humidification; 80 percent was evaporated directly from the sorbents themselves. Humidification air pressure at around 70 psi was used and the water flow rate ranged from 0.2 to 0.8 gpm, depending on the conditions required.

Figure 3.4 Humidification port, sorbent injection port, and duct run where SO_2 is removed.

Figure 3.5 COHPAC microbaghouse, baghouse control trailer, and spent sorbent silo.

3.2.5 Particulate removal

Because of the relatively large size of the Fluesorbents, approximately 250 microns in diameter, most of the gas stream particulate matter is collected by the cyclone. The fine particles that escape this mechanical collector were captured by a pilot COHPAC pulse-jet baghouse which operated at a high air-to-cloth ratio. Air-to-cloth ratios of 8 and 12 acfm/ft² were utilized during the test program. When the pressure drop across the Ryton bags increased to 7 in. WG., the cleaning cycle would actuate and air jets would pulse until a 4 in. WG pressure drop was achieved. Sorbent Technologies is a licensee of the COHPAC technology.

Materials were collected from both the cyclone and the baghouse and recycled to the production skid to increase their sorbent utilization. See Figure 3.5 for a photograph of the microbaghouse, its control trailer, and the spent sorbent bin.

3.2.6 Fly ash injection

To simulate the fly ash loading under simple-retrofit scenario, a pneumatic ash injection system was used during some runs. Dry fly ash collected by the plant ESP was fed by a volumetric feeder at representative rates to the gas stream ahead of the Fluesorbent system. Two bends ensured that the fly ash particles were well-dispersed and no agglomeration was observed. This system was used only in tests simulating Fluesorbent operation without an added microbaghouse.

3.2.7 Sampling and gas analysis

Flue gas samples were drawn from three probes located at the inlet of the duct system, at the outlet of cyclone, and at the outlet of baghouse. The sample gases were continuously drawn through particulate filters and heated sampling lines to the process control room where the sample-gas conditioning unit was located. The conditioning unit condensed the moisture from the sample gases, regulated their pressures and flow rates, and fed the gases to SO₂ and O₂ analyzers. SO₂ was measured with an Horiba PIR 2000 NDIR analyzer. Oxygen was measured with an Horiba CMA 321 NDIR cross flow modulation magnetopneumatic analyzer. The oxygen concentrations were measured in order to correct the SO₂ readings to account for things like dilution caused by the humidification and pneumatic injection air and any sampling line dilution, which might indicate artificially-high SO₂ removal rates.

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. 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 90 seconds of each sampling were averaged and recorded. The gas analysis system also provided reference gases and a regulated vacuum source required by the analyzers. The Horiba instruments were calibrated using zero and SO₂ span gases before and after each run. Additionally, every three hours during testing the sample lines would be back-purged with compressed air to insure that they remained clean.

Table 3.2 Data collection summary.

Parameter	Sampling	Instrumentation
Dry-bulb temperatures	8 places in flue gas stream	K-type thermocouples
Wet-bulb temperatures	Manual, at the sorber outlet	K-type thermocouple covered with a wetted wick.
Pressure drop	5 places	transducers, pitot tubes
Gas flow rate	In-line	venturi with 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.
O ₂	Before humidification Before sorber After sorber	Horiba CMA 231 using a magnetopneumatic detector.
Data acquisition	Averages after values reach equilibrium	Dell 486 PC and LabTech Notebook XE software.

3.2.8 Data acquisition and control

A PC-based data acquisition and control system monitored most of the pilot plant operation. The data acquisition system included a Dell 486 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. In addition to SO₂ and O₂ concentrations at the three sample points, system temperatures at eight different points were measured and recorded, absolute or differential pressures were measured at five points, relative humidity was continuously monitored, and the flow control damper was electronically controlled. A separate automatic control system was used for the microbaghouse. Manual readings were periodically taken of wet bulb temperatures. As an added precaution, the important conditions and performance data were also periodically manually recorded during test runs.

4. Parametric Studies

Initial pilot plant testing consisted of various parametric tests, where different process parameters were varied and the corresponding effects on overall performance were determined.

4.1 Gas and Sorbent Parameters

The power plant slipstream offered only limited flexibility in varying the chemical composition of the flue gas. Because of the scale, the SO_2 level could not be readily changed. Chemically, the flue gas slipstream to the pilot plant varied from about 1000 - 2200 ppm SO_2 and 6.5 - 10.0% O_2 , depending on the coal fired and the plant operating conditions. The flue gas entering the supported-sorbent system usually had a dry bulb temperature of about 300 F and a wet bulb temperature of from 115 to 120 F.

4.1.1 Moisture content of the gas

By adding water to the sorbents or with supplemental humidification, the moisture level of the flue gas could be modified. The sulfur dioxide removal ability of lime-based sorbents varies greatly with the relative amount of water in the gas stream. A measure of the moisture content of a gas is its approach to adiabatic saturation ("approach temperature"), which can be measured as the difference between the gas dry-bulb temperature and its wet-bulb temperature. In one set of three low-stoichiometry once-through pilot plant runs with calcitic lime and vermiculite sorbents, the gas wet-bulb temperature was varied between 20 and 60 F. The corresponding removal rate relationship is plotted in Figure 4.1. As others have observed with plain lime injection, the SO_2 removal rate of supported sorbents increases significantly at lower approach temperatures.

Figure 4.1 Effect of approach temperature at $\text{Ca}:\text{SO}_2 = 2$.

4.1.2 Sorbent variations

Various sorbent compositions were also examined in the parametric testing. Below is a relative comparison of various once-through SO₂-removal results of low-stoichiometric injection-rate runs with different sorbent compositions. The stoichiometric injection ratios varied between 1.60 and 2.70 in these runs, so the results are reported as sorbent utilization to normalize the comparison. Higher utilizations at higher approach temperatures are better. The approach temperature of each run is also listed. All materials were 60 wt% alkaline reactant and 40 wt% vermiculite, except the lime alone, which was 100% commercial-grade Ca(OH)₂.

Table 4.1 Relative performance of different sorbent compositions.

Sorbent Composition	Utilization	Utilization	Comments
Calcitic lime/verm.	0.26 @ 30F	0.17 @ 46F	very good performance.
Dolomitic lime/verm.	0.17 @ 33F	0.12 @ 46F	modest performance.
Magnesia/vermiculite	0.22 @ 25F	---	modest performance.
Lime alone	0.15 @ 32F	0.12 @ 42F	high duct deposition; particulate control problems.
Sodium/vermiculite	---	---	poor sorbent quality; injection not attempted.

In this duct-injection mode, the highest parametric performance was exhibited by sorbent made with calcitic hydrated lime. The calcitic lime that was used in most of the project runs was obtained from the Dravo Corporation's Black River plant. Calcium-based sorbents performed significantly better than those containing magnesia. Dolomitic lime, from GenLime of Genoa, Ohio, only performed modestly. Dolomite contains a significant amount of magnesium oxide replacing the calcium oxide. Supported sorbents made exclusively from magnesia also performed only modestly. The magnesia was acquired from Premier Services Corporation of Bettsville, Ohio.

Hydrated lime, without any vermiculite or perlite supports, was run as a baseline. Its performance was modest and corresponded to what other researchers have observed. However, significant operational problems were experienced when the lime was injected without the supports. Sorbent deposits quickly accumulated on the duct walls. Additionally, the fine lime particles passed through the cyclone and the baghouse became overloaded, which necessitated continuous bag pulsing in order to lower the pressure drop. Adding the large, moisture-retaining mineral supports to the sorbents alleviated the problems.

4.1.3 Stoichiometric injection ratio (SR)

The more unreacted sorbent that there is in the duct at any one time, the higher the SO_2 removal rate will be. Data from five runs with different injection rates are plotted logarithmically in Figure 4.2. By recycling some supported sorbent back for reinjection, the higher removal rates on the right of this plot can be exploited.

Figure 4.2 Effect of stoichiometric injection ratio.

4.1.4 Sorbent moisture

Lime/vermiculite sorbents with 20, 25, and 30 wt% water were injected into the ductwork in another parametric run. The outlet temperature was held constant by simultaneously decreasing supplemental humidification. No significant sorbent performance differences were noted. Consequently, most remaining runs were done with 25 wt% moisture in the sorbents, which minimized any handling problems.

4.1.5 Flue gas velocity

By cutting back the volumetric gas flow, the velocity of the gas and the injected sorbent, and their residence times in the duct, could be varied. As the gas velocity is lowered, at some point the sorbents will not remain entrained and begin to drop out. Sorbents of calcitic lime and perlite were tested for this potential limitation. See the data in Table 4.2. As long as the flue gas velocity remained above about 30 fps, sorbent drop-out was not significant. As most utility flue gas velocities are in the range of 60 fps, the applicable turn-down ratio of a supported sorbent installation appears adequate.

Table 4.2 Effect of gas velocity and duct residence time.

Gas Flow (ft/sec)	Residence Time (sec)	Observations
30	2.0	very slight drop-out
40	1.5	no deposition
60	1.0	no deposition

In the relevant range, the flue gas velocity and associated duct residence time, by themselves, did not appear to effect the SO₂ removal rate. Earlier bench-scale results showed that Fluesorbent reaction rates are very fast and that once the water has evaporated from the sorbents, little additional SO₂ removal takes place. Consequently, given adequate mixing, longer residence times in the duct are not significantly advantageous.

The earlier bench-scale testing narrowed down or eliminated some of the parameters originally scheduled for larger-scale testing. For example, it was found that a dry sorbent composition containing 60 wt% alkali proved to be the optimum loading and that fine limes were preferable to coarse limes. Thus, these variables were not to be tested significantly at the pilot scale. Nor was a sodium sorbent scheduled to be run, as it was found to make a physically poor sorbent and smaller-scale runs showed little promise. Also, supported sorbent, by itself, proved not to sorb mercury, so mercury removal was not pursued further. Instead, substitution runs examining different limes were added to the test program (dolomitic lime, Chemical Lime calcitic lime) and, because of good initial results and favorable projected economics, the test program for perlite supports was significantly expanded. Additionally, parametric runs were added examining various equipment and process variables that were found to be very important. These included: injecting humidification-first versus sorbent-first; injecting upstream versus downstream; injecting with and without a flared nozzle; and injecting with and without a delumper.

4.2 Design Parameters

4.2.1 Injecting humidification-first versus sorbent-first

The pilot unit was designed to allow the placement of the supplemental humidification to be either before or after the supported sorbent injection. SO_2 removal performance proved better with the humidification first. With the humidification first and an approximate 25 °F approach, average five-cycle SO_2 -removal was 91% at a 2.5:1 injection ratio and 87% at a 2:1 ratio. With the sorbent injection first, corresponding values were only 75% and 71%.

More importantly, when the sorbent was injected ahead of the supplemental humidification, sorbent duct deposits were observed. On the other hand, when the humidification occurred first, the ductwork remained clean.

4.2.2 Injecting upstream versus downstream

The sorbent pneumatic injection nozzle could be pointed either upstream, back at the gas flow, or downstream, in the direction of the gas flow. A parametric run with the nozzle pointing upstream was made. There was no improvement in SO_2 removal compared to the downstream runs. By completely changing the injection direction, however, some of the moist sorbent impacted the nozzle itself after it changed directions in the duct and built up a deposit. It was therefore concluded that downstream injection was preferable.

4.2.3 Injecting with and without a flared nozzle

Because SO_2 sorption rates are very fast with Fluesorbents, a wide initial dispersion of the sorbent in the ductwork is necessary. A special flared nozzle was constructed and its performance was compared with that of a simple open pipe. No noticeable SO_2 removal differences were noted.

4.2.4 Injecting with and without a delumper

Early runs had a rotary, mechanical delumper in the pneumatic sorbent injection circuit. Its purpose was to break down any sorbent clumps being injected. Parametric experience, however, proved that the delumper was unnecessary. Any sorbent clumps made by the production skid seemed to break apart in the injection line and equivalent SO_2 performance resulted. The delumper proved unnecessary and was taken out of the circuit.

4.2.5 Baghouse air-to-cloth ratio

The microbaghouse collects any fine lime that breaks off from the sorbents, as well as any injected fly ash. By inserting more bags into the baghouse's largely empty tube sheet, its air-to-cloth (A:C) ratio could be changed. During the parametric testing, where low stoichiometries were used to magnify performance differences, the COHPAC operated satisfactorily at an air-to-cloth ratio of 12 fpm. When the recycle runs began, additional bags were added to bring the microbaghouse A:C down to 8 fps and insure an acceptable pressure drop. No significant problems were observed operating at 8 fps.

5. Recycle and Long-Term Runs

5.1 Recycle Runs

The primary effort in the program was a series of recycle runs testing both vermiculite- and perlite-based sorbents in both the simple-retrofit and added-microbaghouse modes. These runs were performed with conditions optimized in the parametric runs: humidification first, injection downstream, 1.0 second residence time, 20 to 25°F approach temperature, 20 to 25 wt% sorbent moisture, and a net economic SR of 2.0.

A sorbent recycle rate of 4 was chosen for these runs, meaning that each sorbent batch was injected a total of five times into the duct. In an actual plant situation, this would mean a nominal SR of 10 would be continually injected, with 80 wt% of the collected sorbents remoistened and reinjected, and 20 wt% continually drawn off for by-products and replaced with fresh sorbent ($SR = 10/5 = 2:1$). Rather than test in such a continuous mode, however, each recycle test was performed as a series of five separate seriatim injection runs with the same batch of sorbents. This allowed for cleaner data and easier operations. As each sorbent batch was recycled through the duct, it would become further saturated and its performance would decrease.

The first recycle series tested standard lime/vermiculite Fluesorbents in an added-microbaghouse mode, that is, without fly ash. Approximately 2,500 lb of sorbent were injected per cycle. Data from these runs appear below.

Table 5.1 Recycle performance of lime/vermiculite sorbents.

Cycle	Approach Temp.	Nominal Stoich.	Reactive Stoich.	Cycle In-Duct Removal	Cycle Total SO ₂ Rem.	Econ. Stoich.	Average SO ₂ Removal
1	30F	8.2	8.2	82%	92%	8.2	92%
2	24F	9.5	8.0	91%	94%	4.3	93%
3	23F	10.4	7.3	84%	88%	2.9	91%
4	23F	12.4	7.4	81%	90%	2.3	91%
5	24F	10.7	5.5	65%	70%	1.9	87%

As shown above, the SO₂ removal results were excellent. Total SO₂ removal averaged 87% at a Ca:S ratio of 1.9:1. By the fifth run the material had become quite saturated and its performance began to drop.

It is important to differentiate between three different types of stoichiometric injection ratios in understanding the recycle run results:

1. The "nominal" SR is calculated based on the mass of sorbent injected assuming that all the calcium exists as potentially reactive hydrated lime.

2. The "reactive" SR is calculated based on only the reactive portion of the lime injected; it takes into account the lime that has been sulfited or carbonated on previous runs and is no longer available. The in-duct and total SO₂ removal rates corresponding to the reactive SR are those actually observed in that cycle's run.
3. The "economic" SR is the effective stoichiometry that the user sees. The user only buys the lime once. Thus, if the same batch of sorbents is injected five times, the economic SR is the SR divided by five. The removal rate corresponding to this economic SR is the average of the removal rates achieved up to that point.

The economic SRs and average removal rates are the appropriate values to use in evaluating supported-sorbent performance because they reflect the actual lime consumption and SO₂ removal observed. These values for this recycle series are summarized in Table 5.2.

Table 5.2 Recycle performance summary.

Cycle	Economic Stoich.	Total SO ₂ Removal	Utilization
4	2.33	91%	0.395
5	1.86	87%	0.471

A similar series of runs was performed with perlite-based sorbents. A figure of the perlite and vermiculite performance data appears in Figure 5.1. Mechanically, the perlite performed very similarly to the vermiculite. The SO₂-removal levels were also similar, with 74% removal in the duct at a net economic SR of 2.0 and 81% removal overall, counting the baghouse. After four cycles, when the economic SR was 2.5, the corresponding average removal rates were 79% and 87%.

A similar series of runs was performed with the two sorbents in the simple-retrofit mode. In these tests, a representative amount of Burger fly ash was injected upstream of the Fluesorbent and captured and recycled along with the Fluesorbent. This fly ash, however, did not significantly degrade the Fluesorbent performance. See the SO₂-removal results in Figure 5.2. At an SR of 2.0 and an average approach temperature of 23°F, vermiculite Fluesorbents averaged 81% SO₂ removal through five cycles; at an 19°F approach, perlite Fluesorbents similarly removed 81%.

See Appendix C for the various individual run data for both vermiculite and perlite sorbents in both the added-microbaghouse and simple-retrofit modes.

Figure 5.1 SO₂ removal in the ash-free added-microbaghouse configuration.

Figure 5.2 SO₂ removal with fly ash in the simple-retrofit configuration.

5.2 Forty-Hour Run

A longer-term continuous run was also carried out to collect further data and to see if any operational problems might become evident with time, such as injection problems or duct build-ups. The system was operated continuously, with multiple work shifts, for nearly 40 hours of run time, injecting standard 60:40 vermiculite Fluesorbents at a 20°F approach temperature in the added-microbaghouse mode. Average data for the ten serial four-hour saturation cycles is presented in Figure 5.3

In the first seventeen hours, operating at an economic SR of about 2.5, average total SO_2 -removal was 89%. In the second twenty hours, operating at a SR of 2.0, the SO_2 -removal was 82%. See Appendix C for details. Through 37 hours, when sorbent stocks ran out, over 90,000 lb of sorbent and recycle materials had been injected into ten million scf of flue gas, removing over 2,700 lb. of SO_2 .

Overall, the equipment ran relatively smoothly. In the early part of the test, mechanical problems were experienced with a sorbent feeder. After it was discovered that the feeder had been improperly reassembled, however, the pilot plant system operated as expected. No significant duct deposits were noted after the test.

Figure 5.3 SO_2 removals observed during the long-term run.

5.3 Particulate Removal

Despite the recycled Fluesorbent and fly ash injected into the gas stream, the COHPAC microbaghouse limited particulate emissions to very low levels. See Table 5.3 for particulate data taken during a perlite Fluesorbent and fly ash recycle run. Two separate measurements were made with an EPA Method 5 sampling train and procedures. Net particulate emissions amounted to only 0.0007 gr/dscf each time. Consequently, when operated with the additional microbaghouse, a Fluesorbent installation should not only achieve high SO₂ removals, but significantly reduced particulate emissions could be expected as well. To the extent that the microbaghouse captures heavy-metal particulates, air-toxic emissions would be also lowered.

Table 5.3 Net particulate removal data with the addition of a microbaghouse.

Measurement Location	Baghouse Air:Cloth	Particulate			Net Control Efficiency**
		gr/dscf	g/Nm ³	lb/MMBtu	
Inlet*	—	2.95	5.93	5.70	—
BH outlet, sample 1	7.6	0.00067	0.0015	0.0015	99.97%
BH outlet, sample 2	7.6	0.00072	0.0016	0.0016	99.97%

* Fly ash was injected into the system at this rate, which is a representative pre-ESP value for a coal-fired gas stream.

** Based on fly ash alone, not added sorbents. The gross particulate reduction efficiency would be even higher.

6. Spent Sorbent By-Products

6.1 Agricultural By-Products

A central feature of this project's technology is that once the sorbents have been used for flue gas desulfurization, they are still valuable as agricultural materials. Thus the Fluesorbent technology results in useful by-products, instead of wastes that must be disposed of. The spent sorbent materials can be used either alone as liming agents and beneficial soil amendments or be pelletized with optional additives into slow-release agricultural fertilizers.

By themselves, the new FGD materials contain the mineral supports commonly added to greenhouse soils, as well as unutilized liming values, which can buffer Ohio's acidic soils or spoils. The spent sorbent also has sulfur that is frequently beneficial to plant growth. Its granular nature makes it easy to pelletize, if a larger granule is desired.

The uses targeted are relatively high-value, with products currently serving these markets costing from \$10 to \$1000 per ton. If \$20 to \$50 per ton of value can be extracted from the saturated FGD materials, the economics of the new technology will look particularly attractive for coal-fired utilities and their ratepayers.

By pelletizing or agglomerating the spent sorbent materials with added fertilizer or pesticide compounds, an even higher-value product can be created. The materials look to be an excellent and inexpensive source of substrate for slow-release agricultural and turf grass products. The substrate of vermiculite and lime of the saturated sorbents is not dissimilar from some compositions being commercially marketed today.

Figure 6.1 Saturated Fluesorbent, small agricultural pellets, and large pellets.

6.2 Greenhouse Test Results

The Ohio Agricultural Research and Development Center (OARDC) was contracted by Sorbent Technologies Corporation to test various by-product materials from the Burger plant in the greenhouse. Saturated vermiculite and perlite Fluesorbent from the Burger runs, with and without fly ash, were used in these trials. Both raw sorbent and pelletized samples were tested. Some pellets incorporated fertilizer nitrogen (N) to test a higher-value slow-release product. A total of 138 pots were used, with three repetitions of 46 different treatments.

Unlike other FGD wastes, spent Fluesorbents are easy to pelletize because they are already granular in nature. Two forms of agricultural by-products were made in pilot-scale pelletization equipment for the proof-of-concept greenhouse tests. See the photograph in Figure 6.1. A California pellet mill produced relatively large pellets; an LCI Corp. die-extruder made smaller pellets. Raw saturated Fluesorbent was also tested in the greenhouse trials.

The greenhouse testing was performed on two different soils: 1) a quality Wooster silt loam soil and 2) a distressed, acidic, coal mine spoil. The Wooster farming soil was collected at the Natural Resources Farm of the OARDC. The spoil was collected from an abandoned mine site located west of Dover, Ohio. The soil had a pH of 4.8 and a lime test index of 6.5. The spoil had pH of 3.0 and a lime test index of 46.

To test the beneficial properties of the Fluesorbent to in improving soil properties and plant growth, the soil and spoil were mixed with the various trial by-products at a rate of 1/2X, 1X, and 2X the lime requirement (LR) value. The lime equivalency of the FGD by-products ranged from 28% to 54%.

Figure 6.2 OARDC greenhouse trials of turf grass by-products produced from spent sorbent from the Burger station Fluesorbent trials.

Two grams of ryegrass seed were planted into each of the 138 greenhouse pots, each containing 1.20 kg of the FGD-treated soil or spoil. To control for other soil deficiencies in the liming tests, nitrogen, as urea, was applied at 200 lbs/acre and P and K were supplied according to soil test requirements. Several controls were also designed. One control was unamended soil or spoil. A second control was soil or spoil treated with N, P, and K and a competitive product, commercial limestone. Dry-weights from four harvests of these pots were used to evaluate by-product performance. Some of the more interesting results follow.

6.2.1 Farming soil

Ryegrass growth in the untreated farming soil pots was modest. The commercial lime control at the recommended lime requirement produced a good response. However, Fluesorbent by-products produced essentially the same growth response over the four cuttings and at only half the recommended lime-equivalency rate. See the comparison below. Results from both raw and pelletized sorbent are shown. Spent Fluesorbent may thus be a competitive amendment for quality farming soils.

Figure 6.3 Comparison of Fluesorbent by-products with controls in farming soil.

6.2.2 Distressed soil

Some of the pellets were produced from Burger trials of the simple-retrofit FGD configuration. These by-products contained the full fly ash load from the plant. These materials were tested in a degraded spoil.

Ryegrass growth in the untreated spoil pots was virtually nil. The commercial lime control at the recommended lime requirement produced an acceptable response. Vermiculite-based Fluesorbent pellets with the fly ash, however, produced over almost three times the growth of the commercial lime. See the Figures 6.4 and 6.5. So spent Fluesorbent may also be an excellent amendment for acidic, distressed soils.

Figure 6.4 Fourth cutting growth of control samples and Fluesorbent pellets with fly ash. No treatment (far left), commercial lime (left), and Fluesorbent/fly ash pellets at 0.5, 1.0, and 2.0 liming rates (right).

Figure 6.5 Normalized dry cutting weights.

6.2.3 Leachability tests

Because the Fluesorbents were exposed to coal-burning boiler flue gases, there is always a potential concern that heavy metals might appear in the by-products, particularly in the simple retrofit mode, where fly ash becomes mixed in with the sorbents. For this reason, Toxic Characteristic Leaching Procedure tests (TCLP) were performed on various spent Fluesorbent samples and by-products by the analytical laboratory of the Ohio Agricultural Research & Development Center. The results of these tests are summarized in Table 6.1. 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. In no case were the leachate levels high enough to qualify the materials as a solid waste and in most cases the levels even met drinking water standards.

Table 6.1 Toxic Characteristic Leaching Procedure results.

	EP Toxicity Drinking Water Standard (mg/liter)	EP Toxicity Solid Waste Classification (mg/l)	Saturated Vermiculite Fluesorbent (mg/l)	Pelletized Saturated Fluesorbent (mg/l)	Fluesorbent Pellets with Fly Ash (mg/l)	Wooster Farming Soil (mg/l)
Arsenic	0.050	1.500	0.070	0.140	0.130	<0.040
Aluminum	—	—	0.560	0.580	0.099	0.310
Cadmium	0.010	0.300	0.004	0.005	0.004	0.003
Chromium	0.050	1.500	0.010	0.010	0.010	0.020
Copper	—	—	0.003	0.005	0.003	0.005
Iron	—	—	0.040	0.020	0.180	0.040
Lead	0.050	1.500	<0.020	<0.020	0.020	<0.020
Nickel	—	—	0.140	<0.040	0.130	0.010
Selenium	0.010	0.300	<0.100	0.190	0.130	0.400
Silver	0.050	1.500	<0.010	<0.010	<0.010	<0.010
Vanadium	—	—	0.090	0.080	0.090	<0.005
Zinc	—	—	0.010	<0.001	0.020	0.050

6.2.4 Plant uptake

In addition to the leachate tests, the degree of elemental uptake in the plant biomasses was also measured. Ryegrass samples were dried, digested, and subject to elemental analysis to see if the various treatments allowed adequate amounts of major and micro nutrients to reach the plants and whether excessive amounts of heavy metals were consumed.

The availability of the major plant nutrients from the agricultural soil and the spoil was not affected by application of the various FGD by-products as compared to the commercial lime. The concentrations of the major plant nutrients in the ryegrass were all in the normal range. There was insufficient biomass for analysis of plant uptake data from the untreated clay-spoil control.

For essential micro nutrients which are required at lower concentrations, B was increased and Mn and Zn were decreased in plants growing in the agricultural soil when compared to the untreated control. However, the concentrations of these elements, with the exception of B, were all within the normal range for ryegrass. While B is one of the most widely applied micronutrients, it can be toxic to plants in excessive concentrations and should be watched. However, when Ca availability is high, as with lime or FGD by-product additions, there is a greater plant requirement for B.

Table 6.2 Concentrations of elements in ryegrass biomass from first harvest.

	Agricultural Soil					Clay-Spoil				
	No-Trtmt.Comm.		Spent Sorbent			No-Trtmt.Comm.		Spent Sorbent		
	Control	Lime	Raw	Pellets	w/Ash	Control	Lime	Raw	Pellets	w/Ash
<u>Major Nutrients</u>										
N	4.5	5.5	5.5	5.0	4.9	not enough biomass to measure	5.3	4.9	4.3	4.9
P	4.6	3.9	3.6	4.5	4.2		4.0	3.7	3.8	3.7
K	29.5	37.9	30.7	31.5	31.3		42.0	45.7	27.4	28.2
Ca	8.9	12.4	12.2	10.5	9.1		8.5	8.6	7.8	7.1
Mg	4.2	3.1	3.2	4.3	3.6		3.4	4.0	4.7	4.4
S	3.4	4.1	4.1	4.1	4.0		5.0	3.8	4.2	4.8
<u>Micronutrients</u>										
Fe	429	405	454	448	392		433	419	846	325
B	14.1	10.1	37.0	66.8	108		9.1	46.6	133	144
Cu	26.8	21.6	21.8	23.9	21.2		24.5	27.8	22.7	22.5
Mn	315	78	166	219	171		229	127	136	115
Mo	0.76	2.26	1.67	1.01	0.85		1.78	1.59	1.71	0.61
Zn	182	61.1	60.5	74.5	65.4		68.2	61.1	122	50.6
<u>Heavy Metals</u>										
As	<1.75	4.03	3.99	6.26	<1.75		2.04	<1.75	5.06	<1.75
Ba	129	76.8	19.6	19.1	22.8		9.86	8.67	14.9	9.87
Cd	0.33	0.24	0.27	0.35	0.21		0.11	0.14	3.97	0.39
Co	0.71	<0.30	<0.30	0.43	0.65		0.87	1.51	0.61	3.25
Cr	0.94	1.21	1.19	1.77	2.18		1.69	2.50	2.73	1.69
Hg	<2.30	3.09	3.45	2.37	3.94		<2.30	3.92	2.38	<2.30
Ni	5.61	3.43	4.30	4.08	3.44		7.48	7.37	5.88	5.25
Pb	3.45	2.47	1.35	2.30	4.58		2.91	<1.00	5.24	3.59
Se	19.2	<5.0	17.5	16.9	<5.0		30.1	13.4	33.7	<5.00
V	1.18	1.89	16.3	12.4	8.81		6.6	17.3	16.6	10.6

Units: N, P, & K in g/Kg, all other elements in mg/kg.

All treatments applied at 1x the recommended liming rate.

Be and Sb concentrations in all samples <0.001 and <5.30 respectively.

7. Economics

The project helped to establish a better base from which to estimate the economics of a full-scale application of the Fluesorbent concept. On the following tables, such an estimate is carried out. This economic model considers a retrofit installation at a 100-MW plant burning a 2.5%-sulfur Ohio coal. See Table 7.1 for the power plant assumptions and pollution control parameters. The calculations are based on Fluesorbent performance at 85% SO₂ removal. Vermiculite is assumed to be the sorbent support; if perlite were used, costs would be roughly similar. Costs for both a simple-retrofit installation and an added-microbaghouse arrangement are calculated.

Table 7.1 Fluesorbent installation at a 100-MW Ohio plant.

Power Plant Parameters	
Power Plant	100 MWe
Net Operating Factor	0.50
Coal Type	Ohio Bitum.
Coal Btus	11,000 Btu/lb
Coal Burned / Year	172 K Tpy
Coal Sulfur Wt%	2.5%
SO ₂ Produced (@ 95% Coal S)	8.2 K Tpy
SO ₂ Removal Rate	85%
SO ₂ Captured	7.0 K Tpy
Sorbent Usage Summary	
Tons of Lime Consumed	19 K Tpy
Tons of Vermiculite Consumed	14 K Tpy
Tons of Fluesorbent Produced (dry)	32 K Tpy
Ashfree By-Product (dry)	40 K Tpy
By-Product Revenues	\$1.0 M/yr
or	
By-Product with Fly Ash (dry)	61 K Tpy
By-Product Revenues	\$1.5 M/yr

7.1 Capital Costs

In line with the standard economic analysis methodology of the DOE's Clean Coal program, various air pollution control plant elements were broken down and capital costs have been estimated for each. See Table 7.2. Sorbent production is assumed to be done at the power plant and the scale of this facility is based on the calculated sorbent requirements. Engineering costs are included with each component. The most expensive capital cost elements are the various storage bins and the microbaghouse.

The various equipment requirements are estimated to total about \$6.9 million for the model 100-MW simple-retrofit plant, or \$69/kW, including a 15% contingency. In the added-microbaghouse mode, these costs are \$10.1 million and \$101/kW. Based on a short 10-year life, this translates to respective capital charges of \$135 and \$197 per ton of SO₂ removed. Relative to other technologies under these conditions, the capital costs are very low.

Table 7.2 Capital costs.

Element	Simple Retrofit	Added (\$Mil) Baghouse
Vermiculite Expander Facilities	\$0.93	\$0.93
Storage & Process Bins	3.06	3.06
Materials Handling Equipment	0.30	0.37
Scalping Cyclone & Ductwork	0.26	0.26
Humidification System	0.22	0.22
Controls & Instrumentation	0.30	0.37
Foundations, Steel, Bdg., & Electrical	0.74	1.30
Baghouse		1.58
ID Fan		0.50
Pelletizing Facilities	\$0.19	\$0.16
Total Equipment	\$6.00	\$8.75
Contingency (@ 15% Eqpmt.)	0.90	1.31
Total Capital Costs	\$6.90	\$10.07
Levelizing Period	10 yrs	10 yrs
Levelizing Factor (@ 6%)	0.136	0.136
Levelized Capital Cost (\$/Year)	\$0.94 M/yr	\$1.37 M/yr
Levelized Capital Cost (\$/kW)	\$69 \$/kW	\$101 \$/kW
Levelized Capital Cost (\$/T SO ₂)	\$135 /T SO ₂	\$197 /T SO ₂

7.2 Operating Costs

Operating costs include process costs, sorbent costs, and by-product credits. Details are outlined in Table 7.3. The main process costs are the power costs for pressure drop and humidification air. Labor and maintenance costs assume two full-time workers for two shifts and one worker for one shift per day.

The major operating costs are the sorbent raw material costs. If the vermiculite ore cost is \$65/ton, net costs are \$71/ton when 8.5 wt% evaporation losses are included. The net operating costs decrease depending on the value of the agricultural by-products.

Adding the annual capital contribution costs to the operating costs provides the total costs of the Fluesorbent system. The process removes residual particulates and some air toxics as well as SO₂, however all the costs are attributed to SO₂ control and are calculated on a per-ton-of-SO₂-removed basis. In the simple-retrofit mode, net costs are \$465/T SO₂ removed. In the added-microbaghouse mode, net costs are \$639/T SO₂. For a larger facility, these costs would be appropriately lowered due to economies of scale.

Table 7.3 Operating costs.

				Simple Retrofit	Added Baghouse
Non-Sorbent Costs					
Electricity				\$20	\$42 /T SO ₂
Water				3	3 /T SO ₂
Labor				14	20 /T SO ₂
Maintenance & Repair				22	33 /T SO ₂
Total Non-Sorbent Operating Costs				\$59	\$98 /T SO₂
<hr/>					
Sorbent Production	\$/T	Frt.	Cost	Wt%	
Hydrated Lime	\$60	\$18	\$78	0.60	\$47
Vermiculite Ore	\$71	\$24	\$95	0.40	\$38
Raw Materials, Delivered				1.00	\$85 /T
Processing Costs					\$23 /T
Cost/T Fluesorbent					\$108 /T
<hr/>					
Ca:SO ₂ Economic Stoichiometric Ratio				2	:1
Continuous Recycle Ratio				6	:1
Ca Utilization				43%	
T SO ₂ Captured/T Fluesorbent				0.22	
Total Sorbent Costs					\$489 /T SO₂
<hr/>					
By-Product Processing Cost					\$5 /T
By-Product Value Credit (\$/T Dry Saturated Sorbent)					\$25 /T
<hr/>					
				Simple Retrofit	Added Baghouse
Net Operating Costs (w/ By-Prod. Revs.)				\$330	\$443 /T SO ₂
NET TOTAL COSTS (w/ By-Prod. Revs.)				\$465	\$639 /T SO₂

8. Marketing and Commercialization

8.1 Markets

8.1.1 Target market for Fluesorbent flue gas desulfurization

The Fluesorbent technology is targeted for a part of the market that is currently not being served by other technologies. Customers for the process will be those who value the technology's two distinguishing features, its relatively low capital costs and its no-waste nature.

Existing FGD processes such as wet scrubbing, spray drying, and regenerable technologies, are capital intensive. Four factors help to determine how sensitive a plant will be to high capital costs: the length of its remaining life; its extent and level of operation (operating factor); its ability to capture economies-of-scale; and its retrofit difficulty. For example, large base-loaded plants with many years of life ahead of them can justify the high capital costs of wet scrubbers to achieve low marginal control costs on a dollars-per-ton-of-SO₂ basis. However, for smaller, older, difficult-to-retrofit plants, there are many fewer tons of SO₂ to allocate high capital costs over. This latter market is most appropriate for Fluesorbent. See the diagram below.

Figure 8.1 FGD market factors.

The majority of Fluesorbent costs are operating costs, which are only incurred when the plant is operating. Consequently, the process competes directly with the option of switching from a high-sulfur coal to a low-sulfur coal. In both cases, the added costs are operating costs.

The wastefree nature of the process is also a major competitive strength. Increasingly, it is unacceptable to landfill large quantities of FGD wastes, and few, if any inexpensive processes are wastefree. This factor alone could justify its selection in some instances.

The Fluesorbent process has wide applicability. It can be retrofitted onto the broadest possible range of boiler types and sizes. There also may be advantages in following a second, low-removal-rate process, such as furnace-injection. The added microbaghouse could solve any particulate control problems that are generated. Because the concept is a back-end process, it can be coupled with just about any other SO₂ or NO_x control technology.

8.1.2 Cost comparison

Unfortunately, direct comparisons of the cost of the Fluesorbent technology are not easily made with those of competing processes. In order to minimize the appearance of net costs on a per-ton-of-SO₂-removed basis, the costs of other, more capital-intensive technologies are usually calculated with large plants, greenfield sites, 30-year lifetimes, and high operating factors. If, instead, their costs were based on a 100 MW retrofit, a 10-year remaining life, and a 50% operating factor, as in the Fluesorbent economics example, their large capital-cost components would balloon significantly. But the costs in these instances are never published.

Because the costs of other technologies are never reported for the same market applications as Fluesorbents, a direct comparison cannot easily be made. However, the costs reported in the previous Economics chapter are quite low for the assumed conditions and are expected to be lower than that of most, if not all, comparable technologies.

8.1.3 Target market for Fluesorbent by-products

Fluesorbent by-products are capable of being sold into a number of different agricultural and turf grass markets. When saturated, the Fluesorbent materials contain four separate components which have soil-conditioning use: lime, inorganic micronutrients, sulfur, and granular vermiculite or perlite.

At the lowest economic level, the by-products contain significant alkalinity from unutilized lime. Raw or pelletized, they can compete with lime and pelletized limestone to buffer widespread acidic soils. Micronutrients provided by any incorporated fly ash would provide higher value, as evidenced by the dramatically better performance exhibited by the greenhouse tests on degraded soils.

At a higher economic value, the by-products contain the sulfur captured from the gas stream. A large fertilizer producer is interested in the by-products for their sulfur values alone. Mixed with their regular NPK fertilizer products, the materials could substitute for specially-made sulfur-containing pellets. This is probably the most likely market for the by-products, with large quantities already in demand.

At the highest economic level are the granularity and slow-release properties of the vermiculite or perlite substrates. By moderating the release of added nitrogen chemicals or pesticides, the materials can reduce both costs and incidental water pollution. Markets for the by-products' substrate values could generate the highest prices, but might adsorb smaller overall quantities.

Field studies are now underway to determine by-product performance in these various markets.

8.1.4 Ohio market penetration

Because the Burger effort was a pilot project rather than a full-scale, permanent installation, it had no direct effect on Ohio coal sales. However, the market potential for full-scale Fluesorbent FGD looks particularly good in Ohio. This is primarily because the process is designed for low capital costs and retrofit installation, which are strong competitive advantages here. Ohio's large existing boiler stock needs retrofit technologies, not greenfield technologies.

Unfortunately for Ohio ratepayers and Ohio high-sulfur coal producers, much of the state's electrical production comes from smaller, aging coal plants. See the graphic below, compiled with data from U.S. EPA's report "Evaluation of SO₂ Emissions and FGD Retrofit Feasibility at the 200 Top Emitting Generating Stations." Coal-switching is typically favored by these types of plants, which are difficult and expensive to retrofit with wet scrubbers. Because Fluesorbents and coal-switching have similar cost structures – with most costs as operating costs – they will directly compete, unlike some other technologies being developed.

100% = 68 Ohio utility boilers

Figure 8.2 Ohio coal boiler population.

Ohio, of course, is a major farming state with significant crops of soybeans, corn, hay, and wheat. Consequently, Ohio is also a good potential market for Fluesorbent by-products. Like nearly all states east of the Mississippi River, Ohio has acidic soils and the state's farmers purchased over 1,500,000 tons of broken limestone in 1990. According to a major Ohio fertilizer producer, there is also good and increasing demand for fertilizers with added sulfur values. These markets, along with Ohio's many abandoned strip-mine areas, hold significant local potential.

8.2 Commercialization Efforts

To translate the results of this project to the marketplace and further the commercialization of this technology, it is important to communicate to the coal-consuming community that this technology has been developed and is available for use. To that end, a number of papers and presentations have been made to the industry. These include:

- "Low-Capital-Cost Technology for SO₂ Control," Nelson, S. and C. Zhang, 1996 Air & Waste Mgmt. Assoc. Annual Meeting; Nashville TN; June, 1996.
- "Fluesorbent Dry Scrubbing at Ohio Edison's Burger Station," Nelson, S., Second North American Conference: Emerging Clean Air Technologies and Business Opportunities; Orlando, FL; November, 1996.
- "Fluesorbent Dry Scrubbing at Ohio Edison's Burger Station," Nelson, S., 13th Annual Pittsburgh Coal Conference; September, 1996.
- "Wastefree In-Duct FGD," Nelson, S., 12th Annual Pittsburgh Coal Conference, September, 1995.
- "Supported-Sorbent Injection," Nelson, S., First North American Conference: Emerging Clean Air Technologies and Business Opportunities; Toronto, Canada; September, 1994.
- "Supported Sorbents," Nelson, S., Joint EPA/DOE/EPRI 1993 SO₂ Control Symposium, Boston, MA, Aug. 1993.

Numerous industry publications have also reported on the project, including:

- "Fluesorbents are Pay Dirt," McIlvaine Fabric Filter Newsletter (April 1996).
- "Sorbent Sets Sights on Duct Injection," Pollution Engineering (June 1, 1993).
- "Sulfur Free and Recyclable, Too," Coal Voice (May/June 1993).

Sorbent Technologies Corporation is now actively seeking to commercialize the Fluesorbent technology. A senior manager has been hired to spearhead sales and marketing efforts to put together a first full-scale, permanent Fluesorbent installation project. The Company is looking for a project in the range of 5 to 40 MW to demonstrate the technology and to operate as a model plant from which to construct other, and larger, installations.

Actual field demonstrations of the efficacy of Fluesorbent by-products are required before significant commercialization can be expected. Consequently, a multi-year field program is also now underway. With saturated sorbent from the Burger runs, the Company is developing pelletization procedures for large-scale by-product production. A program with the Ohio Agricultural Research and Development Center has begun to test the Fluesorbent by-products on Ohio alfalfa acreage for three growing seasons. Turf grass and corn crops will also be grown on by-product-enhanced soils. Sorbent Technologies, itself, has plans to get into the market of processing spent power-plant Fluesorbent and selling the by-products into agricultural and turf grass applications.

10. Conclusions and Recommendations

1. The 2-MWe Fluesorbent pilot plant at Ohio Edison's R.E. Burger station demonstrated that high, 80 to 90% SO₂ removal rates are possible with an easily-retrofitable duct-injection technology if sorbent supports are added to the hydrated lime.
2. Either expanded vermiculite or perlite can be used as the mineral supports. The technology can be applied either in a simple-retrofit made before an ESP or in an added-microbaghouse mode following an ESP.
3. By using the sorbent supports, traditional duct-injection problems with wall deposits, particulate control, and waste disposal are eliminated.
4. In greenhouse trials by the Ohio Agricultural Research and Development Center, agricultural by-products made from the Burger-saturated materials performed at least as well as currently-commercial products.
5. This technology is targeted for coal-fired retrofits at older, smaller, typically non-base-loaded plants. For a difficult 100-MW plant with 10 years of life left and a 50% operating factor, capital costs for a simple retrofit are estimated to be \$69/kW and totals costs, \$465/ton-of-SO₂-removed. Respective costs in the added-microbaghouse mode would be \$101/kW and \$639/T SO₂.
6. Based on the results achieved, a small, permanent, full-scale demonstration of the technology is recommended.

Appendices

Appendix A: Data Summary of Preliminary Testing

Sorbent Composition Tests

		<u>Stoich. Ratio</u>	<u>T_{approach}</u>	<u>Ppm SO₂</u>	<u>SO₂ Removal</u>
<u>baseline/control</u>					
1.	lime only	1.5	34F	1800	0.10
2.	lime only	2.0	34F	1800	0.17
3.	lime only	3.0	33F	1800	0.20
4.	lime only	7.0	30F	1800	0.57
<u>injection parametrics</u>					
5.	standard sorbent	1.5	30F	1800	0.21
6.	standard sorbent	2.2	30F	1800	0.30
7.	standard sorbent	2.8	30F	1800	0.38
8.	standard sorbent	6.0	10F	1800	0.79
9.	standard sorbent	6.0	15F	1800	0.71
10.	standard sorbent	6.0	20F	1800	0.68
11.	standard sorbent	6.0	30F	1800	0.59
12.	standard sorbent	6.0	45F	600	0.64
13.	standard sorbent	6.0	40F	1200	0.72
<u>sorbent variations</u>					
14.	30 wt% lime	2.7	15F	1800	0.44
15.	30 wt% lime	2.8	32F	1800	0.36
16.	vermiculite < 100 μ	1.25	44F	1800	0.17
17.	vermiculite < 100 μ	1.7	36F	1800	0.27
18.	vermiculite < 100 μ	2.0	34F	1800	0.30
19.	vermiculite > 300 μ	2.2	32F	600	0.35
20.	vermiculite > 300 μ	6.0	32F	600	0.80
21.	heat-treated	1.25	30F	1800	0.28
22.	heat-treated	2.0	30F	1800	0.39
23.	heat-treated	3.0	30F	1800	0.57
24.	perlite-based	6.0	35F	1800	0.51
25.	perlite-based	6.0	50F	1800	0.57
<u>different moisture levels</u>					
26.	15 wt% moisture	2.7	33F	1800	0.25
27.	20 wt% moisture	2.6	35F	1800	0.28
28.	20 wt% moisture	7.0	45F	1800	0.70
29.	20 wt% moisture	9.3	45F	1800	0.93
30.	25 wt% moisture	2.2	35F	1800	0.26
31.	35 wt% moisture	2.6	30F	1800	0.36
32.	35 wt% moisture	5.0	45F	1800	0.68

Sorbent Recycle Tests

		<u>Econ.Stoich.</u>	<u>T_{approach}</u>	<u>Ppm SO₂</u>	<u>Avg.SO₂ Removal</u>
33.	standard sorbent series	6.0	24F	1800	0.63
34.	standard sorbent series	3.0	30F	1800	0.63
35.	standard sorbent series	2.0	30F	1800	0.62
36.	standard sorbent series	1.5	30F	1800	0.59
37.	standard sorbent series	10.0	42F	600	0.97
38.	standard sorbent series	5.0	30F	600	0.90
39.	standard sorbent series	3.3	30F	600	0.85
40.	standard sorbent series	2.5	37F	600	0.60
41.	standard sorbent series	2.0	30F	600	0.70
42.	perlite sorbent series	8.0	40F	1800	0.93
43.	perlite sorbent series	4.0	30F	1800	0.91
44.	perlite sorbent series	2.7	30F	1800	0.85
45.	perlite sorbent series	2.0	32F	1800	0.62

Appendix B: Mass and Heat Transfer Model

Introduction

The fluid-particle behavior and mass-transfer characteristics of the large, injected Fluesorbents are very different than that of fine powders or liquid slurries. In order to develop an understanding of Fluesorbent injection so that the process can be optimized and scaled up, Sorbent Technologies was awarded a modelling grant by the National Science Foundation (NSF SBIR Phase I Award Number III-9360087). With the assistance of Dr. P. Harriott of Cornell University, Sorbent Technologies developed and tested the model, which can be used to predict Fluesorbent performance in large-scale systems.

Derivation of the Fluesorbent Model for SO₂ Removal

The removal of SO₂ from flue gas by contact with moistened lime particles takes place in two stages. In Stage I, when water is present, the reaction takes place very rapidly. In modelling this first stage, mass transfer of SO₂ from the gas phase to the external surface of the sorbent particles is assumed to be the rate-limiting step. Most of the SO₂ removal that will occur takes place during this Stage I, while the sorbent particles are in the process of drying. The second stage of the process is a much slower reaction of SO₂ with lime in the dry or nearly-dry particles. This Stage II takes place in the particulate collection device and only to a minor extent in the duct. The following model is intended only for Stage I. It tries to describe "In-Duct" removal. The "Total" removal rates would also include the smaller Stage II contribution.

If the gas in the duct is in plug flow and the sorbent is uniformly dispersed in the gas, the mass transfer of SO₂ to the sorbent particles is given by the following equation:

$$S u \rho_m dy = -K_g a S dl P y \quad (1)$$

where:

S	=	cross section of duct;
u	=	superficial velocity of gas;
ρ_m	=	molar density of gas;
y	=	mole fraction SO ₂ ;
$K_g a$	=	volumetric mass transfer coefficient for SO ₂ ;
l	=	length of duct;
P	=	total pressure; and
y	=	mole fraction SO ₂ in gas.

We can assume that $K_g a$ is constant while the water is evaporating, because the particle sizes do not change significantly and a decrease in particle density has only a small effect on K_g , the mass transfer coefficient. The term "a," the effective mass transfer area per unit volume of gas, may change because of changing suspension density, complete reaction of lime on sparsely covered surface portions, or particle agglomeration, but these effects are secondary and not in the model.

Equation (1) can then be arranged for integration:

$$\int -\frac{dy}{y} = -\ln \frac{y_2}{y_1} = \frac{K_g a P}{\rho_m} \int \frac{dl}{u} \quad (2)$$

Since $dt = dl/u$:

$$-\ln\left(\frac{y_2}{y_1}\right) = \frac{K_g a P t_{dry}}{\rho_m} \quad (3)$$

where: t_{dry} = time for sorbent particle to reach final water content.

The in-duct SO_2 removal rate, ϵ_{SO_2} , can therefore be approximated by:

$$\epsilon_{SO_2} = 1 - \left(\frac{y_2}{y_1}\right) = 1 - e^{-X} \quad (4)$$

where:

$$X = \frac{K_g a P t_{dry}}{\rho_m} \quad (5)$$

As shown by Equations (3) and (5), the key variables affecting SO_2 removal in Stage I are: K_g , P , ρ_m , a , and t_{dry} .

K_g . The coefficient K_g depends on the diffusivity of SO_2 in flue gas and the average thickness of the concentration boundary layer around the sorbent particles. Predicting K_g is difficult because of the irregular shapes of the particles and the uncertain effect of gas-phase turbulence on the mass transfer coefficient. However, for a given sorbent and typical velocities of 10 to 15 m/s, K_g can be considered constant for a series of runs at different loadings and temperatures.

P and ρ_m . The total pressure P is essentially constant at one atmosphere and the molar density ρ_m does not vary much over the range of operating conditions experienced. For all practical purposes, these two terms are also constants.

a . The mass transfer area " a " is directly proportional to the amount of sorbent injected per unit volume of gas and can be expressed as:

$$a = \frac{6f_1f_2M}{d_p \rho_p} \quad (6)$$

where:

M	=	mass of lime particles per volume of gas;
f_1	=	fraction of external surface covered by lime ($f_1 < 1$);
f_2	=	shape factor for non-spherical ($f_2 > 1$) grains;
d_p	=	average particle diameter; and
ρ_p	=	particle density.

and the value 6 in the numerator comes from the ratio of the surface area of a sphere to its volume. This area can also be directly related to the stoichiometric injection ratio.

The stoichiometric ratio, SR , is the moles of hydrated lime fed into the duct per mole of SO_2 in the flue gas:

$$SR = \frac{M(1-w)x_L}{74.1 y_1 \rho_m} \quad (7)$$

where:

w	=	wt. fraction water in sorbent (usually 0.30); and
x_L	=	wt. fraction lime in dry sorbent (usually 0.60).

Combining Equations (6) and (7):

$$a = \frac{6f_1f_2}{d_p \rho_p} \frac{(74.1)y_1 \rho_m SR}{x_L(1-w)} \quad (8)$$

Many of these variables change little in a given situation or balance off against each other. For a given feed rate, for example, if the initial SO₂ level, y_1 decreases, SR increases proportionately and X remains unchanged. Similarly, lowering the water content increases $(1-w)$, but simultaneously decreases ρ_p , so "a" is unchanged. A smaller particle size means more area per unit mass of particles, as shown by Equation (8), but since the smaller particles dry more rapidly, the two effects tend to cancel each other as long as the solid residence time is great enough for all the particles to become essentially dry. In summary, for a given Fluesorbent, such as the 60/40 lime-vermiculite with 30% H₂O, the mass transfer area per unit volume depends primarily on SR, the stoichiometric injection ratio. In practice, the SR can easily be controlled and calculated for each run.

t_{dry} . The effective sorbent drying time, t_{dry} , is a function of the temperature driving force, which is the difference between the gas temperature and the temperature of the gas-liquid interface. During the Stage I evaporation process, this interface temperature is about equal to the adiabatic saturation temperature, T_{as} , or the wet-bulb temperature. For plug-flow gas, the effective driving force, then, is the logarithmic mean of this difference, $(\Delta T)_{lm}$:

$$(\Delta T)_{lm} = (T - T_{as})_{lm} = \frac{(T_1 - T_2)}{\ln \left(\frac{T_1 - T_{as}}{T_2 - T_{as}} \right)} \quad (9)$$

where:

T_1	=	gas temperature at sorbent injection;
T_2	=	gas temperature at sorbent exit, after evaporative cooling;
T_{as}	=	gas wet-bulb temperature, also denoted as T_w .

The term $(T_2 - T_{as})$ is the final approach to adiabatic saturation or "approach temperature." Variable $(\Delta T)_{lm}$ is thus a measure of the effective average approach temperature that the sorbent experiences while it is reactive (i.e. during Stage I).

The term t_{dry} can be derived by equating the product of the drying time and the average rate of heat transfer with the energy needed to evaporate the sorbent water. A one-kilogram unit mass of sorbent is a convenient basis for the calculation:

$$Q = t_{dry} h A (\Delta T)_{lm} = w (\Delta H_v) \quad (10)$$

or

$$t_{dry} = \frac{w (\Delta H_v)}{h A (\Delta T)_{lm}} \quad (11)$$

where:

Q	=	energy needed per kg of Fluesorbent;
h	=	heat transfer coefficient of sorbent particles;
A	=	heat transfer surface area per kg of sorbent; and
ΔH_v	=	heat of vaporization at T_w .

Moreover:

$$A = \frac{6f_2}{d_p \rho_p} \quad (12)$$

(Note that Equations (10) and (11) neglect the energy needed to heat the sorbent to the wet-bulb temperature, which is typically 5 to 10% of the heat used for vaporization. However, the discharged sorbent still contains 2 to 4% moisture, so only 90 to 95% of the water evaporates. These two effects almost cancel out, making the equations essentially correct.)

Combining Equations (5), (8), (11), and (12):

$$X = \left[\frac{K_g P f_1 (74.1) y_1 \Delta H_v}{h x_L} \frac{w}{1-w} \right] \frac{SR}{(\Delta T)_{lm}} \quad (13)$$

For tests in a given system, all the terms of Equation (12) inside the brackets would be nearly constant or balancing and can be together treated as a proportionality constant, C . Combining this with the SO_2 removal rate Equation (4) yields:

$$X = -\ln(1-\epsilon_{SO_2}) = C \left(\frac{SR}{(\Delta T)_{lm}} \right) \quad (14)$$

This result is a surprisingly simple model that is both easily verifiable and powerful. It is powerful because many variables that might otherwise be thought to be important in determining SO_2 removal efficiency, such as SO_2 concentration and particle size, turn out to be largely irrelevant. The stoichiometric injection ratio and system temperatures, by themselves, will largely predict Fluesorbent performance.

Empirically verifying the model should be simple. After testing over a wide range of conditions, a plot of X , as $-\ln(1-\epsilon_{SO_2})$, against $SR/(\Delta T)_{lm}$ should yield a linear relationship, the slope being the constant C .

Model Validation

Data from the laboratory duct-injection test runs can be applied to test this model. Many of these runs included data points at multiple approach temperatures or injection stoichiometries. A graph which summarizes all this data, and appears to validate the model, appears on the following page.

The SO_2 -removal model derived from heat and mass transfer principles and described by Equation (14) predicted a linear relationship between X , the number of SO_2 mass transfer units, and the term $SR/(\Delta T)_{lm}$. To test this relationship, ϵ_{SO_2} , X , and $(\Delta T)_{lm}$ were calculated for each data point according to Equations (4), (14), and (9) respectively, and plotted. Simple linear regression yields a Fluesorbent in-duct SO_2 -removal model relationship of:

$$X = -\ln(1-\epsilon_{SO_2}) = 9.73 \left(\frac{SR}{(\Delta T)_{lm}} \right). \quad (15)$$

Figure B.1 Model validation relation.

At the very high end of the scale, at high stoichiometric injection ratios, the model relation graph seems to go non-linear, or at least becomes much steeper, yielding very high removal rates. This end of the curve can be exploited by recycling the sorbents. A similar relationship for the runs with dry lime and no vermiculite is also plotted on the graph. As can be seen, the performance plain lime is far below that of Fluesorbents.

The fit of this linear relationship is very good over a wide range of data, with 57 observations and an $R^2 = 0.89$. A plot of predicted in-duct removal rates versus actual measured values for the once-through data appears below.

Figure B.2 Predicted versus actual SO₂ removals.

Appendix C: Individual Pilot Plant Run Data

<u>Saturation Run</u>	<u>Approach Temperature</u>	<u>Nominal Stoichiometry</u>	<u>In-Duct SO₂ Removal</u>	<u>Total SO₂ Removal</u>	<u>% Lime Utilization</u>
Vermiculite/Lime					
1	30F	8.2	0.82	0.92	11.2
2	24F	9.5	0.91	0.94	9.9
3	23F	10.4	0.84	0.88	8.5
4	23F	12.4	0.81	0.90	7.5
<u>5</u>	<u>24F</u>	<u>10.7</u>	<u>0.65</u>	<u>0.70</u>	<u>6.5</u>
Avg./Cum.	25F	10.2	0.81	0.87	43.6
Perlite/Lime					
1	20F	9.0	*	*	*
2	19F	10.1	0.85	0.94	9.4
3	18F	9.3	0.83	0.91	9.6
4	24F	8.2	0.64	0.71	8.7
<u>5</u>	<u>22F</u>	<u>9.5</u>	<u>0.55</u>	<u>0.57</u>	<u>6.0</u>
Avg./Cum.	21F	9.2	0.74	0.81	43.7
Vermiculite/Lime with Fly Ash					
1	21F	9.2	0.73	0.75	8.0
2	23F	10.1	0.85	0.92	9.3
3	24F	11.4	0.80	0.89	7.7
4	20F	10.9	0.75	0.87	8.0
<u>5</u>	<u>25F</u>	<u>10.8</u>	<u>0.53</u>	<u>0.60</u>	<u>5.6</u>
Avg./Cum.	23F	10.5	0.73	0.81	38.6
Perlite/Lime with Fly Ash					
1	19F	10.0	0.89	**	**
2	20F	10.2	0.77	0.92	9.0
3	20F	10.2	0.77	0.92	9.0
4	17F	7.8	0.69	0.70	9.0
<u>5</u>	<u>18F</u>	<u>6.9</u>	<u>0.52</u>	<u>0.56</u>	<u>8.1</u>
Avg./Cum.	19F	9.0	0.73	0.81	44.3

* Sampling line problem. Results assumed to be 0.83 and 0.90 removal, and 10.0% utilization respectively.

** Sampling line problem. Results assumed to be 0.92 total removal and 9.2% utilization.

Forty-Hour-Run Series

<u>Saturation Run</u>	<u>Approach Temperature</u>	<u>Nominal Stoichiometry</u>	<u>In-Duct SO₂ Removal</u>	<u>Total SO₂ Removal</u>	<u>% Lime Utilization</u>
Vermiculite/Lime					
1	17F	9.8	0.87	0.91	9.3
2	20F	12.3	0.88	0.93	7.6
3	18F	13.4	0.89	0.92	6.9
4	18F	13.4	0.73	0.88	6.6
<u>5</u>	<u>14F</u>	<u>13.6</u>	<u>0.59</u>	<u>0.79</u>	<u>5.8</u>
Avg./Cum.	17F	12.3	0.79	0.89	36.2

Vermiculite/Lime					
1	17F	8.8	0.72	0.85	9.7
2	19F	11.0	0.92	0.93	8.5
3	18F	12.0	0.83	0.90	7.0
4	17F	9.1	0.83	0.77	8.5
<u>5</u>	<u>15F</u>	<u>8.7</u>	<u>0.62</u>	<u>0.68</u>	<u>7.8</u>
Avg./Cum.	17F	9.8	0.77	0.82	41.5

Appendix D: Abbreviated Terms

A:C	Air-to-Cloth ratio; a measure of the gas flow through a fabric filter in units of cubic feet of gas per minute per square foot of fabric area.
Ca:S (or Ca:SO ₂)	Calcium-to-Sulfur (or sulfur dioxide) ratio; relative numbers of atoms of calcium in the injected sorbent to the number of atoms of sulfur in the gas stream.
COHPAC	Compact Hybrid Particulate Collector; a small pulse-jet baghouse used to back up an electrostatic precipitator for greater particulate removal capabilities.
EPRI	Electric Power Research Institute; non-profit research group sponsored by electric utility companies that contributed use of a COHPAC to the project.
FRP	Fiberglass Reinforced Plastic; a composite material, stronger than plastic alone, used to make structural ductwork.
LR	Liming Ratio; an amount of alkalinity added to a soil relative to the amount required to bring the soil to a standard pH value.
OARDC	Ohio Agricultural Research and Development Center; the agricultural research organization of The Ohio State University.
OCDO	Ohio Coal Development Office; the State of Ohio government agency within the Ohio Department of Development that co-sponsored the project.
ppm	parts-per-million; molar ratio of one component in a gas to one million molecules of the total.
SR	Stoichiometric Ratio; molar ratio of one component to another, here usually used as the ratio of Ca(OH) ₂ molecules to SO ₂ molecules.
TCLP	Toxic Characteristic Leaching Procedure; a standard procedure to measure the leachability of metals from a sample.