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APPLICATION OF A NEW SORBENT FOR COMBINED SO₂ AND NO_x REMOVAL

FINAL REPORT

BURN OHIO COAL

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SEPTEMBER 1989

This project was funded in part by
the Ohio Coal Development Office,
Department of Development, State of Ohio.

MASTER

SANITECH, INC.

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EXECUTIVE SUMMARY

The overall objective of this project was to further develop the application of a new class of dry, granular, SO_2/NO_x -sorbent materials to bring them closer towards commercial usage in utility and industrial air-pollution control systems.

The new sorbents are composite materials consisting of magnesium oxide (MgO) or calcium oxide (CaO) bonded to and reacted with vermiculite, a low-cost expanded silicate carrier. The sorbents possess some very unique and desirable properties. These properties include a higher-than-normal affinity for sulfur and nitrogen oxides in stack gases, excellent SO_2 -removal efficiencies and attractive utilization rates at common stack gas temperatures, and the ability to be regenerated. The materials typically remove 99 percent of the SO_2 and a significant percentage of the NO_x in flue gases with high sorbent utilizations.

Specific objectives of the project were to evaluate the performance of different continuous methods of employing the new sorbent materials in removing SO_2 and NO_x from a power plant flue gas, to examine the regeneration of one particularly promising sorbent composition: 45 wt% MgO -55 wt% Vermiculite, and to develop a sorption-regeneration system and cost estimates based on this material. The objectives were met in the project. Four continuous sorption methods were investigated on a 300 ACFM sidestream of flue gas at Ohio Edison's Gorge power plant. Of these methods, a panel-bed approach gave the best results. In the panel-bed approach, the sorber consisted of a thin bed of sorbent moving slowly downward through the flue gas duct between two screens or louvers. The movement of sorbent to and from the sorber was found best performed pneumatically or by belt conveyor. The moisture level of the flue gas was found to be critical in achieving optimum SO_2 removal. The moisture level of the flue was satisfactorily increased by spraying water into the flue gas duct immediately in front of the panel bed. Excellent sorbent regeneration was achieved by heating saturated sorbent at 750°C or higher in a nitrogen-methane atmosphere containing a minimum of 30 percent methane. Under these conditions, the evolved NO_x is reduced to nitrogen and some elemental sulfur is produced. Economic studies indicated that a process based on the new sorbent will cost \$400 to \$700 per T of SO_2 removed, which is considerably less than the best available SO_2 -control technology today. And, the removal of NO_x comes essentially free. No wastes are expected to be generated by the new technology and by-products are elemental sulfur and small quantities of sorbent removed from the process that appears to have marketable value.

The cost of the 15-month project was \$229,717, of which OCDO provided \$149,972 and Sanitech provided the remainder. In addition, Sanitech and Ohio Edison made significant in-kind contributions to the project, in the form of existing facilities and equipment.

The results of this project should help move the new technology forward toward commercialization. Required now are scale-ups of the new technology at more meaningful sizes. Hopefully the new technology will be demonstrated by Sanitech at a 1 MWe size by the end of 1990 and at a 5 to 10 MWe size by early 1993. With continued State of Ohio and Federal support, these goals can be accomplished. If suitably developed and commercialized, the new technology will have a positive effect on Ohio coal use, because Ohio coals perform well with the new technology.

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INTRODUCTION

Since 1985, Sanitech engineers have been working on a new class of dry SO_2/NO_x sorbents. The new materials have the ability to remove both SO_2 and NO_x simultaneously and selectively from a flue gas with a very high degree of sorbent utilization.

The new sorbents are a composite material. They consist of a low-cost mineral oxide, either MgO or CaO , bonded to and reacted with a low-cost expanded silicate carrier, either vermiculite or perlite. By coating the large surface area of expanded vermiculite with a reactive oxide such as MgO , for example, dry granular sorbents are created which can be utilized to provide the sufficient gas/sorbent mixing and contact time required for excellent SO_2 and NO_x removal.

These materials possess some very unique and desirable properties. The very large surface area of the vermiculite permits high oxide loading, and the materials appear to be catalytic and very reactive. Because the sorbents are granular and porous, low pressure drops are observed when they are used in beds or filter layers. Unlike vermiculite alone, the materials are relatively strong and can be handled easily, both before and, if needed, after saturation. They are simple to prepare, can be used dry or moist, and work well at typical pre-stack gas temperatures. Importantly, certain of the compositions are readily regenerable with simple heating to relatively low temperatures. One promising aspect of the new technology is that there should be no wastes involved in the use of the sorbent. The sorbent is used over and over again, NO_x is destroyed in regeneration, SO_2 is converted to by-product elemental sulfur, and the small amount of waste sorbent generated appears to have useful value.

The characteristics of the new sorbents should permit them to be used in simple, inexpensive, space-efficient designs. This ability should make the sorbents prime candidates for difficult retrofit flue-gas desulfurization and NO_x removal applications...the major need in the effort to sustain and expand the use of Ohio coal.

During the 1985-1987 period, Sanitech performed more than two hundred runs involving different variations of the new sorbent in small fixed beds in the laboratory. It carried this work forward into the field with larger fixed beds treating a sidestream of flue gas at Ohio Edison's Gorge power plant. During trials at the Gorge power plant, which burns almost exclusively Ohio bituminous coals, over 99 percent removal of SO_2 and up to 40 percent removal of NO_x were routinely observed.

The overall objective of this project was to develop the application of this new class of SO_2/NO_x sorbent materials to bring them closer to commercial usage in utility and industrial air pollution control systems. Prior to this project, Sanitech devoted its efforts to testing the new sorbents in fixed beds. Although fixed beds may be practical for small-scale applications, they are probably less suitable for large utility-scale applications. A method that can be used continuously is needed for large applications. With a moving bed, for example, one might continuously introduce fresh sorbent and continuously

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remove saturated sorbent from a flue gas stream. The first technical objective of the proposed research, then, was to evaluate the relative effectiveness of several continuous applications of the new sorbents in removing SO_2 and NO_x from a power plant flue gas. The goals were to collect operating data on different methods and to identify one or more methods that will give satisfactory results when operating on a flue-gas sidestream at the Gorge power plant. An additional goal was to demonstrate high SO_2 and NO_x removal efficiencies and high sorbent utilizations with one or more of these methods.

A regeneration process for the new sorbents was developed in a project supported by the U.S. Environmental Protection Agency. In the new regeneration process, saturated MgO -vermiculite sorbents are regenerated at about 700°C in a slightly reducing atmosphere. With methane added to the regeneration gas, the released NO_x is destroyed and a portion of the released SO_2 is converted directly to elemental sulfur. The second technical objective of this project was to examine further the use of methane in regeneration, with the specific goals of determining how much methane should be used in the regeneration atmosphere and how an MgO -vermiculite sorbent performs through many cycles of sorption and regeneration. A further goal was to integrate the entire sorbent application, culminating in the design and a cost estimate for a system applicable to a 500-MWe power plant.

Most past work relating to the new technology has been performed by Sanitech engineers. Most recently several Kent State University researchers have been assisting Sanitech under an Edison Program grant. Additional support has come from the U.S. DOE and the U.S. EPA. Ohio Edison has made valuable contributions to the development by providing its facilities for tests and by assigning personnel to follow the work and review the results.

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TECHNICAL DISCUSSIONS

SORBENT PREPARATION

General

The manner in which the sorbent is prepared markedly affects its properties, and particularly its ability to sorb and remove SO_2 from a flue gas. It was found earlier that the following procedures result in an optimum product when applied to MgO-vermiculite sorbents.

Starting materials for the preparation of MgO-vermiculite sorbents are dry magnesium oxide (MgO), dry expanded vermiculite, and water. The MgO should be the reactive grade, not dead-burned, and should be of small size, preferably -325 mesh or smaller. The individual expanded vermiculite particles should normally be 0.1 cm or larger, and preferably larger than 0.3 cm. The source and quality of the reactive MgO or of the expanded vermiculite do not appear to affect the final performance of the sorbent significantly.

In preparing the sorbent, water is initially mixed with the expanded vermiculite. Enough water is added to wet the material well, but not so much as to result in free-standing water. The moistened vermiculite is mixed extensively so the water becomes disbursed evenly throughout. The MgO is then sifted into the moist vermiculite, while the vermiculite is continually mixed. The result is an even build-up of MgO on the surfaces of the vermiculite. MgO is added until MgO makes up 45 percent by dry weight of the MgO-vermiculite mixture. Adding MgO beyond this point often results in large numbers of free MgO particles.

The newly-prepared moist MgO-vermiculite particles are held for a short time in air, then dried, and finally heated to 550°C for about 30 minutes. This latter conditioning treatment greatly improves the sorbent's ability to remove SO_2 and NO_x . The maximum surface area is obtained with this treatment, and the particles appear strengthened. Following the conditioning treatment, the sorbent is ready for use.

Task Objectives

The objectives of this task were to develop sorbent preparation techniques suitable for large-scale production and to use these techniques to prepare large quantities of sorbent of uniform quality for use in the project.

Preparation Activities

Prior to this project, small batches of sorbent were readily prepared in the laboratory using conventional glassware and laboratory furnaces. However, for large-scale runs requiring large amounts of sorbent, as planned for the project, bigger equipment and improved production methods were needed.

The steps required in preparing the new sorbent are: (1) mixing of vermiculite with water; (2) blending in MgO; (3) drying; and (4) heat-conditioning. It was found that the first two steps, mixing and blending, can be conveniently carried out in a simple cement mixer, although for a commercial plant a specially designed mixer or mixers would be employed. With a cement mixer, large batches of moist sorbent were prepared quickly and efficiently.

The second two steps, drying and conditioning, can be performed separately or together in one furnace. Two combined drying-conditioning approaches were examined in the project. The first approach involved placing large batches of moist MgO-vermiculite granules into rectangular, screened containers and placing the containers into heat-treating furnaces normally used for treating steel. This work was performed at Universal Heat Treating, Inc. in Cleveland, Ohio. The second approach involved feeding moist granules continuously into a slightly inclined rotary kiln. This work was performed in Sanitech's laboratories in Cleveland. The kiln is shown in Exhibit 1.

Suitable quality sorbent was prepared with both approaches. However, each approach showed certain drawbacks. The heat-treating furnace approach was a batch process in which sorbent beds 8 to 12 inches in depth were employed. With beds of this depth, it was found difficult to obtain uniform heating of the bed. Vermiculite is an excellent insulator. Long heating times, up to eight hours, and occasional mixing of the bed were required to obtain a

EXHIBIT 1. Pilot-Scale Rotary Kiln Furnace

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satisfactory product. The major disadvantage of using the rotary kiln is that the sorbent is tumbled perhaps a hundred times or more during processing. This results in a compaction of the particles, a reduction in MgO surface area, and a generation of fines. The total surface area of the MgO phase was found to be reduced about 30 percent upon processing, in comparison with furnace heat-treated material. This reduced surface area was expected to reflect on SO₂ sorption performance, but only a very small decrease in performance was noted. The tumbling in the kiln resulted in 1 to 2 percent fines production, an amount that is not excessive. The fines were readily removed by screening. The compaction that occurred may actually have a beneficial effect; it appeared to strengthen the particles.

The majority of sorbent for project was prepared by employing a cement mixer and the rotary kiln. Approximately 200 Kg of sorbent was prepared. This material was stored and transported in eight sealed drums (See Exhibit 2).

EXHIBIT 2. Freshly Prepared Sorbent

SANITECH, INC.EQUIPMENT DESIGN AND CONSTRUCTIONTask Objectives

The objectives of this task were to design and to construct small pilot-scale facilities suitable for testing several different continuous SO₂ and NO_x sorption approaches and laboratory facilities suitable for preparing fresh sorbent and for regenerating spent sorbents.

Facilities Design and Construction

Prior to the project, a small slipstream of flue gas at Ohio Edison's Gorge power plant in Akron, Ohio was used for fixed-bed tests with the new sorbent. This system was modified and enlarged to the configurations shown in Exhibit 3 for the project. In modifying the system, the following additions were made: (1) a small building erected on the power plant roof to house the sorption equipment (this building is shown in Exhibit 4); (2) two separate piping systems, a direct system from the main flue gas duct to the sorption building and an indirect system consisting of approximately 40 feet of 4-inch duct between the main duct and the sorption building; (3) suitable equipment for evaluating four different sorption methods; and (4) means for introducing fresh sorbent into the system and for removing spent sorbent.

The special building was installed because only limited space existed next to the main duct, and because working conditions there were less than desirable (often temperatures of 130°F or higher). The second indirect piping system was installed specifically to evaluate the entrained-flow sorption approach.

The sorption systems were designed to remove and process up to 300 ACFM of flue gas. Flue gas after processing was returned to the main flue gas duct.

Exhibit 5 shows schematic drawings of the principal equipment used in the four sorption approaches that were examined. The vessel employed in vertical moving-bed tests (A) was 12-in in diameter and 29-in long and contained an internal stainless steel screen in the shape of an inverted cone to support the sorbent bed. The conic screen had a hole at its apex for the extraction of spent sorbent. The angle of the cone was 50°. Different feeders and extracting means were examined for introducing and removing sorbent; they included screw feeders, vibration feeders, and pneumatic feeders. Special distributors designed to uniformly spray a fine mist of water over the top surface of the bed were installed inside the vessel for several test runs. They consisted of copper tubing containing small holes and brazed into circular, triangular and star shapes. A special gas distributor was designed and installed in the top of the vessel to spread the entering flue gas uniformly over the sorbent bed surface.

A sorbent vessel almost identical to the one employed in vertical moving-bed experiments was used in entrained-flow runs. This vessel (B), however, contained nothing inside except a filter bag constructed of Aramid.

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EXHIBIT 3. Sidestream Configurations Employed in Test Work

EXHIBIT 4. Building Containing Sorption Equipment

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(A) VERTICAL MOVING BED

(C) ALTERNATING FIXED BEDS

(B) ENTRAINED FLOW

(D) PANEL BED

EXHIBIT 5.

Sorption Approaches Examined

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The filter material, supplied by Tex Tech Industries, Inc., is one that is widely used commercially. The filter bag was 18 in. long and 10 in. in diameter. A special manually-operated sorbent feeder was designed and installed to introduce sorbent into the flue gas stream. Moisture was introduced by several approaches; these will be discussed in detail in a later section of this report.

For alternating fixed-bed tests (C), the two vessels used in moving-bed tests and in entrained-flow tests were placed in parallel. Installed in each of these vessels were two flat screens between which fresh sorbent was introduced and extracted. Also installed within the vessels were flue-gas deflectors and means for introducing water. The flue gas duct was modified to allow manual switching of flue gas flow from one vessel to the other and back again.

A special apparatus was designed and constructed to evaluate the panel-bed filter approach to SO_2 and NO_x sorption (D). The panel bed consisted of two parallel vertical screens placed across the flue gas duct perpendicular to the direction of flue gas flow. Sorbent was introduced into the space between the two screens. The apparatus was constructed to allow beds of different sizes to be evaluated. It incorporated enclosed hoppers for fresh sorbent and for spent sorbent. Removable screens of different materials were also prepared. A variable-speed star valve was installed at the base of the panel bed for the removal of sorbent.

Prior to the installation of facilities at the Gorge power plant, plastic mock-ups of the moving-bed, entrained-flow, and panel-bed filter equipment were constructed for evaluations in the laboratory.

The design of the laboratory system that was employed to regenerate sorbents is shown in Exhibit 6. It consisted of a modified electric muffle furnace, special glassware, gas supply and monitoring equipment, and gas analysis equipment. An existing filter evaluation system, shown in Exhibit 7, was employed to saturate sorbent materials during sorption-regeneration cycles.

The major components of the sorption systems were fabricated by Spirit Fabricating, Ltd. of Macedonia, Ohio. Equipment for preparing the sorbents was purchased from Sears and from Federal Equipment of Cleveland. Existing laboratory furnaces and a special glassware system fabricated by Custom Lab Glass of Parma, Ohio were employed in regenerating the sorbent.

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SIDE VIEW SCHEMATIC

PROCESS FLOW DIAGRAM

EXHIBIT 6. Test Apparatus for Regeneration Tests

- P : PRESSURE INDICATOR
 F : ROTAMETER, FLOW INDICATOR
 T : TEMPERATURE GAGE
 ΔP : DIFFERENTIAL PRESSURE GAGE
 S : SO₂ ANALYSIS SAMPLE PORT

EXHIBIT 7. Apparatus for Filter Evaluations and for Saturating Sorbents

SANITECH, INC.AN EXAMINATION OF SORBENT CONVEYING METHODSBackground

It was recognized early in the development of the new technology that sorbent conveying, or the manner in which sorbent is moved within the plant, can play an important part in its commercial success or failure. A major drawback of the Activated Coke process for SO₂/NO_x control that is under development in Europe, for example, is the degradation of the coke sorbent during conveying between sorption and regeneration sites. Degradation of the sorbent during movement through the system is also a problem with other sorbents, such as copper oxide, in the Copper Oxide process. The new Sanitech sorbent is believed to be stronger and more resilient than activated coke, but how well it will perform is not known. For this reason it was deemed important to evaluate the performance of the new sorbent when conveyed in different manners.

Task Objective

The objective of this task was to examine four conveying methods, screw conveying, vibrating conveying, pneumatic conveying, and belt conveying, as a suitable means for moving the new sorbent between processing steps.

Approach

Samples of partially saturated 45 wt% MgO-55 wt% Vermiculite sorbent, fresh sorbent, and expanded vermiculite were examined in separate screw-conveyor tests, vibratory-conveyor tests, pneumatic-conveyor tests, and belt-conveyor tests.

Screw-conveyor tests consisted of feeding 150-g samples of material to a conventional Dayton screw conveyor having a screw diameter of 1.5 in, a velocity of 7 revolutions per min, and a path length of 11 in and collecting the samples after their passage. Vibrating-conveyor tests consisted of feeding 150-g samples of material into a 1.0 in ID stainless steel tube vibrated by an FMC Syntron Model B magnetic vibrator, allowing them to pass through the tube's 27-in length, and collecting them in individual 500-ml beakers. Pneumatic conveyor tests consisted of passing 500-g samples of material through 26.5 ft of 2-in D PVC pipe having two 90-degree angles, several S-curves, and a violent spin at the end. The samples were pulled through the tube by suction provided by a 25-gal Shop Vac (Model 870) wet/dry vacuum cleaner. The velocity of the gas carrying the sorbent was 7200 fpm (82 MPH). Belt-conveyor tests consisted of feeding 150-g samples of material to an 18-in belt conveyor moving at a velocity of 350 fpm, and collecting the samples at the end of the belt. Photographs showing the screw conveyor, vibratory-conveyor, and pneumatic system are shown in Exhibits 8, 9, and 10, respectively.

In all cases, the individual samples of material were sized before testing. Two or more 50-g smaller samples were then removed and resized after each five passes through or across the conveyor. After each sizing analysis, the 50-g

EXHIBIT 8. Screw Conveyor Employed in Tests

EXHIBIT 9. Vibrating Conveyor Employed in Tests

EXHIBIT 10. Pneumatic Conveying System Employed in Tests

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samples were returned to the system. Pneumatic conveyor tests consisted of 20 passes of material through the system; screw-conveyor, vibratory-conveyor, and belt-conveyor tests were limited to 10 passes.

Discussion of Results

The results of the conveyor tests are summarized in Exhibit 11. All values represent averages of two or more samples. Samples were screened into three size fractions: +14 mesh (large granules); -14 mesh +28 mesh (small granules); and -28 mesh (fines). The percentages reported are for the fractions of small granules (pieces) and fines.

It should be kept in mind in examining the data in Exhibit 11 that the severity of testing conditions with each conveyor system was not the same. The conveyor with the longest travel distance and the most impacts was the pneumatic system; the conveyor with the shortest distance travelled was the screw conveyor.

The results showed that vibratory conveying, belt conveying, and pneumatic conveying are methods that can be employed satisfactorily to move sorbent from one site to another in the new process. Screw conveying, on the other hand, is not a satisfactory method. With screw conveying, the sorbent material is crushed and rapidly attrited.

With belt conveying and vibratory conveying, there is very little impact on individual particles. Consequently, very little break-up of particles occurs. Vibratory conveying, however, was found to be suitable only where there was no significant movement of air, no pressure, and no outside vibrations. The controlled feeding of sorbent into a sorber vessel with a vibratory feeder was not possible.

The percentage size reduction that occurred in pneumatic conveying would appear acceptable in a commercial process. An average of less than 1.0 percent increase in fines and small pieces per pass were produced during the first 10 passes, and less than 0.4 percent per pass occurred during the second 10 passes. In a process in which 10 percent of the sorbent stream is removed during each sorption-regeneration cycle, it should not be difficult to include this 1 percent of small particles in the extracted fraction.

Data for expanded vermiculite and for perlite were included in Exhibit 11 for comparison purposes. As-received vermiculite performed significantly better than the sorbent in screw-conveyor tests. However, in pneumatic conveying tests, it did significantly poorer.

SANITECH, INC.**EXHIBIT 11.****Conveyor Test Results**

	<u>Material Before</u>		<u>Percentage by Weight After 5 Passes</u>		<u>After 10 Passes</u>	
	<u>Small Pcs.</u>	<u>Fines</u>	<u>Small Pcs.</u>	<u>Fines</u>	<u>Small Pcs.</u>	<u>Fines</u>
<u>Vibrating Conveyor</u>						
Dry Sorbent	0.2	0.6	0.3	0.4	0.6	0.6
Vermiculite	0.2	0.1	0.3	0.1	0.6	0.3
<u>Screw Conveyor</u>						
Dry Sorbent	0.4	0.4	15.1	20.5	20.7	33.7
Vermiculite	0.3	0.0	4.7	1.2	6.2	2.4
<u>Belt Conveyor</u>						
Dry Sorbent	0.2	0.4	0.5	0.6	0.5	0.7
Vermiculite	0.2	0.2	0.3	0.1	0.3	0.1
<u>Pneumatic Conveyor</u>						
Dry Sorbent	0.3	0.3	1.5	5.1	2.7	6.3
Vermiculite	0.1	0.0	6.9	3.6	12.2	5.8
Perlite	0.7	0.0	1.6	4.4	2.7	6.6
Moist Sorbent	1.4	0.9	2.6	2.7	2.2	3.8

	<u>Material Before</u>		<u>Percentage by Weight After 15 Passes</u>		<u>After 20 Passes</u>	
	<u>Small Pcs.</u>	<u>Fines</u>	<u>Small Pcs.</u>	<u>Fines</u>	<u>Small Pcs.</u>	<u>Fines</u>
<u>Pneumatic Conveyor</u>						
Dry Sorbent	0.3	0.3	3.1	8.2	2.7	10.9
Vermiculite	0.1	0.1	15.4	7.9	15.0	8.7
Perlite	0.7	0.0	4.0	7.9	5.1	14.4
Moist Sorbent	1.4	0.9	6.7	6.0	4.3	6.7

SANITECH, INC.EXAMINATION OF CONTINUOUS SO₂/NO_x SORPTION APPROACHESBackground

Sorbents can be exposed to flue gases in a variety of manners. Approaches that have been suggested or used in the past include:

- 1) Employing replaceable fixed beds
- 2) Employing fluidized beds
- 3) Employing vertically moving beds
- 4) Injecting sorbent directly into the flue gas stream
- 5) Employing alternating fixed beds
- 6) Employing moving panel beds

Use of replaceable fixed beds of sorbent may be feasible for very small applications. In these cases, sorbent beds may be added or removed from gas duct much as conventional furnace filters are used today. For large applications, such as for industrial or power plant boilers, this approach is probably impractical.

Fluidized beds have been the first choice of developers of other regenerable sorbents that remove SO₂ and NO_x from a flue gas simultaneously. It is believed that fluidized beds likewise could be a satisfactory way of employing the new sorbents. Because fluidized-bed pilot systems are relatively expensive and because Sanitech engineers have only limited experience with fluidized beds, the fluidized-bed approach was not included in the present project. It should be noted, however, that Dr. Thomas C. Keener of the University of Cincinnati hopes to examine the new sorbents in a fluidized bed in a future project.

The last four approaches above all can be employed continuously to remove SO₂ and NO_x. Because it was believed that these approaches could be examined in a relatively easy manner on an existing slipstream of flue gas at Ohio Edison's Gorge power plant, they were selected for further study.

Task Objectives

The objectives of this task was to examine and evaluate each of these four methods, use of vertical moving beds, injecting sorbent directly into the flue gas stream, use of alternating fixed beds, and use of moving panel beds, as a suitable means to remove SO₂ and NO_x continuously from a flue gas stream.

Experimental Approach

The various equipment systems used in sorption studies were shown earlier. (See Exhibit 5). A separate series of experiments was performed evaluating each method.

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Vertical Moving Beds

In employing the moving-bed approach, a bed of fresh sorbent is first introduced into the sorption vessel, and after flue-gas flow is initiated, additional fresh sorbent is continuously added to the top of the bed while spent sorbent is continuously extracted from the bottom. Although simple in concept, the moving-bed approach has several difficult requirements for satisfactory performance. For example, to maintain a constant bed size and therefore control of the process, fresh material must be added to the bed at exactly the same rate as spent sorbent is extracted. Also, to maintain uniform bed thicknesses and even reactions across the bed, added fresh sorbent must be distributed as evenly as possible over the top surface of the bed. In addition, to maintain uniform SO₂ and NO_x removal and to prevent premature breakthroughs, sorbent particles must move uniformly downward in the sorption vessel during processing. Processing of flue-gas using a vertical moving bed of sorbent to achieve optimal results then requires close control of the movement of sorbent within the sorbent vessel.

The apparatus that was employed in moving-bed tests is shown in Exhibit 12. During each run, the composition and temperature of the flue gas entering and leaving the sorbent bed were continuously monitored, as were the pressure drop across the bed and the velocity and flow rate of the flue gas. The sorbent feed and removal systems were calibrated in the laboratory under simulated conditions before the test runs. The flue gas normally contained about 1000 ppm SO₂ and 400 ppm NO_x. These levels were somewhat lower than those of the flue gas in the main duct. Air leakage through the fan and into the slipstream duct during the drawing of flue gas from the main duct appeared to be responsible for the lower SO₂ and NO_x levels. The dilution that occurred also resulted in a small reduction in flue-gas temperature. Typical flue gas velocities during tests involving a 12-in moving bed were in the range of 200 to 300 ft/min.

Sorbent Injection & Entrainment in the Flue Gas

Duct injection has recently received considerable attention as a method to reduce SO₂ levels of flue gases. Three duct-injection test programs, Bechtel National, Inc.'s Confined Zone Dispersion (CZD) program involving duct spray drying with dual fluid nozzle atomizers, General Electric's In-Duct Scrubbing (IDS) program involving a rotary atomizer, and Dravo Line's Hydrate Addition at Low Temperature (HALT) program involving injection of a dry sorbent along with humidification water, were completed during the past several months. Although mixed results and relatively poor sorbent utilizations (50 percent or less) were observed, they met the goal of 50 percent SO₂ removal, at least for short times.

One goal of the project was to determine how the new sorbent would perform in a duct-injection process similar to that used in the HALT program.

The approach taken in sorbent-injection tests was to inject moisture directly into the duct carrying flue gas, to inject sorbent downstream simultaneously, and to collect the sorbent in a fabric bag, simulating a baghouse filter. The duct arrangement for sorbent-injection tests consisted of an approximately 45-ft length of 4-in duct leading from the flue-gas fan to the filter bag. Owing to space restrictions, this length was arranged as a large

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vertical loop having five 90° angle turns and an upward lift of 80 in. and two vertical drops before entering the filter bag.

A stoichiometric ratio of 1.5:1 (moles magnesium per mole of sulfur in the flue gas) was employed in sorbent-injection tests. The flue-gas velocity was typically 3500 ft/min, although the velocity decreased appreciably after the bag filled with sorbent. As in most tests, the incoming flue gas contained 1000-1200 ppm SO₂ and 400-500 ppm NO_x. The flue gas temperature after moisture injection was about 200°F, but generally varied widely during each test run.

EXHIBIT 12.

Apparatus Employed in Moving Bed Tests

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Alternating Fixed Beds

The concept of alternating fixed beds consists of employing two or more sorbent beds in parallel and switching the flue gas stream from one bed to a second bed after the first bed becomes saturated. In the laboratory and in small pilot plants, this concept can be demonstrated readily because the flue gas ducts at these scales are relatively small. There is some question, however, whether this concept would be feasible for large power plants where the ducts are very large and the equipment required to damper off these ducts would by necessity be huge.

A single test run examining the use of alternating fixed beds was carried out at the Gorge power plant. The equipment used in this run was described earlier. A sorption vessel containing a 10-in sorbent bed was exposed to the Gorge power plant flue gas for about six hours. After this time, the flue gas stream was diverted manually to a second, almost identical vessel containing sorbent. The sorbent in the second vessel was then exposed to flue gas for an additional six-hour period.

Moving Panel Beds

The panel-bed filter, because of its simplicity, offers great promise as a retrofitting approach applicable to existing power plants. The space requirements of this concept appear to be small, in comparison with other processes for the removal of SO_2 and NO_x .

The procedures that were followed in running panel-bed tests at the Gorge power plant were fairly straightforward. Of all the test runs performed in the project, the panel-bed tests were the easiest to run.

The apparatus that was employed in all panel-bed runs is shown in Exhibit 13. In operating this apparatus, fresh sorbent was first charged into the hopper at the top of the unit during which time sorbent also filled the panel bed. A star valve at the bottom of the bed prevented sorbent from entering the spent sorbent hopper at the bottom of the unit. After the feed hopper was fully filled, it was sealed off at the top and flue gas was allowed to pass through the panel bed. The flow of the sorbent downward through the panel bed was controlled by the rotation of the star valve. Material passing through the valve dropped into the spent sorbent hopper. Periodically this hopper was emptied pneumatically.

As in all runs with the other systems, the compositions, temperatures, and flow rates of the flue gas before and after the bed were monitored continuously. Data on the pressure drop across the bed and on the drafts in sampling lines were also collected. Three, and sometimes four, different techniques or apparatuses for chemical analysis were employed. These included an Enerac 2000 combustion analyzer and a Landcom 2000-46 Flue Gas Analyzer, both employing electrochemical cells, Matheson-Kitagawa length-of-stain analyses tubes, and an EPA Method 6 apparatus for SO_2 .

EXHIBIT 13.

Sorption with a Panel-Bed Filter Apparatus

Discussions of Results

Vertical Moving Beds

A half dozen runs were performed using the 45 wt% MgO-55 wt% Vermiculite sorbent. Runs were made with different methods of sorbent feed and extraction and with and without moisture additions. The major problems encountered in these runs included:

- 1) difficulties in feeding and extracting sorbent to the sorption vessel;
- 2) poor movement of the sorbent over the bottom screen; and
- 3) agglomeration of sorbent particles at the bottom of the sorbent bed when large water additions were made to the flue gas at the sorbent bed surface.

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Difficulties in feeding and extracting sorbent were exacerbated by the pressure conditions appearing in the system. Sorbent was introduced in regions above the bed which were under strong positive pressure; removals were performed below the bed where pressures were negative. Attempts to equilibrate and control pressures were only partially successful. It was found impossible to control the flow of sorbents into and out from the sorber when vibratory equipment was used. Screw conveyors supplied sorbent to the unit and removed it at controllable rates but they generally attrited the material (as in separate studies described earlier). They also often became blocked at the entry port during sorbent extraction. Pneumatic conveying appeared to be the most versatile method of feeding and extracting sorbent.

Because flue-gas flow and sorbent flow are both downward in the vertical moving-bed process, individual sorbent particles are forced into the bottom screen. With this action, the particles tend to become keyed or wedged into the screen. This keying action results in obstructions that stop the free movement of particles. Stationary build-ups of material on the screen eventually occur that ultimately results in a bridging over of the exit hole at the bottom of the screen. This problem was observed to be even more serious when large quantities of water were added to the flue gas or to the top of the bed. In these cases, it is believed that the surfaces of the sorbents within the bed become moist (MgSO_3 is soluble in water). Liquid phases on particle surfaces in contact with each other solidify as the particles move downward and are heated by the incoming flue gas. On solidification, individual particles weakly bond to each other.

Despite the problems alluded to above, good SO_2 and NO_x removal efficiencies (generally above 90% SO_2 removal and 30% or more NO_x removal) were observed during the initial one to two hours of each run involving water additions to the top of the bed. In every case, however, the test run had to be terminated thereafter because sorbent material could not be effectively removed from the bottom of the bed. In runs involving no water additions, SO_2 removal efficiencies were 75% or lower.

Sorbent Injection & Entrainment in the Flue Gas

The results obtained in entrainment runs were generally no better than those reported in the HALT program. Poor SO_2 and NO_x reductions occurred until appreciable sorbent built up on the inside of the filter bag. Although SO_2 reductions of greater than 85 percent were seen, they occurred at times when the collection bags were nearly full and the flue gas flow rate was significantly reduced. Very little NO_x reduction was observed in any of the sorbent injection runs.

A number of problems occurred in carrying out the entrained-flow runs. Difficulties were encountered in getting moisture into the flue gas. Two different spraying systems were employed, a coarse spray and a fine spray. Neither system appeared to perform well. Owing to the small size of the duct (4 in. ID), much of the sprayed water struck the inside duct walls and became less effective in humidifying and cooling the gas.

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The time of a typical sorbent injection run was about two hours. During that time 1500-g of sorbent was injected into the flue gas. Of this amount, up to about half remained in the flue gas duct, never reaching the fabric bag filter. Most material remaining in the duct was retained during the last half of each run when the gas velocity was reduced. Many sorbent particles were not able to climb the 80-in vertical duct length in the system.

Alternating Fixed Beds

The results of the alternating fixed-bed tests were essentially the same as those observed during the first two hours of the moving-bed tests. Excellent SO₂ removals and appreciable NO_x removals were observed.

Exhibit 14 is a graph of SO₂ removal versus sorbent utilization for the first bed of the alternating fixed-bed run. The results obtained with the second bed of the run duplicated well the results of the first bed. As can be seen from the data in Exhibit 14, a sorbent utilization well above 100 percent was obtained. Also, an average SO₂ removal rate of about 87 percent can be expected with a sorbent utilization of 80 percent. The higher-than-100% utilization observed is believed due to multiple sorption mechanisms; SO₂ is sorbed by not only chemical reaction with the MgO phase, but by capillary micropore condensation, the mechanism by which SO₂ is removed in the Activated Coke Process.

Moving Panel Beds

After several panel-bed test runs, it was clear that the panel bed offered some important advantages over the other three approaches that were evaluated. Two of these advantages are ease of operation and good performance.

The results that were obtained with the 45 wt% MgO-55 wt% Vermiculite sorbent during a four-hour run were similar to those seen in the earlier fixed-bed runs; high SO₂ removals were attained and even higher sorbent utilizations were achieved.

The favorable results obtained with the panel bed encouraged a further investigation and development of this approach. A study examining how changes in processing variables affect the performance of the panel bed was therefore performed and is discussed in the next section of this report.

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EXHIBIT 14.

SO₂ Sorption vs Sorbent Utilization
for an MgO-Vermiculite Sorbent Exposed in a Fixed-Bed

SANITECH, INC.ADDITIONAL PANEL-BED FILTER STUDIESBackground

In the previous task, some very promising results were observed with the panel-bed filter approach. To use the new sorbents in panel beds, it is important to know under what conditions the sorbents will perform well and under what conditions they will not. Also, basic parametric data are needed to design larger equipment that may be used in the future.

Task Objective

The objective of this task was to examine the effects of changes in various operating parameters on the performance of the new sorbents in a panel-bed sorber.

Parametric Studies

Six variables in the panel-bed filter approach were investigated as they affect SO_2 and NO_x removal from a flue gas. These variables were (1) the thickness of the sorbent bed, (2) the level of SO_2 and NO_x in the flue gas, (3) the temperature of the flue gas, (4) the manner in which water is added to the system, (5) the composition of the sorbent, and (6) sorption time.

Sorbent Bed Thickness

Exhibit 15 is a schematic drawing of the panel bed system that was employed in experiment work at the Gorge power plant. Flue gas was delivered to the panel-bed unit in the system through 4-in duct at an open-chamber face velocity of about 4400 fpm (630 ACFM). This velocity varied from time to time based on the operating level of the power plant. The gas face velocity was decreased somewhat as the gas passed through sorbent beds in the unit's 7.5-in x 7.5-in chamber. The panel bed intersected the flow of flue gas as shown in the drawing. Several panel-bed thicknesses were examined to determine the effects of changes in bed thickness on sorption performance. Panel-bed thickness was varied by changing the distance between screens holding the bed. Beds with 2-in, 4-in, and 8-in thicknesses were investigated. The results of these studies are summarized in graph form in Exhibit 16.

As might be expected, SO_2 and NO_x sorption performance improved with increase in bed thickness. A bed thickness of only two inches was found to remove some SO_2 and NO_x , but not enough to be judged satisfactory. A bed thickness of four inches, on the other hand, proved to be adequate in removing on an average more than 90 percent of the SO_2 present in the flue gas and appreciable NO_x . Eight-inch beds performed even more effectively.

Changes in bed thickness in the test program affected SO_2 and NO_x removal in two ways. Increased thickness of the spent bed meant increased sorbent-flue gas contact time and increased availability of MgO and surface porosity. Because the speed of the fan employed in the test program could not be

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EXHIBIT 15.

Schematic Drawing of the Panel-Bed Filter System

(All values indicate average percentages of SO₂ or NO_x removed during a 2-3 hour test period in a moving panel-bed with the flue gas velocities indicated in paranthesis. All 2-in and 8-in beds were run dry; the 4-in beds were run with moisture added to the flue gas.)

EXHIBIT 16. The Effect of Bed Thickness on Average SO₂ and NO_x Removal Performance

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controlled, increasing the bed thickness also resulted in a reduction in the flow rate of gas through the bed. Typically face velocities were reduced from 900-2000 fpm with 2-in beds to about 400-800 fpm with 10-in beds. With lower gas flow rates, fewer SO₂ and NO_x molecules required capture per unit of sorbent, so improved performance could be expected.

Flue Gas SO₂ and NO_x Levels

Owing to the nature of the test site, there was only limited flexibility in changing the SO₂ and NO_x concentrations of the flue gas. The SO₂ and NO_x levels of the flue gas in the main duct was typically about 1500 ppm and 500 ppm, respectively, although wide swings in concentrations often occurred during each day. Although the SO₂ and NO_x concentrations of the flue gas could have been increased by making SO₂ and NO_x additions to the gas, this was not done at the power plant because of anticipated mixing problems and plant safety considerations. Instead, the SO₂ and NO_x concentrations of the gas were changed by diluting the gas with air at the fan where there was a controllable leak. Parallel tests, however, were performed in the laboratory in which SO₂ concentrations of up to 5000 ppm were examined in simulated flue gases.

The results of experiments with flue gases having 200 to 1200 ppm SO₂ and 100 to 500 ppm NO_x in the field and up to 5000 ppm SO₂ and 1000 ppm NO_x in the laboratory showed that SO₂ and NO_x levels within these ranges have little effect on sorption performance.

An interesting observation made on a number of occasions was that the presence of sulfur in the sorbent bed appears to improve NO_x removal. This was seen in both fixed bed and panel-bed runs. As the beds became saturated with sulfur, NO_x removal invariably increased.

Flue-Gas Temperature

In past work it became apparent that two variables, flue-gas temperature and flue-gas moisture level, affect the performance of the new sorbents. Because oftentimes these two variables are inter-related (adding water to a flue gas generally lowers its temperature), it has been difficult to define clearly which variable is most important.

The results of over 40 panel-bed runs were analyzed on the basis of flue-gas temperature. The results varied significantly since the effects of other factors, such as the moisture content of the flue gas and bed thickness, appeared to have a greater effect on sorption and masked the results. Nevertheless, a trend could be observed indicating a decrease in SO₂ removal performance with an increase in flue-gas temperature over the temperature range 150° to 290°F. With a flue gas at 180°F, average SO₂ removals were generally above 95 percent. The average SO₂ removal efficiency for flue gases at 270°-275°F when sufficient moisture was present was about 70 percent. The trend was less clear for NO_x-removal performance since some good removal rates, about 60 percent, occurred with the flue gas at the highest temperatures observed (285°-290°F).

An interesting observation during the test program was that on cold, wet, rainy days, the temperature of the power plant flue gas was notably lower than

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on dry days, perhaps 100 F degrees lower. On these rainy days, particularly if the coal employed at the plant was exposed to rain for a day or more, the SO₂ and NO_x removals were invariably good, even when no moisture was added to the flue gas. On dry days, on the other hand, the flue gas was always hotter and unless moisture was added to the gas, the SO₂ removal performance was usually poor, averaging 30 percent or less.

Moisture in the Flue Gas

Moisture plays a very important part in SO₂ removal with the new sorbent. This observation was made in the laboratory by Sanitech researchers earlier. It was also made by Dr. Sheila Hedges of the Pittsburgh Energy Technology Center (PETC) of the U.S. Department of Energy (DOE), who evaluated samples of the new sorbent. Dr. Hedges' results showed that the sorbent very effectively removed SO₂ when the flue gas possessed high humidity (18 to 20 percent moist), but was much less effective when the flue gas was almost devoid of moisture.

A series of runs were performed at Gorge in which the moisture addition method was varied to determine which method gave the best SO₂ and NO_x sorption-efficiency results. The following methods were examined in combination with panel beds:

- 1) Coarse spraying into the duct well ahead of the bed.
- 2) Fine spraying (with a mist) into the duct well ahead of the bed.
- 3) Adding moisture to the duct in the form of steam.
- 4) Fine spraying into a special 1-ft diameter vessel filled with plastic rings with the vessel placed before the bed.
- 5) Wetting the sorbent particles before introducing them into the panel bed.
- 6) Coarse and fine spraying within the sorber vessel itself (in front of the front screen).

All methods, except steam additions, were found to reduce the temperature of the flue gas stream. Steam additions in some cases actually increased the flue-gas temperature. Superheated steam was employed in all steam runs. Coarse spraying and fine-spraying directly into the duct were the least effective methods for reducing flue-gas temperatures, while fine spraying into the special vessel filled with plastic rings appeared to be the most effective method to reduce temperatures.

The one method that resulted in the best overall SO₂ and NO_x removals was spraying water within the sorber vessel itself. Wetting the sorbent appreciably before feeding it to the bed appeared to improve sorption efficiency momentarily, but with a dry gas this extra moisture evaporated rapidly and efficiency fell off quickly.

No clearly best way to add moisture to the flue gas was identified. All were effective in introducing some degree of moisture to the flue gas.

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Spraying water onto the screen inside the sorber resulted in not only the highest SO₂ removal efficiencies seen (often 100 percent), but also the highest sorbent utilizations. With this approach, however, flue gas temperatures were usually reduced significantly, perhaps more so than desired, and sorbent-particle agglomeration sometimes occurred in the bed.

Sorbent utilization as relates to the MgO-Vermiculite sorbent is measured as the percentage of the MgO that is converted to MgSO₃. A 100 percent utilization means 100 percent of the MgO in the sorbent theoretically has been converted to MgSO₃. If a utilization of greater than 100 percent occurs, this means SO₂ is being removed by reactions or mechanisms other than $\text{MgO} + \text{SO}_2 \rightarrow \text{MgSO}_3$. With the MgO-Vermiculite sorbent, utilizations of up to 300 percent were measured. Kent State University researchers have identified micropore condensation as the mechanism that is occurring in addition to MgSO₃ formation for the new sorbent.

Mixed results were obtained with steam additions. Additional test work with steam additions appears warranted because this approach was found to be simplest to use and results in little or no flue gas temperature loss. In a commercial process, steam usage will have a negative effect on operating costs.

Composition of the Sorbent

Past research results, particularly laboratory results, indicated that MgO-Vermiculite combinations provide the good properties being sought in a SO₂/NO_x sorbent. In the MgO-Vermiculite family, a composition consisting of 45 wt% MgO and 55 wt% Vermiculite was found to display optimum properties. Most attention therefore was given to this sorbent composition in the project.

Several other sorbent families, similar to MgO-Vermiculite, have shown promising results in the past. These families include MgO-Perlite, CaO-Vermiculite, and CaO-Perlite. Members of the latter two families are not normally regenerable, but are somewhat less expensive to prepare and could be employed in once-through systems.

Several-hundred-gram quantities of fresh sorbent of the following compositions were prepared:

- 1) 45 wt% MgO-55 wt% Perlite
- 2) 45 wt% CaO-55 wt% Vermiculite
- 3) 45 wt% CaO-55 wt% Perlite

Each of these materials was then run in panel-bed tests, along with a sample of 45 wt% MgO-55 wt% Vermiculite, for comparison. A 4-in sorbent bed was employed in each case. The results of these runs, in the form of SO₂ removal efficiency-sorbent utilization curves are given in Exhibits 17 through 20.

These results show that none of the three new materials showed as good SO₂ sorption properties as the 45 wt% MgO-55 wt% Vermiculite sorbent. From the average SO₂ efficiency curves in Exhibits 17 through 20, one can see for a sorber operating with an average sorbent utilization of 100 percent, he or she could expect the following average SO₂ removal efficiencies:

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EXHIBIT 17. SO₂ Removal Efficiency vs Sorbent Utilization
for 45 MgO-55 Vermiculite

EXHIBIT 18. SO₂ Removal Efficiency vs Sorbent Utilization
for 45 MgO-55 Perlite

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EXHIBIT 19. SO₂ Removal Efficiency vs Sorbent Utilization
for 45 CaO-55 Vermiculite

EXHIBIT 20. SO₂ Removal Efficiency vs Sorbent Utilization
for 45 CaO-55 Perlite

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<u>Sorbent</u>	<u>SO₂ Removal Efficiency</u>
(1) 45 MgO-55 Vermiculite	99 percent
(2) 45 MgO-55 Perlite	83 percent
(3) 45 CaO-55 Vermiculite	70 percent
(4) 45 CaO-55 Perlite	92 percent

In respect to sorbent utilization, however, some surprising results were seen. All sorbents showed utilizations well above 100 percent, indicating capillary pore condensation, as a sorption mechanism, occurred in all cases. Of the three new materials, the 45 wt% CaO-55 wt% Perlite material (the lowest cost sorbent) gave the best results. If only a 70 percent SO₂ removal were required, the CaO-Vermiculite sorbent would remove twice the quantity of SO₂ per unit CaO weight that CaO removes today in wet scrubbing.

NO_x removals with the four materials were about the same, in the range 30 to 45 percent.

SO₂ and NO_x Removal vs. Time

Curves showing SO₂ and NO_x removal efficiencies as a function of time for a run in which an 8-in bed of 45 wt% MgO-55 wt% Vermiculite was exposed to a flue gas containing 600-750 ppm SO₂ and 400-650 ppm NO_x (typically 500 ppm NO and 5 ppm NO₂) are given in Exhibit 21. These curves are representative of curves for samples of the new sorbents when exposed as stationary beds. Typically, SO₂ removals remain fairly constant at a high level for a period of time and then slowly fall off as the sorbent becomes saturated. NO_x-removal efficiency, on the other hand, usually remains constant or rises with time.

EXHIBIT 21. SO₂ and NO_x Removals as a Function of Time
During a Typical Panel-Bed Run

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A long-term (12-hr) run was performed with a 4-in bed of the 45 wt% MgO-55 wt% Vermiculite, during which time the bed was replaced each time the SO₂ removal efficiency dropped below 70 percent. The run was performed continuously. A curve of SO₂ removal efficiency versus time for this run is shown in Exhibit 22. The average SO₂ removal efficiency for this run was 89.1 percent. The average sorbent utilization was 180 percent. The saw-toothed nature of the average SO₂-removal curve can be eliminated by adding sorbent continuously to the top of the bed and removing sorbent simultaneously from the bottom. This procedure generally works well, except on occasion, holes in the bed develop as material fails to move downward uniformly. This problem appears to be more acute with thin beds than with thick beds.

EXHIBIT 22.

SO₂ Removal Efficiency During a 12-Hour Run
With 45 wt% MgO-55 wt% Vermiculite

SANITECH, INC.REGENERATION IN A REDUCING ATMOSPHEREBackground

Prior to this project, it was discovered in a program supported by the U.S. Environmental Protection Agency (EPA) that MgO-Vermiculite materials saturated with SO₂ and NO_x could be regenerated by heating. During heating, SO₂ and NO_x evolved as concentrated streams. Further, it was learned that heating in a reducing atmosphere resulted in a destruction of the NO_x (converted to N₂) and a conversion of a significant portion of the SO₂ to elemental sulfur and H₂S. Additions of hydrogen, CO, or methane could be employed to achieve a reducing atmosphere. Of these additions, methane appears most attractive from cost and safety standpoints, and, for this reason, nitrogen-methane (air) combinations are being considered at present for regeneration atmospheres. In a commercial system it is envisioned that a small amount of methane would be combusted with air and the resulting combustion products would be enriched with methane to make up the regeneration-gas atmosphere.

Task Objective

The objective of this task was to determine the optimum composition of methane-nitrogen atmosphere and the optimum temperature that should be employed in regenerating the 45 wt% MgO-55 wt% Vermiculite sorbent.

Discussion of Results

During the regeneration of saturated sorbents, SO₂ and NO_x are given off which results in sample weight losses. The extent of weight loss provides an indication of the regenerability of the saturated sorbent. Past research has shown that regeneration temperature, atmosphere, time, and, to a lesser extent, the rate of flow of gas over the sorbent during regeneration affect the regenerability of sorbents.

A series of experiments were performed to investigate the effects of changes in the composition of the atmosphere and in temperature on regenerability when nitrogen-methane atmospheres are employed. A large number of sorbent samples partially saturated with SO₂ and NO_x were regenerated in atmospheres consisting of 100 percent nitrogen, 100 percent methane, and combinations of nitrogen and methane. Regenerations were carried out for 30 minutes at temperatures of 550 to 850°C. Weight loss data that were collected are given in Exhibit 23.

The results of the regeneration tests showed that regeneration performance increases with the percentage of methane in the nitrogen-methane atmosphere and with regeneration temperature. Good performance can be expected with atmospheres containing 10 percent or more methane as long as the regeneration temperature is 750°C or higher. Earlier results indicated that for good NO_x destruction during regeneration, the level of methane in the atmosphere should be at least 30 percent.

SANITECH, INC.**EXHIBIT 23.**

**Regeneration Performance of Partially Saturated
45 wt% MgO-55 wt% Vermiculite in Nitrogen-Methane Atmospheres**

<u>Methane (%)</u>	<u>Nitrogen (%)</u>	<u>Temperature (°C)</u>	<u>Weight Loss (%)</u>		<u>Average</u>
			<u>Sample 1</u>	<u>Sample 2</u>	
0	100	750	39.5	38.1	38.8
5	95	750	38.2	38.9	38.5
10	90	750	39.3	41.1	40.2
20	80	750	40.0	39.8	39.9
50	50	750	40.7	41.2	40.9
100	0	750	41.8	42.2	42.0
20	80	550	17.6	18.8	18.2
50	50	550	19.2	20.7	19.9
100	0	550	35.8	37.8	36.8
20	80	550	17.6	18.8	18.2
20	80	650	21.0	45.8	33.4
20	80	750	40.0	39.8	39.9
20	80	850	41.6	41.3	41.4

NOTE: Saturated samples beforehand contained approximately 36% SO₂ and NO_x.
The weight losses higher than 36% above indicate that additional species
are coming off, such as combined water that was detected in the exiting
gases.

MULTIPLE SORPTION AND REGENERATIONSBackground

Exhibit 24 below shows a sample of fresh sorbent and a sample of spent sorbent saturated with SO_2 and NO_x . Upon regeneration, the appearance of the spent sorbent changes back to that of the fresh sorbent on the left.

In a commercial process, the new MgO-Vermiculite sorbent will be saturated with SO_2 and NO_x and then regenerated back hopefully to its near-original condition many times. It is of interest to know how the sorbent will perform in removing SO_2 and NO_x after it has undergone a number of recycles. Also, it is of interest to know the physical condition of the sorbent after it has undergone multiple recycles.

Task Objective

The objective of this task was to determine how multiple sorption and regeneration cycles of the new sorbent affect its performance in removing SO_2 and NO_x from flue gases and affect its physical condition.

EXHIBIT 24. Photograph of Fresh and Saturated (Spent) MgO-Vermiculite Sorbent

SANITECH, INC.Discussion of Results

In a multiple sorption-regeneration study conducted in the laboratory, duplicate beds of 45 wt% MgO-55 wt% Vermiculite sorbent were processed through 18 consecutive sorption-regeneration cycles. Regenerations were performed in a nitrogen-methane atmosphere containing 40 percent methane at 750°-800°C. Data collected during these 18 cycles are summarized in Exhibit 25.

During the sorption-regeneration runs, the sorbents were handled in a rough manner to simulate a worst-case scenario in actual practice. The results of the multiple runs indicated the following:

- 1) The sorption ability of the sorbent, in terms of utilization or grams of SO₂ removed per gram of sorbent, remained satisfactory during the multiple runs. The sorbent removed SO₂ from the flue gas well through 14 cycles.
- 2) Significant losses of sorbent weight occurred during the 18 cycles, and particularly after 10 cycles. Losses were believed attributable (1) to sorbent left behind in the filter vessels after sorption or adhering to the holding vessels during drying and regenerating, or on transferring of material from one vessel to another; (2) to abrasion and dusting of the sorbents during processing; (3) to wetting and washing of the sorbent beds by condensing water; and (4) to possible decomposition of the sorbent.
- 3) Physical degradation of the sorbent was not a problem through 12 cycles. During later cycles, however, some degradation occurred. After 18 cycles, the particle size of the sorbent consisted of:

Large Particles (Greater than 28 Mesh)	72.3%
Small Particles (28 Mesh to 200 Mesh)	27.6%
Dust (Less than 200 Mesh)	0.1%

- 4) Regenerating the sorbent appeared to improve its NO-capture ability. NO-removal-efficiency peaked at 80 percent during the 3rd cycle and averaged about 50 percent during all cycles. NO₂-removal-efficiency averaged 90 percent during the 18 cycles.

SANITECH, INC.**EXHIBIT 25.**

**SO₂, NO, and NO₂ Removal
Performance During 18 Cycles**

<u>Cycle Number</u>	<u>Initial Sample (g) Dry Wt*</u>	<u>SO₂ Removal Efficiency (%) At 20 Min.</u>	<u>SO₂ Removal Effectiveness (%) Avg. for 60 Min.</u>	<u>NO Removal Effectiveness (%) Avg. for 180 Min.</u>	<u>NO₂ Removal Effectiveness (%) Avg. for 180 Min.</u>
1st	10.00	99.9	90.0***	31.3	78.0
2nd	9.49	99.8	96.0	40.0	100.0
3rd	9.36	99.9	96.2	80.0	100.0
4th	8.95	98.4	86.4	60.0	100.0
5th	8.68	99.8	76.5	48.2	95.0
6th	8.86	98.8	83.9	45.0	83.5
<hr/>					
7th	8.52	99.9	75.4	56.3	92.5
8th	8.08	99.8	70.0	37.5	90.0
9th	7.85	99.9	85.5	57.1	88.6
10th	8.22	96.4	62.8	57.1	93.8
11th	7.74	98.9	73.0	37.5	88.3
12th	6.78	99.6	92.4	20.0	92.5
<hr/>					
13th	6.06	73.1**	65.4	ND	ND
14th	5.51	82.7	54.7	ND	ND
15th	4.57	50.0	40.6	ND	ND
16th	4.07	41.7	46.7	ND	ND
17th	3.51	30.0	29.5	ND	ND
18th	3.16	39.3	38.4	62.5	68.0

* - All data are Averages for Duplicate Samples

** - The effects of a reduced sample size are seen after Cycle 12.

*** - 80% SO₂ Removal Effectiveness for 60 Min. in laboratory tests correlates with 99.9% SO₂ Removal Effectiveness in larger-scale powerplant tests.

ND - Not determined

SORPTION/REGENERATION SYSTEM DESIGN & ECONOMICS

Background

The promising results in the laboratory and at the Gorge power plant led to the following questions: How might the new technology be applied? What will it cost? For answers to these questions, some preliminary designs and cost estimates are required.

Task Objectives

The objectives of this task were to develop a preliminary design for a commercial sorption and regeneration facility and to examine the economics of SO_2 and NO_x removal with the new sorbents.

Process Design

A process flow sheet that was developed to illustrate the application of the new sorbent is shown below. It includes the use of panel-bed sorbers.

EXHIBIT 26. Process Flow Sheet

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The preferred location for the sorbers is following the principal dust-collection system in any flue-gas clean-up application. Fans should be employed to draw the flue gas through the sorbers and out through the smokestacks.

For a 500-MW-scale power plant, four identical, independent 127.5 MWe sorption trains are envisioned, each branching off from the existing ducting going to the stacks. In each train, in-duct water sprays like those demonstrated at Ohio Edison's HALT Demonstration at the Edgewater power plant would cool and humidify the flue gases before they go to the panel-bed sorber array. There, in duct sections only about twice the cross-sectional area of the usual ducting, the gases would pass through one of twelve panel-beds before moving on to an ID fan and out to the stack. Each panel-bed would be about 10 ft x 10 ft x 1 ft. They could be arrayed in four lines of three panels, arranged parallel to the duct direction. With this design, a large gas flow would be accommodated in relatively small equipment.

Each of the two pairs of sorber streams would feed saturated sorbent into one of two regeneration streams. In the regeneration system, the sorbents would be dried of hydrate water, regenerated, mixed with make-up sorbent while a fraction of the spent sorbent is drawn off, and returned to the sorbers. The concentrated regenerator off-gases would be combined, stripped of condensing sulfur, purified, and run through the by-product elemental-sulfur recovery system.

In the proposed design, the sorbent would move slowly downward through each panel-bed sorber perpendicular to the gas stream. As the sorbent becomes saturated with SO_2 and NO_x , it would leave each bed and would be collected in hoppers beneath the units. Each of the two pair of sorber streams would feed saturated sorbent into one of two regeneration streams. Because the spent and regenerated materials can be conveyed readily pneumatically, siting of the regeneration facilities, sulfur-recovery facilities and sorbent-preparations equipment should be no problem. They can be located at any convenient distance from the sorbers.

In each regeneration circuit, the saturated sorbents would be dried of hydrates and adsorbed water in a dryer and fed to an indirectly-fired regenerator unit. A reducing gas (most logically a combustion gas from fuel-rich burning of methane) would pass through the regenerators countercurrent to the direction of the sorbent. This gas would carry away the sulfur species first to a condenser and then to a sulfur-recovery circuit. The regenerated sorbent would be cooled during pneumatic transport, while it was combined with a small amount of fresh make-up sorbent and was sized in cyclones. The oversized sorbent would be sent to the sorbers, while the undersized fraction would be transported to a spent-sorbent bin.

The regeneration gas would leave the regeneration vessel and enter a cooler to reduce its temperature and to condense out elemental sulfur. The resulting gas would then pass sequentially through a RESOX unit and a LO-CAT unit to convert catalytically the SO_2 and H_2S in it to elemental sulfur and water vapor. The tail gas, which would still contain some residual sulfur compounds, would be oxidized to produce SO_2 , which would be recycled back into the process.

SANITECH, INC.Facilities Design

A list of the major pieces of equipment that are expected to be necessary for the sorption/regeneration/sulfur recovery process is given below. Also listed for a 500 MWe facility are the quantity of each type of unit required and the approximate unit sizes for the facility.

<u>Item</u>	<u>Number</u>	<u>Size</u>
Duct water sprayers	12	5 gal/min each
Sorbers	12	10 ft x 10 ft x 1 ft deep
I.D. fans	4	100,000 acfm, 12 in W.G.
Saturated sorbent dryers	2	2500 cu.ft/hr
Reductant gas burners	2	300 scfm
Regeneration vessels	2	2500 cu.ft/hr
Sizing cyclones	2	-
Gas cooler/condenser	1	4500 scfm
RESOX unit	1	2000 scfm
LO-CAT unit	1	2000 scfm

Several possible dryer designs could be employed for drying the saturated sorbent. Fluidized-bed dryers are probably preferred because of their high throughput, uniform heat transfer characteristics, and smaller space requirements. The regeneration vessels can likewise be of several different designs. A multiple-tube design is being proposed at this time.

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Process Economics

In analyzing capital and operating costs, a 500-MWe standard pulverized-coal boiler power plant is assumed. The reference power plant burns a 2.5% sulfur, bituminous coal with a HHV of 12,360 Btu/lb in two boilers rated at 1.8×10^6 lbs steam per hour. The power plant produces 1,090,000 scfm of flue gas which is handled through two separate exhaust systems. The flue gas is assumed to contain 4.5% O₂, 1650 ppm SO₂ and 700 ppm NO_x, and to have a temperature of 300°F at the outlet of the particle-collection system (ESP).

The plant is estimated to have an installed equipment cost of approximately \$49 MM. An additional \$8.5 MM would be needed for general facilities and controls. Engineering and contingency costs of \$11 MM would bring the total plant cost to \$68.5 MM. Initial sorbent changes and chemical costs would be relatively insignificant, \$15,000.

For a retrofit application, the capital costs could be greater than those above, owing to the added problems of designing around existing facilities. However, several characteristics of the new process aid in keeping down retrofitting costs. Because the only parts of the system that require retrofit at specific locations are the water sprays, the sorbers, and the I.D. fans, these can be placed at the end of the flue-gas ductwork, away from most other equipment at the power plant. The remainder of the sorbent system (i.e., the regeneration and sulfur recovery facilities) can be located on sites that are more convenient. To adjust for retrofitting problems, retrofit factors of 1.4 for the sorber system and 1.15 for the regeneration and sulfur-recovery systems were assumed. On these bases, the total capital cost of a retrofit 500-MWe system would be about \$86 MM, or \$172 per KW installed.

Operating costs can be classed into five principal categories: maintenance costs; labor costs; variable operating costs; parasitic power; and by-product costs and credits. These cost categories are shown in the table below. The two largest components of operating cost are the make-up sorbent cost and the power needed to drive the I.D. fans. The fresh sorbent's cost will be about \$550/Ton (delivered). This price is based on the sorbent seeing an average 10 sorption-regeneration cycles. Sulfur credits at \$94.50/Ton of sulfur and by-product sorbent credits at \$20/Ton of sorbent were considered in estimating by-product costs and credits.

	Hourly Costs or Credits for 500 MWe Plant
Maintenance Cost	\$ 237/hr
Labor Cost	\$ 251/hr
Variable Operating Costs	\$ 115/hr
Fresh Sorbent Costs	\$ 936/hr
Parasitic Power	\$ 910/hr
By-Product Costs and Credits	(\$ 610/hr)
Total	\$1,839/hr

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Because approximately 8 tons of SO₂ would be removed from the flue gas during each hour at the 500-MWe plant, the total operating cost of the system would be \$230-per-ton of SO₂ removed.

The costs of Sanitech system should compare very favorably with those of competitive systems. It is likely that levelized costs will be in the range of \$400 to \$700/T SO₂ removed. (An average SO₂ removal efficiency of 85-95 percent is assumed.)

Costs of other alternatives were estimated in a recent article in Environmental Progress ("Retrofit SO₂ and NO_x Control Technologies for Coal-Fired Power Plants," August, 1986, pages 171-177). The author of the paper, Michael J. Miller of the Electric Power Research Institute (EPRI), listed the following technologies and their cost effectiveness ranges:

<u>Retrofit Technology</u>	<u>Midpoint</u>	<u>Range</u>
Limestone FGD	\$ 850	\$ 576 - 1,126
Forced Oxidation	\$ 800	\$ 560 - 1,048
FGD Chiyoda Advanced Throwaway FGD	\$ 780	\$ 425 - 935
Wellman-Lord Regenerable FGD	\$1,100	\$ 754 - 1,429
Spray Dry FGD	\$1,800	\$ 778 - 2,831
Furnace Sorbent Injection	\$ 650	\$ 512 - 812
Post-Furnace Trona Injection	\$2,000	\$1,462 - 2,651
Atmospheric Fluidized Bed	\$1,000	\$ 511 - 1,518
New Sanitech Sorbents	\$ 550	\$ 400 - 700

The cost effectiveness figures listed above are in 1982 dollars per ton of SO₂ removed. The lower range values generally represent easy retrofit conditions with low sulfur coal; the higher values, difficult retrofit conditions with high sulfur coal. The various technologies have different removal efficiencies, each representative of the particular technology. For example, the furnace sorbent injection costs represent only 50% sulfur removal.

The estimated \$400-\$700 figures for the new Sanitech process look extremely promising when compared with competing technologies.

SANITECH, INC.WASTE, BY-PRODUCT AND OTHER CONSIDERATIONSEffluents, Wastes, and By-Products

A process based on the new sorbent is expected to have no wastes of major concern. In this respect, it should rank high in environmental attractiveness. Few, if any, competing acid-rain control processes compare as favorably with respect to the environment as does the new sorbent technology.

In respect to effluents, the new technology may be analyzed according to the three major sub-processes involved: (1) Sorbent preparation or production; (2) Sorption of SO_2 and NO_x ; and (3) Regeneration of spent sorbents.

Sorbent Preparation

No more than two effluent streams can be expected in a sorbent-production process. The first is a gaseous exhaust stream emanating from the dryer-conditioner. In drying-conditioning, it is envisioned that a small natural-gas burner will dry and heat damp, newly-produced sorbent granules. The small amount of fine magnesia entrained in this stream will be recycled back to a magnesia storage area after being collected in a particulate device, leaving the exhaust stream a clean, steam-like emission.

The second effluent stream, the fines fraction that is screened from the final product before shipment, is really a by-product stream. This material, expected to be equivalent to from one to two percent of production, either can be recycled back to sorbent mixing for re-agglomeration into fresh sorbent, or can be mixed in with waste sorbent for by-product use.

 SO_2 / NO_x Sorption

The sorption step yields no significant effluent streams. The small amount of water that may be sprayed into the flue gas for cooling and humidification is either incorporated into the sorbent or is emitted as moisture from the stack.

Regeneration of Spent Sorbent

Effluent streams from the regeneration circuit are expected to include a regenerator heating stream, a regenerant gas stream, elemental sulfur, and captured sorbent waste and particulates.

In a commercial process, regenerators of several designs may be used. In most cases, a natural-gas burner will provide heat for regeneration, and its combustion products will flow to the main duct and be expelled through the stack. The regenerator itself will produce an effluent stream that will contain gaseous sulfur. Sulfur, liberated during regeneration, will be transformed into a liquid, and later to a marketable by-product solid in a condenser circuit. The remainder of this stream will be processed through a modified Claus unit, converting the remaining SO_2 and H_2S to additional elemental sulfur.

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It is expected that a certain percentage of the sorbent, 5 to 12 percent, will be removed from the system during each cycle. This material, removed as the smallest particles and fines, is expected to have commercial value, although much work remains to be done to evaluate the performance of this material in by-product commercial applications. A small amount of fly ash and attrited sorbent is expected to be collected from the pneumatic sorbent-transport system, moving material between the sorber and the regenerator. This material will be combined and disposed of with the regular boiler fly ash.

Impact on the Environment, Health, and Socio-Economics

The new technology is expected to have a major positive impact in the areas of the environment, health, and socio-economics. More specifically,

- ° In the area of Air Quality and Emissions, the technology should be outstanding because it removes SO_2 , NO_x , and fine particulates from flue gases. The amount of dust (MgO and broken sorbent) that may enter the atmosphere from handling the sorbents is expected to be very small, particularly in comparison to the amounts of fine particulates that are removed from the flue gas streams.

- ° In the area of Water Quality and Effluents, the technology should be excellent, because the sorption process is essentially a dry one. No water streams that require disposal are involved.

- ° In the area of Solid Waste Disposal, there will be no solid wastes that must be disposed of, if planned agricultural and other demonstrations are successful.

- ° In the area of Water Resource Requirements, only small amounts of process water will be required. These amounts can normally be supplied by the existing sites.

- ° In the areas of Health, Safety and Socio-economics, the new technology should have a very positive impact. Reductions of SO_2 , NO_x and particulates in the air should benefit everyone, directly or indirectly. Plant and animal life, and even building structures, automobiles, etc., should benefit. The sorbents are non-toxic. Outside of natural gas, no potentially dangerous gases, liquid, or solids are involved in the new technology. No potentially explosive conditions are involved. Standard safety procedures can be followed. Major cost savings are expected with the new technology. Hopefully, these cost savings will be passed along to the general population, in the form of lower utility rates, lower prices, etc. The technology should be particularly attractive to Ohio, because it will make the processing of high-sulfur Ohio coal possible, which, in turn, will help the Ohio Coal Industry and add employment in Ohio.

CONCLUSIONS AND RECOMMENDATIONS

On the basis of the project results, the following conclusions have been made:

1. Preparation of the new MgO-vermiculite sorbent in large quantities can be readily accomplished. Standard, commercially-available equipment can be used.
2. Belt conveying and pneumatic conveying are two methods that can be employed satisfactorily to transport the new sorbent from place to place in a sorption-regression process. Vibratory conveyors perform well only in static gas environments. Screw conveyors are not appropriate for moving the new sorbent because they crush and attrite the sorbent. Moving fresh or spent sorbent through a 2-in pipe pneumatically at high speeds results in only a small amount of fines being generated.
3. Sorption approaches that demonstrated high SO₂ and NO_x removals and high sorbent utilizations while processing flue gas continuously were: (1) use of a vertically moving sorbent bed where the bed moves in the same direction as flue-gas flow, (2) use of a vertically moving panel bed of sorbent where the bed moves in a direction perpendicular to flue-gas flow, and (3) use of two fixed beds where the flue gas stream is cycled from one bed to the other. Relatively poor SO₂ and NO_x removals (less than 50 percent) and low sorbent utilizations were obtained when the sorbent was entrained in the flue gas stream and collected in a filter downstream.
4. Of the sorption approaches examined, the panel-bed approach gave the best results. SO₂ removals approaching 100 percent were often seen and sorbent utilizations well over 200 percent were achieved. Higher than 100-percent sorbent utilizations appear to be the result of two mechanisms, reaction of MgO with SO₂ and moisture, and capillary micropore condensation. NO_x removals with the sorbent in panel beds varied from 10 to 90 percent.
5. With 45 wt% MgO-55 wt% Vermiculite in panel-beds, sorption performance increased with increased bed thickness, with increased moisture level in the flue gas, and, to a lesser extent, with decreased temperature, within the range 150° to 290°F. The moisture level of the flue gas is critical in achieving optimum sorbent performance.
6. The levels of SO₂ and NO_x in the flue gas do not appear to significantly affect sorption performance.
7. For a static bed of sorbent, SO₂-sorption performance generally decreases with exposure time, while NO_x-sorption performance often increases.
8. In panel-bed runs, 45 wt% MgO-55 wt% Vermiculite displayed better sorption performance than 45 wt% MgO-55 wt% Perlite, 45 wt% CaO-55 wt% Vermiculite, and 45 wt% CaO-55 wt% Perlite. Sorbent utilizations of over 100 percent were observed for all four materials.
9. For saturated 45 wt% MgO-55 wt% Vermiculite, good regeneration and the destruction of NO_x will occur if regeneration is carried out at 750°C or

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higher in a nitrogen-methane atmosphere having a minimum of 30 percent methane.

10. The 45 wt% MgO-55 wt% Vermiculite sorbent will continue to remove SO₂ and NO_x satisfactorily from a flue gas after 18 sorption-regeneration cycles when a nitrogen-methane atmosphere is employed in regeneration. The sorbent, however, appears to lose weight during recycling and to lose strength after the 12th cycle.
11. No more than six regenerations are required to make the use of the new sorbent very attractive economically. Obtaining more than six regenerations improves the process economics, but only marginally.
12. A process employing the new sorbent is expected to have no waste streams and to produce two by-products, elemental sulfur and by-product waste sorbent. The latter is expected to be useful in agricultural, construction, and/or insulation applications.

These conclusions lead Sanitech to make the following recommendations:

1. A maximum effort should be put forth to fully develop the new technology because of its promising nature. It is recommended that funds be made available to scale-up and to demonstrate the new process first at a 1 MWe level and then at a 5 to 10 MWe level.
2. It is further recommended that additional research be performed in areas that can have a major impact on the performance and economics of the new technology. Specific studies should be performed addressing (1) the use of fluidized bed systems for SO₂/NO_x sorption and for regeneration of the new sorbents, (2) the possible use of sorbents removed from the process in agricultural, construction, and thermal applications, and (3) raw materials studies to identify the best and cheapest starting materials for the new sorbents.

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MARKETING/COMMERCIALIZATION DISCUSSIONS

ADVANTAGES OF THE NEW TECHNOLOGY

The new concept combines the best ingredients of several competing technologies: the high sulfur-removal ability of wet scrubbing; the retrofitability of dry sorbent injection; the ability to reduce NO_x of SCR processes; and the environmental acceptability and by-product credits of regenerable processes. Most importantly, however, the new concept offers the potential for very low costs for each ton of SO₂ and NO_x removed.

In particular, the new sorbent technology is expected to provide the following advantages to utilities and their ratepayers:

1. High sulfur removal efficiencies and sorbent utilizations;
2. Ease in retrofitting existing facilities;
3. Ability to remove NO_x and small particulates, in addition to SO₂;
4. Environmental attractiveness;
5. Low capital and operating costs.

High Sulfur Removal and High Sorbent Utilization

The new sorbents are capable of extremely high-sulfur removal efficiencies, much higher than with other inexpensive dry FGD processes. In the laboratory, removals of 99 percent SO₂ are achieved with good sorbent utilization. In the field, with flow rates above 200 acfm, removal efficiencies of 90+ percent are routinely achieved with excellent utilization.

With use of the new sorbents, sulfur removal is achieved by two different mechanisms. According to Kent State University researchers, who are working with Sanitech, the two mechanisms involved are chemical absorption with the MgO and physical adsorption through capillary pore condensation. The latter mechanism is the process by which SO₂ is removed by activated carbon in the Activated Coke Process under development in Germany. Owing to multiple mechanisms operating, utilizations exceeding 100 percent are possible and were, in fact, realized in the pilot-plant trials in the project.

As with all sorbent processes, a trade-off exists between sulfur-removal efficiency and sorbent utilization. Consequently, when a lower sulfur-removal efficiency is permitted, the sorbents can be operated with greater utilization, and thus, decreased cost. Sanitech anticipates that most retrofit applications involving the new sorbent will operate at about 80 to 90 percent sulfur-removal efficiency and with about 80 percent average sorbent utilization per cycle.

Ease of Retrofit

Unlike with most current technologies, applications of the new sorbent should be easily retrofitted at existing power plants, by far the largest potential market.

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A process utilizing the new sorbents should have low plant-space requirements. The sorbents can be installed directly before the stack, so little or no power plant reconstruction should be needed. Massive water or sorbent recirculation systems are not required, nor are flue gas reheaters. (Wet scrubbers, the dominant existing technology, usually require over 60 gallons of water to be recirculated for each thousand cubic feet of gas processed.)

Spray dryers and wet scrubbers require extremely large, complex, and expensive systems. Also, wet scrubbing systems generally require huge areas for waste disposal, which are often simply not available. Fluidized-bed combustion and gasification/combined-cycle technologies, on the other hand, apply only to new constructions or very major reconstructions. Switching to a significantly lower-sulfur coal, for which a plant was not designed, usually requires major boiler reconstruction and derating the power plant. Dry sorbent injection schemes require expensive additional particulate-collection systems.

Additional NOx and Particulates Control

Nitrogen oxides are very difficult to remove cheaply from flue gas streams. The new sorbents have been shown to remove most of the NO₂ (nitrogen dioxide) and up to 90 percent of the NO (nitric oxide) species. In pilot tests, NOx removal appears to increase with exposure time. Apparently the presence of sulfur in the sorbent bed acts as a catalyst to improve NOx removal efficiency. Also, it has been observed that NOx removal efficiency improves with the number of regenerations performed.

Beds of the new sorbent have been found to capture effectively small particulates not picked up by particulate-control systems. Much of these collected dust particles can be removed from sorbent granules by mechanical means, such as cyclones.

Environmental Acceptability

In reality, most air pollution control technologies simply turn air pollution problems into water or solid-waste pollution problems. The sulfite-sulfate sludges and wastes of scrubbers, for example, can fill entire valleys. The disposal of large volumes of fine, leachable waste products from dry processes can also create problems. There are at least two reasons why this is not the case with the new sorbents.

First, the sorbents are used essentially dry, requiring less water than spray dryers. The small amount of water that is used humidifies the flue gas, lowers its temperature and provides the desired SO₂ reaction chemistry. Humidification is kept below gas saturation levels and no wastewater streams are envisioned.

Second, the sorbents are regenerable. There are no waste products, only saleable by-products: sulfur products and spent sorbent, both of which have profitable uses.

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Low Capital and Operating Costs

While high capture efficiency, ease of retrofit, the ability to remove NOx, and environmental attractiveness are major competitive advantages, the new sorbent's greatest comparative strength is its low cost.

Compared with other alternatives, usage of the new sorbent is expected to require significantly less capital equipment. The sorbents can be utilized as a simple panel-bed filter, for example. Also, most regeneration and auxiliary equipment is available off-the-shelf. Low capital costs are important because a large fraction of current utility capacity is found at older plants where large new investments such as those associated with scrubbers cannot be amortized over many years of remaining life.

Low operating costs are also very important. Use of the new sorbents is expected to be outstanding in this respect because:

- the sorbent raw materials are inexpensive and readily available,
- the sorbents are regenerable,
- credits are received for by-product sales,
- the nearly-dry process means low scaling and maintenance,
- the granular sorbents mean low pressure drops and easy handling,
- expensive slurry pumping and gas reheat are not required, and
- disposal costs are nil.

Advantages to Ohio

If Federal legislation were passed today requiring utilities and others that burn Ohio coals meet rigid SO₂ standards, they would have two alternatives, (1) install currently available SO₂-control technology or (2) import low-sulfur coal from outside Ohio. Because the best available SO₂-control technology today is wet lime or limestone scrubbing and because the utilities are well aware of the monstrous problems associated with wet scrubbers, the most likely alternative that will be selected would be the importation of low-sulfur coals. Substitution of out-of-state coals for Ohio coals will hurt Ohio. Obviously it will mean fewer jobs for Ohioans.

Because the new SO₂-control technology promises to have few of the problems that wet scrubbing has and because it will be significantly cheaper, it is highly likely that utilities and others would opt to use the new technology. Use of the new technology then will mean saving all those jobs that would otherwise be lost. Further, because the new technology should be applicable to plants everywhere and because the sulfur level in coal is not a major factor in applicability, one could expect a significant increase in Ohio coal use, perhaps two or three times today's rate of production (to 64 million tons per year or more).

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Economics of the New Technology

Compared with other sorbents, particularly dry sorbents, on a \$-per-ton of SO₂ or NO_x-removed basis, the usage costs with the new sorbent should be low. This is primarily because:

- the sorbent raw materials are readily available in large quantities, usable in low-cost, industrial grades;
- the oxide loading on the sorbent supports is very high, as is their oxide utilizations, so the sorber can be small and very little material needs to be regenerated and moved around;
- the sorbents are regenerable -- their initial cost is divided among numerous cycles, by-products credits are received for sulfur and spent sorbent products, and there are no significant waste streams to process, transport, and dispose of; and
- as an add-on system directly before the stack, very little power plant reconstruction is required in retrofit situations.

Potential cost advantages can be found in sorbent production, sorption, regeneration, by-product production, and NO_x removal. A calculation of average sorbent cost-per-ton of SO₂ removed is given in Exhibit 27.

The Economics of Sorbent Production

The major cost components in the production of sorbents are the raw materials themselves. The two main sorbent ingredients in MgO-vermiculite sorbents are caustic magnesia, which is the reactive oxide, and exfoliated vermiculite, which acts as a high-surface-area catalytic support for the magnesium species. (Also, in the future, Sanitech is planning to experiment with different chemical additives to see if any provide marginal benefits that outweigh their marginal costs.)

(1) Magnesia

Magnesia is the oxide of magnesium, one of the earth's most abundant metals. Commercially it comes in two varieties, deadburned magnesia and caustic magnesia. Deadburned magnesia, which is used in refractory applications, is prepared at very high temperatures. Caustic magnesia, the type used in the new sorbents, is calcined at low temperatures, so that it does not lose its high chemical reactivity. Today, caustic magnesia is used in a wide range of applications, ranging from hydroxide production to cattle mineral licks.

Magnesium oxide is an excellent choice for an acid-gas sorbing oxide because it is available and abundant; because it readily converts to a highly reactive hydroxide; because it is thermally regenerable at moderate temperatures; and because it has a low molecular weight, providing more sorption per given weight.

Magnesia is commercially available from three different sources: seawater, inland brines, and magnesite ore. Magnesia derived from seawater, generally

SANITECH, INC.**EXHIBIT 27.****Sorbent Cost Calculation****NELSORBENT**

Cost Element	Mat'l \$/T	Freight	Total \$/T	Wt.%	Wt.\$
Caustic Magnesia (90%)	\$200	\$ 40	\$240	0.45	\$108
Vermiculite Ore (Medium)	\$120	\$ 25	\$145	0.55	\$ 80
Processing Cost					\$ 40
Cost of Goods Sold / T Sorbent				1.00	\$228
Royalty / T Sorbent					\$ 20
Total Cost / T Sorbent					\$248

SO₂ REMOVAL

MgO Purity	90%
Tons of SO ₂ Removed per Ton of Sorbent (@ 100% Utiliz.)	0.64
Regeneration Cost (\$/Ton Original Sorbent)	\$ 20
Net Processing Charge of Regeneration S-Gas (\$/Ton Sulfur)	\$ 20
Spent Sorbent By-Product Credit (\$/Ton Sorbent)	\$ 20
SO ₂ Removal Efficiency (@ Average Utilization)	85-95%

AVERAGE SORBENT COST PER TON OF SO₂ REMOVED

Number of Cycles	Cycle SO ₂ Utiliz.	Average SO ₂ Utiliz.	T SO ₂ per T Sorb.	Sorbent Cost \$/T SO ₂	Regen. Cost \$/T SO ₂	Net S-Gas Proc. Cost \$/T SO ₂	Avg. Total Var. Costs \$/T SO ₂
1	75%	75%	0.48	\$472	\$ 41	\$ 10	\$524
2	75%	75%	0.48	\$236	\$ 41	\$ 10	\$288
3	70%	73%	0.47	\$161	\$ 42	\$ 10	\$213
4	70%	73%	0.47	\$122	\$ 43	\$ 10	\$175
5	65%	71%	0.46	\$100	\$ 44	\$ 10	\$154
6	65%	70%	0.45	\$ 84	\$ 44	\$ 10	\$139
7	60%	69%	0.44	\$ 74	\$ 45	\$ 10	\$129
8	60%	68%	0.43	\$ 66	\$ 46	\$ 10	\$122
9	50%	66%	0.42	\$ 60	\$ 47	\$ 10	\$117
10	50%	64%	0.41	\$ 55	\$ 49	\$ 10	\$114

NO_x REMOVAL

NO _x Removal Efficiency (@ Average Utilization)	30-50%
Total Avg. Sorbent-Related Variable Costs Per Ton NO _x Removed	\$ 0
(i.e. all costs are attributed to SO ₂ removal. NO _x reduction is free.)	

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the highest grade product at 97 to 99+% MgO, is probably too expensive for a large-scale sorbent installation. However, brine magnesia, generally at 93-97% MgO, and magnesite-derived magnesia, at roughly 90-93% MgO, are both economically suitable for sorbent production. Although brine magnesia is originally more expensive than magnesite-derived magnesia, it is, because of its higher purity, less expensive to regenerate on a \$-per-ton-of-SO₂-removed basis. After a number of regeneration cycles, net SO₂-removal costs can be nearly the same. Sanitech has used both brine magnesia and magnesite magnesia and both have worked well. Magnesite rock (magnesium carbonate) is mined inexpensively from surface deposits. Ground and calcined, this material is the feedstock assumed in the sorbent cost calculation example. A volume purchase price of \$200 per ton is assumed, with approximately \$40/T in shipping costs. Each ton of sorbent is made with 45% MgO by weight, so the caustic magnesia costs contribute about \$108 toward the net cost of each ton of sorbent.

(2) Vermiculite

Vermiculite, the other important ingredient, is another industrial mineral, with deposits widely scattered. Vermiculite is a micaceous alteration mineral, a magnesium-aluminum-silicate with molecular water layers imbedded within its plated, crystalline structure. With low-temperature heating, these waters turn to steam and explode the vermiculite ore into accordion-like exfoliates. The granular, exfoliated vermiculite is very light, has a very high external surface area, and possesses some cation-exchange properties.

Vermiculite ore is available both domestically and from foreign sources, and it comes in a variety of sizes and grades. The exfoliates range in size from very fine to granules of about half an inch in diameter. In all its preparation work with the new sorbents, Sanitech has traditionally used medium-grade vermiculite, which is the most widely available, and this is the type assumed in the cost example.

Currently vermiculite ores are shipped in bulk to exfoliators who expand it and then sell it regionally for a variety of applications, including thermal insulation, fireproofing and soundproofing wallboard, lightweight cements, and packing materials. Owing to its high void-space volume and sponge-like ability to soak up and hold water, it finds extensive use in horticulture as a soil aerator and conditioner. (Note: perlite, another readily-available industrial mineral can also be used in the new sorbents. High-surface-area, popped perlite is cheaper than vermiculite, but its oxide loadings, SO₂-removal rates, and utilizations do not match those of vermiculite.

The sorbent cost calculation in Exhibit 27 assumes a volume delivered-cost for medium-grade imported vermiculite ore of \$145 per ton. Because 55% of the new sorbents is vermiculite, 55% of \$145, or \$80, is attributed to the cost of a ton of the new sorbent.

(3) Processing

Sorbent processing is simple and straightforward. The vermiculite ore is exfoliated, wetted, and mixed with the powdered magnesia. The resulting damp granules are then dried, heat-conditioned, sized, and conveyed to a bin. The

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assumed cost of these operations is \$40 per ton of sorbent, with most of the cost attributed to the thermal drying step, which converts $\text{Mg}(\text{OH})_2$ back to MgO and converts the excess water to steam.

The thermal-conditioning step, which is critical, creates a tremendous MgO micro-surface area. Kent State University researchers have measured approximately $150 \text{ m}^2/\text{gm}$ of MgO , with almost 10% of the magnesium atoms actually on the surface.

The Economics of Sorption

The high sorption capacity of the new sorbents per unit volume results in attractive economics. Owing to this ability, sorbent beds can be relatively small and can be operated slowly.

The keys to the high sorption capacity of the new sorbents are the high loading of reactive oxide permitted on the vermiculite supports and the high net chemical utilization achievable. Fully 32% of the weight of the new sorbents is potentially-reactive magnesium. (This compares, for example, with approximately 2% copper in copper oxide sorbents, or 4% sodium in NOXSO sorbents.) Further, this magnesium is capable of a high 65% net design utilization per cycle. (Note that this is really a pseudo-utilization based on an assumed one-to-one $\text{Mg}:\text{SO}_2$ stoichiometry. A significant portion of the SO_2 sorption is believed to be the result of capillary pore condensation, totally apart from chemical absorption.) The high loading, combined with the high net utilization, results in very high sorption efficiency relative to sorbent volume and weight. Further, with the new sorbent, reaction kinetics appear to be fast enough so that flue gas space velocity (i.e. the inverse of the bed residence time) is not a limitation on panel-bed design.

Importantly, the void space in beds of the new sorbent is large. This results in relatively low pressure drops through the material. A relatively high linear face velocity of 4 ft/sec may be used with the new sorbent.

By-Product Economics

On regenerating the new sorbent, two valuable by-product streams are produced: a spent sorbent by-product stream and a sulfur stream.

After approximately ten sorption/regeneration cycles, the average unit of sorbent is expected to be drawn off as spent sorbent. The vermiculite and magnesia in this somewhat degraded product, however, still have value. While \$150/ton virgin exfoliated vermiculite is too expensive for many applications, whole new agricultural and construction markets could open up for a similar \$20/ton material. A \$20/ton net spent sorbent value is therefore assumed in the cost calculations, and this value is subtracted from the new sorbent cost.

The cost calculation example does not include a cost for processing the concentrated regeneration off-gas, which consists primarily of gaseous sulfur, concentrated SO_2 , H_2S , H_2O , CO_2 , and N_2 . The cost of processing this stream will vary with the sulfur by-product desired (e.g. elemental sulfur, sulfuric

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acid, ammonium sulfate), the technology employed to process the stream, the utility coal burnt, and the plant size. (Elemental sulfur production by a modified Claus process is expected to be preferred at large utility plants. Six percent of the sulfur values are assumed to be left in a tail gas that is incinerated (i.e. reoxidized) and recycled to the sorber.)

The cost calculation example assumes that the credits received for the sulfur by-product roughly cover the regeneration-gas processing expenses. In the calculation, an additional charge of \$20/ton of sulfur, above and beyond all credits, is levied on the sorbent costs for this processing (or \$10/ton of SO_2), as a margin of safety.

Adding the three cost components together, the sorbent cost, the regeneration cost, and the net sulfur-gas processing charge, yields the average sorbent-related cost for each number of regeneration cycles. This cost can be seen to level off quickly to about \$100 to \$150 per ton SO_2 at between five and ten regenerations. This value compares very favorably with similar costs of other, once-through, dry sorbents.

The Economics of Regeneration

Because the new sorbents are regenerable, their raw material costs and production costs get divided among many sorption cycles. Also, because the sorbent has a high MgO loading and exhibits high utilizations, less total regeneration energy is necessary for heating, in comparison with other regenerable sorbents under development.

To determine the average sorbent-related costs on a per-ton-of- SO_2 -removed basis, the number of regenerations, sorbent production costs, regeneration costs, and regeneration-gas processing costs must be considered. It was found in the project that SO_2 -removal efficiency does not markedly decrease with reuse if the regeneration of the new sorbent is accomplished in a reducing environment. And NO_x performance actually tends to increase somewhat. The cost calculation example shown in Exhibit 27 assumes a net utilization of 75 percent the first time the new sorbent becomes saturated, decreasing to 50 percent after nine regenerations. (Sanitech bases all utilization numbers on SO_2 sorption alone, ignoring NO_x .)

With some knowledge of how the sorbent's performance varies, it is possible to calculate the average costs for different ultimate levels of sorbent reuse. By averaging the utilizations of the individual cycles, the number of tons of SO_2 that would be sorbed by a ton of the new sorbent can be calculated for each number of cycles. The inverse of this figure represents the number of tons of sorbent required to remove one ton of SO_2 . When this number is multiplied by the net new sorbent cost-per-ton of SO_2 , or by the regeneration cost-per-ton, and the results, in turn, are divided by the number of cycles the sorbent is used, one obtains the sorbent cost and the regeneration cost, per ton of SO_2 removes, respectively. The net new-sorbent cost is the \$248/ton price found in the cost example minus a \$20/ton spent sorbent by-product credit. A conservative regeneration cost-per-ton of unsaturated sorbent of \$20 per cycle is assumed.)

SANITECH, INC.NOx Removal Economics

The cost calculations shown in Exhibit 27 attribute sorbent costs wholly to SO₂ removal, yet the new sorbents simultaneously remove considerable quantities of NOx. No additional capital equipment or operating costs (e.g. ammonia consumption) are necessary. The costs of competitive processes capable of 40% NOx reductions are very high, perhaps \$1000 or more on a per-ton-of-NOx-removed basis. The new technology should provide NOx reductions at essentially zero cost.

Similarly, no additional particulate-control capacity or upgrades should be necessary with an installation of the new process, as often occurs with other easily-retrofitted technologies. In fact, net particulate reductions are expected.

The bottom line is an attractive process with a potentially promising total cost for SO₂, NOx, and particulate control.

SANITECH, INC.POTENTIAL MARKETSMost Attractive Market: Utility Plant Retrofits

The major market for the new technology appears to be in the area of retrofitting existing utility plants that burn coal. This market alone is expected to amount to perhaps 10 million tons per year of SO₂ reduction, equivalent to billions of dollars in sales. There does not appear to be any technical or business-related basis for any limits to market penetration that might be achievable with the new technology. The rate of commercialization will be limited primarily by the costs of the technology, by the performance of plants that are installed, and by the abilities of Sanitech and others to market and supply facilities.

Other Utility Markets

New Coal-Fired Power Plant Construction - While the largest potential market for acid-rain control technologies is the 90% of existing U.S. power plants currently without SO₂ controls, new electrical production facilities constitute another considerable market. With the tremendous costs and uncertainties associated with nuclear power, the vast majority of new and replacement electrical generating capacity to be built over the next few decades will be coal-powered. Existing New Source Performance Standards require that 70% or 90% of the SO₂ produced at these plants be removed.

Although net electrical power consumption in the U.S. is expected to rise by only 2 percent per year, the construction of new coal-fired utility capacity is expected to continue at a moderate pace. According to the annual Power Magazine survey, utilities are planning or have committed coal-fired capacity additions of approximately 25,000 MW for the 1990-2000 period. This is equivalent to about 4 million tons of new SO₂ production per year, meaning approximately 3 million additional tons of annual SO₂ removal will be required.

Oil-Fired Utility Boilers - Oil-fired utility boilers also emit SO₂. High-sulfur oil, the type generally used in electricity production, has a sulfur content per BTU approximating medium-sulfur coal. And medium-sulfur oil is roughly equivalent to low-sulfur coal. Oil-fired plants, therefore, need SO₂ controls too.

Approximately 9 percent of installed U.S. utility generating capacity and 3 percent of actual electricity production is oil-based. Because oil-fired generating capacity often sits idle, high-capital cost pollution controls are particularly unsuitable for these facilities. Sanitech's process should be at a competitive advantage in this application. Also, because oil-fired boilers are less likely to already have significant particulate controls, and these controls are frequently a prerequisite for other dry sorbent technologies, this market may be especially ripe for the new technology.

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Institutional, Industrial, and Commercial Markets

While Sanitech intends to concentrate its efforts, ultimately, on utility retrofit applications, smaller institutional, industrial, and commercial-scale markets will probably be the first to utilize the new technology. Non-utility installations will prove important in demonstrating and scaling up the process and in providing early cash flow to finance growth.

In December of 1987, the U.S. EPA promulgated New Source Performance Standards for industrial boilers with heat input capacities of greater than 250 MM Btu/hr. Although these steam boilers are generally smaller than utility systems, the regulations were equally as strict, requiring 90 percent SO₂ removal and particulate controls for these boilers. In the future, the EPA intends to bring even smaller combustors into the regulatory fold. These recent regulations, as well as any future requirements, potentially create many niche markets for the new sorbent technology.

Current U.S. Industrial Steam Boiler Population

<u>Boiler Size (MM Btu/hr)</u>	<u>Number</u>
> 250	1500
100-250	4500
50-100	7000
10- 50	150,000*

*Mostly oil- or gas-fired.

For smaller institutional, industrial, and commercial boiler operators, ease of use considerations generally outweigh cost-per-unit-of-SO₂-removed concerns. The smaller non-utility boiler owners could use non-regenerable forms of the new sorbent or could have the sorbents regenerated at central facilities. Initial cost calculations suggest that a central Sanitech regeneration facility supporting a number of smaller boilers is eminently feasible. The granular sorbents, either saturated or regenerated, are easily and cheaply transported. Larger, non-utility boilers, which are essentially equivalent to small utility boilers, would justify their own regeneration system.

Cogeneration Plants - The Public Utility Regulation Policy Act (PURPA) created incentives for the establishment of small, non-utility cogenerated facilities. These facilities produce both process steam for private use and significant amounts of excess electricity that is sold to utilities. Many of these small facilities are now in the planning stages and many will burn coal wastes or other fuels that require acid gas treatment. This will be a targeted market.

Other Industrial Acid Gas Cleaning Markets - Sanitech's technology, which operates over a relatively wide range of dilute SO₂ concentrations, can find application anywhere that large gas volumes are contaminated with SO₂. Smelters, for example, are major producers of gaseous SO₂. Smelter flue gas control, therefore, is a potential market. There are many niche markets in industrial flue gas cleaning, each characterized by the industrial process's own waste gas composition and each with its own best processing scheme.

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Municipal Solid Waste Incinerators - While the largest markets are in SO₂ control, Sanitech has shown that their technology works on other acid gases as well. Hydrogen chloride (HCl), for example, is a problem in the waste gases of incineration systems that include plastics among their charges. Dilute hydrogen chloride can be almost totally removed from gas streams using the Sanitech method.

As more and more solid waste landfills across the country are being closed or filled, many communities are now turning to municipal solid waste (MSW) incinerators. The gas emissions of these MSW incinerators, with high HCl, SO₂, and HF concentrations, require acid-gas cleaning. These facilities constitute another potential high-growth market.

International Markets

Acid-gas emissions are a global problem, and, therefore, the market for acid-rain control is a global market. The total worldwide market is at minimum more than twice the size of the U.S. market.

International Acid Rain Control Market

<u>Country</u>	<u>1980 SO₂ Emissions (1000 metric tons)</u>
Canada	4650
Germany	3200
France	3560
Italy	3800
Spain	3620
U.K.	4000
Total Canada and Major European	22,800
United States	23,200

Japan and many European countries already have far stricter air pollution regulations than American legislators are currently considering. West Germany's recent comprehensive TA Luft regulations and the United Kingdom's recent acid-rain decisions are creating large European retrofit markets in the near term. A new Frost & Sullivan report, for example, predicts \$24 Billion in spending over the next decade for European acid-rain control.

The McIlvaine Company, a market research company, predicts that by the end of the 1990s, developing nations such as Brazil, Taiwan, and India will also present large air pollution control markets.

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COMPARISONS WITH OTHER TECHNOLOGIES

A flue-gas treatment process based on the new sorbents is extremely attractive when compared with the best-available-technologies today to remove SO₂ and NO_x, with new SO₂/NO_x removal technologies currently under development, and with alternate approaches of sulfur removal. It is attractive in terms of (1) environmental concerns, (2) ease and convenience of use, and (3) cost.

Environmental Concerns

For plants that burn high-sulfur coals today, wet scrubbing with a slurry of lime or limestone is probably the best available technology for SO₂ control, and selective catalytic reduction (SCR) is probably the best available technology for NO_x control. Both of these processes have serious drawbacks. Most wet scrubbing processes today produce sludge as a waste product....huge quantities of sludge that has a tendency to remain semi-liquid. Most SCR processes introduce small amounts of ammonia into the atmosphere. These processes then, in essence, substitute liquid, solid or other gaseous pollution problems for SO₂ and NO_x control problems. The new Sanitech technology, on the other hand, does none of this. It promises to solve SO₂ and NO_x control problems without producing any auxiliary waste materials.

Ease and Convenience

Application of the new Sanitech technology to a flue gas stream appears to be a simple process. The required equipment need not be large. Temperatures are low. The sorbent is processed essentially dry. The sorbent is used over and over again. All these factors point to a process that is easy to retrofit into existing plants. Wet scrubbers, owing to the large quantities of water that must be processed and to reaction kinetics, involve very large equipment. Newer SO₂/NO_x control technologies, such as NOXSO and the Copper Oxide Process, are relatively complex in their design. The new technology is neither complex in its design nor does it require large equipment.

Cost Advantages

The sorbent costs are very reasonable because the starting materials are relatively inexpensive and because preparation procedures are simple.

All materials are readily available commercially and are usable in industrial grades. The following prices are estimated, based on discussions with suppliers:

Vermiculite	\$120/T	unexpanded
Magnesia (90%)	\$200/T	less than 325 mesh.

In a typical application, raw materials would be transported to the sorbent production site, which could be a central production facility or the power plant itself. Here the vermiculite would be thermally expanded. The

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preparation of fresh sorbent consists of separate mixing and conditioning steps. An estimated cost for these steps in a commercial process is about \$40 per ton of sorbent. The cost of goods sold for a typical 45:55 MgO:Vermiculite sorbent composition would be about \$248 per ton of dry sorbent material.

Sanitech has performed an extensive analysis of sorbent costs variables. An example calculation was presented earlier in this report. In this case for a utility, the utility's net sorbent costs/T SO₂ removed was \$524 after the first use. With 10 regenerations, the average sorbent cost dropped to \$114/T SO₂ removed.

The results of the cost analyses indicate that user sorbent costs become very low when more than four regenerations are carried out. Decreasing advantage is seen in utilizing a very large number of regenerations. Net sorbent costs, including regeneration costs, should be down in the range of only \$200/T SO₂ removed with but a few regenerations.

As a basis for comparison, lime injection schemes have sorbent costs of about \$430/T SO₂ removed, and still can remove only 50 percent of the sulfur from the flue gas. Sodium-based dry-injection sorbents (e.g., trona), at \$900/T SO₂, cost even more. Also, utilizing these fine, dry injection sorbents, such as lime and trona, requires costly additional electrostatic-precipitator or baghouse capacity.

The costs of the new technology are expected to be significantly lower than the costs of other technologies that are commercially available or are presently under development. In an earlier section of this report (under "Process Economics"), a cost comparison of sulfur-removal technologies is presented. A technology involving the new sorbent with a levelized cost of \$400 to \$700/T SO₂ removed should be very attractive to industry. The removal of NO_x comes along essentially free.

SANITECH, INC.FUTURE PLANSContinuing Engineering Development

Sanitech plans to install and begin operating a 1.0 MWe pilot plant during 1990. Support for this work hopefully will come jointly from OCDO and DOE. Sanitech presently has a Phase I SBIR project with DOE. The 1.0 MWe pilot plant work would be partially funded as a Phase II project. The present DOE Phase I project is providing bridging funding between the project described herein and the 1.0 MWe project. In the present Phase I project, the system at Gorge is being increased in size from 300 ACFM to approximately 1000 ACFM. Sanitech has proposed the 1.0 MWe pilot plant project to OCDO. The project has passed the initial technical review stage. It will be evaluated further by OCDO during the coming months.

Following the 1.0 MWe pilot-plant work, Sanitech plans to install and operate a commercial industrial-sized demonstration facility at Kent State University's coal-fired steam plant (or alternately at Ohio Edison's Toronto Power plant). A proposal for support for this work has been prepared and has been submitted to OCDO and to the U.S. DOE, as part of the Clean Coal III program. Proposing with Sanitech are Kent State University, Fluor Daniel (the Engineer-Constructor that will do the majority of design, procurement, and construction on the project), and Ohio Edison. Both Kent State University (under an Edison grant) and Fluor Daniel (the second largest Engineer-Constructor in the U.S.) have been working with Sanitech on the new technology during the past year or more.

Additional data are required on NO_x absorption/adsorption and on regeneration to better characterize NO_x sorption variables and the reduction of NO_x to N₂ upon regeneration. Most work to date has been concentrated on SO₂-sorption parameters. It is also recognized that additional development work in the physical chemistry of sorbent reaction could result in an optimization of the sorbent process.

Other planned future investigations will include:

- a. Spent Sorbent Applications -- to identify applications for the small quantities of sorbent that are removed regularly from the process. Potential markets include agricultural uses, construction uses and insulation uses.
- b. Economics Investigations -- to indicate the directions that should be followed in commercialization and to develop cost data for marketing purposes.
- c. Raw Material Sources Investigations -- to find the lowest cost sources of the best-performing sorbent raw materials.
- d. New Applications Investigations -- to examine new applications for the new sorbent technology, such as municipal solid waste incinerator flue-gas treatment.

SANITECH, INC.Corporate Development Strategy

Two realities guide Sanitech's new sorbent development and commercialization strategy. First, this technology, like any large industrial process, is inherently expensive to develop and demonstrate. And second, the scale-up process inevitably takes time. Obviously, the new sorbent technology must be fully developed and demonstrated before utilities can order it for required acid-rain control.

Sanitech cannot, by itself, internally fund the entire scale-up to utility-sized demonstration and commercialization. Sanitech must leverage its efforts with governmental support, along with the participation of outside capital and probably with large industrial corporation support. Its agreement with Fluor Daniel has been a move in this direction.

Because the utilities' clocks begin running with the enactment of acid-rain controls, a demonstration of the new sorbent technology is critical in order to compete with the other candidate technologies for SO₂ removal. The successful results obtained in this project have proven the new sorbent and process's technical feasibility. A full-scale, well-funded scale-up and commercialization effort is now clearly warranted.

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FINAL BUDGET SUMMATION

The project herein described was completed at a total cost of \$229,717. The planned budget for the project was \$229,008, so the final cost was very near that which was expected. OCDO's budgeted cost and actual cost was \$149,972, which is 65.3 percent of the total final cost. A table showing the original total project budget by major category and indicating the contributions by OCDO and Sanitech, Inc. is provided in Exhibit 28. A similar table showing actual costs by line items is given in Exhibit 29.

EXHIBIT 28. Original Project Budget

	<u>Total Project</u>	<u>OCDO's Cost</u>	<u>Sanitech's Cost</u>
Personnel	\$ 95,348.00	\$ 56,160.25	\$ 39,187.75
Fringe Benefits	26,030.00	15,331.75	10,698.25
Travel	2,700.00	2,700.00	-
Equipment	34,100.00	28,900.00	5,200.00
Supplies	3,100.00	3,100.00	-
Contractual & Others	<u>9,600.00</u>	<u>9,600.00</u>	<u>-</u>
Total Direct Charges	\$170,878.00	\$115,792.00	\$ 55,086.00
Indirect Charges	<u>58,130.00</u>	<u>34,180.00</u>	<u>23,950.65</u>
Total Project Costs	\$229,008.00	\$149,972.00 (65.5%)	\$ 79,036.65 (34.5%)

EXHIBIT 29. Actual Project Costs

	<u>Total Project</u>	<u>OCDO's Expenditures</u>	<u>Sanitech's Expenditures</u>
Personnel	\$ 98,924.26	\$ 56,536.98	\$ 42,387.28
Fringe Benefits	27,005.50	15,434.59	11,570.91
Travel	1,560.80	1,560.80	-
Equipment	29,153.08	26,298.32	2,854.76
Supplies	3,392.20	3,392.20	-
Contractual & Others	<u>9,863.97</u>	<u>9,863.97</u>	<u>-</u>
Total Direct Charges	\$169,899.81	\$113,086.86	\$ 56,812.95
Indirect Charges	<u>59,817.37</u>	<u>36,885.14</u>	<u>22,932.23</u>
Total Project Costs	\$229,717.18	\$149,972.00 (65.3%)	\$ 79,745.18 (34.7%)

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