



# Summary Report

## Sulfur Oxides Control Technology Series: Flue Gas Desulfurization

### Lime/Limestone Processes



# Summary Report

## Sulfur Oxides Control Technology Series: Flue Gas Desulfurization

### Lime/Limestone Processes

April 1981

This report was developed by the  
Industrial Environmental Research Laboratory  
Research Triangle Park NC 27711





Scrubber with additive feed and reaction tank in foreground, Cane Run No. 5



## Introduction

Wet lime/limestone flue gas desulfurization (FGD) processes (Figure 1) employ a scrubbing slurry of lime or limestone to remove sulfur dioxide ( $\text{SO}_2$ ). As a side benefit, these processes also remove fly ash and chlorides.

Lime and limestone FGD processes are similar. Both are nonregenerable. Their operation is based on the ability of an aqueous slurry of slaked lime  $[\text{Ca}(\text{OH})_2]$  or wet ground limestone ( $\text{CaCO}_3$ ) to absorb  $\text{SO}_2$  from flue gas. Absorbed  $\text{SO}_2$  is removed from solution by a chemical reaction that forms a calcium sulfite and calcium sulfate  $[(1-x)\text{CaSO}_3 \cdot x\text{CaSO}_4 \cdot \frac{1}{2}\text{H}_2\text{O}]$  solid solution and insoluble calcium sulfate dihydrate (gypsum,  $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$ ). These salts precipitate in a holding tank. A continuous bleed stream removes part of the slurry from the holding tank to be concentrated and, as an optional step, stabilized. It is common practice to dispose of the

resulting solids in ponds or as landfill.

Because lime/limestone processes are nonregenerable, they may consume large quantities of feed material and produce large quantities of waste solids. These characteristics could place them at a disadvantage compared with regenerable processes. Regenerable processes, however, still require disposal of waste fly ash and chlorides by environmentally acceptable methods, and these waste products amount to as much as 50 percent of the volume of solid waste produced by lime/limestone processes.

Lime/limestone systems are usually less complex than regenerable systems, and they cost less to install and operate than other FGD processes. Consequently, lime/limestone FGD processes are the most widely used FGD systems in operation. As of June 1980,

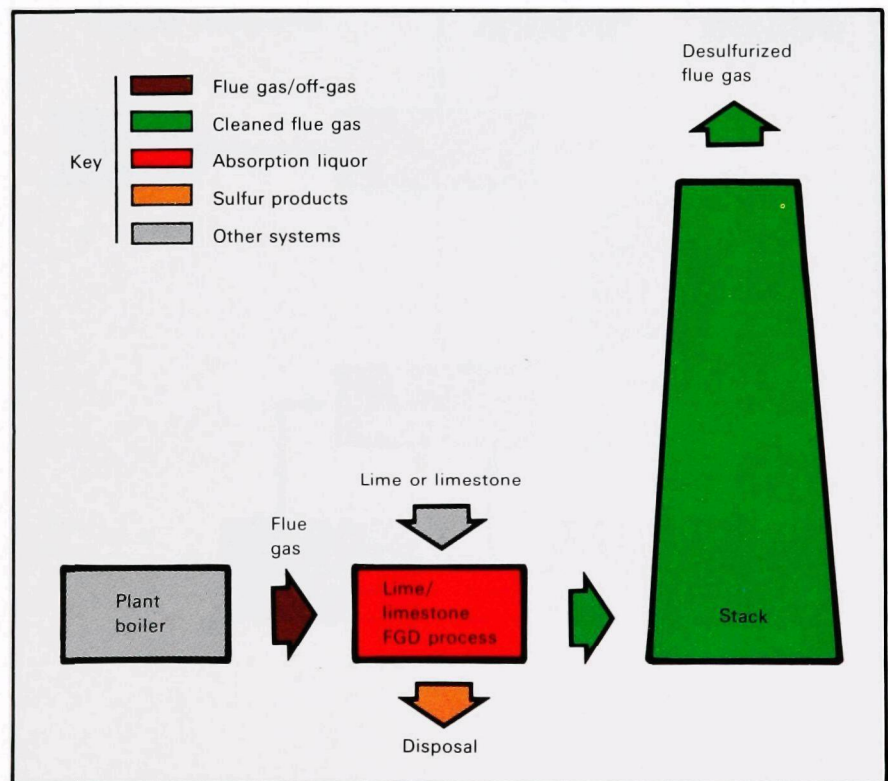


Figure 1.

Major Components of Lime/Limestone FGD Processes



---

58 lime or limestone slurry scrubbing systems were in use to remove SO<sub>2</sub> from power plant flue gas; 71 more were under construction or in the planning stage.<sup>1</sup>

This summary report is intended to provide a basic understanding of the lime/limestone FGD processes to those unfamiliar with FGD technology. More detailed information appears in the literature cited. A new manual, *Lime FGD Systems Data Book*, was sponsored jointly by the Electric Power Research

Institute and the U.S. Environmental Protection Agency (EPA).<sup>2</sup> The manual provides the design engineer with detailed guidelines and specific procedures to select a lime-based FGD system. EPA is also preparing a manual on limestone FGD, to be available in 1981.



## Process Description

Lime/limestone FGD processes consist of four steps:

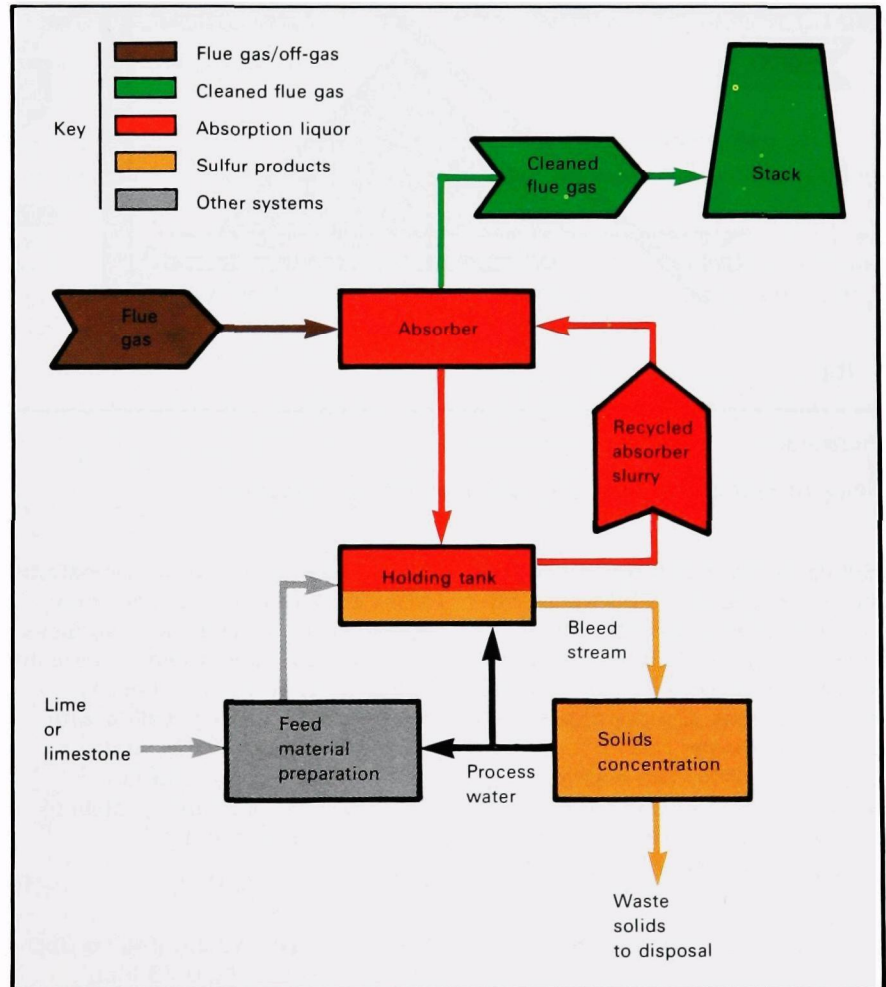
- Feed material processing
- Absorption
- Solids precipitation
- Solids concentration and disposal

Figure 2 illustrates the process flow for a typical lime/limestone installation.

Flue gas enters the absorber, where it comes in contact with the circulating scrubbing slurry containing calcium ions from dissolved lime or limestone. Sulfur dioxide, fly ash, and chlorides contained in the flue gas are removed by the circulating slurry. Alkaline species in the liquor neutralize the absorbed  $\text{SO}_2$ , promoting the formation of

ions of sulfite ( $\text{SO}_3^{2-}$ ) and sulfate ( $\text{SO}_4^{2-}$ ). Water droplets are removed from the cleaned flue gas as it leaves the absorber. The clean flue gas is reheated, if necessary, then exhausted through the stack to the atmosphere.

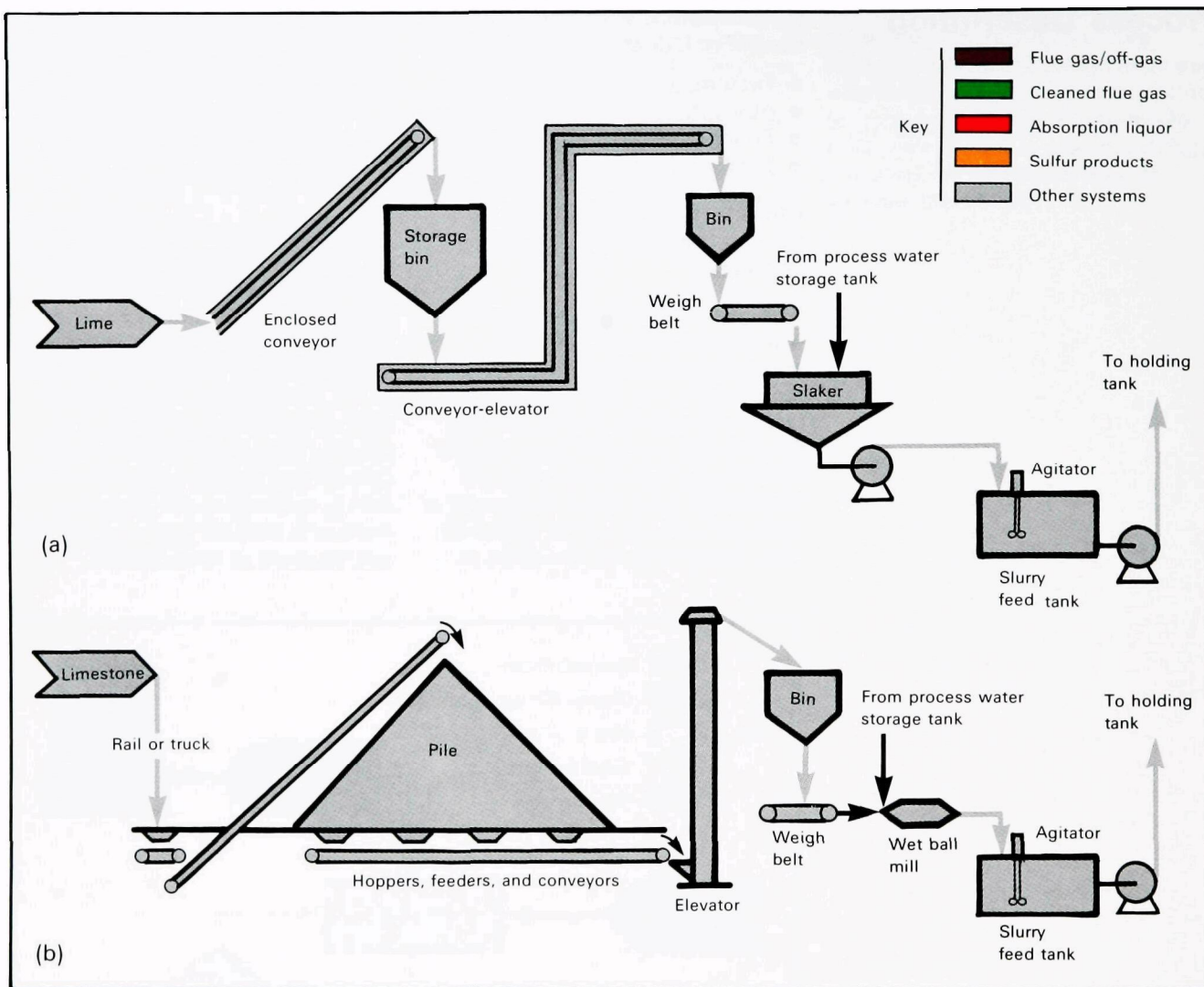
The scrubbing slurry—which may be supersaturated with calcium sulfite and sulfate solids  $[(1-x)\text{CaSO}_3 \cdot x\text{CaSO}_4 \cdot \frac{1}{2}\text{H}_2\text{O}]$  and gypsum ( $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$ )—flows to an effluent holding tank or precipitation vessel. In the holding tank fresh makeup lime or limestone is added, and reaction products are precipitated. One effluent stream from the holding tank is recycled to the absorber; another is bled off for concentration and disposal of waste solids.



**Figure 2.**

Typical Lime/Limestone FGD Process Flow





**Figure 3.**

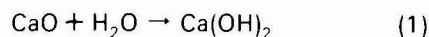
Reagent-Processing Systems: (a) Lime and (b) Limestone

Solids in the bleed stream may be concentrated in a thickener, filter, or centrifuge, or may be sent directly to a holding/settling pond. Clarified process water is returned to the process. Concentrated solids may be disposed of in ponds or used for landfill. The waste solids are sometimes stabilized, or they can be processed for commercial use in gypsum or Portland cement.

### Feed Material Processing

Feed material commonly is prepared on site for lime/limestone FGD processes. In a lime system (Figure

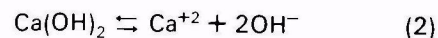
3a), pebble lime from a calcination plant is stored in bins, and then conveyed to a slaker that produces a slurry containing about 25 percent solids by weight. The slurry is diluted to 15 percent solids with recycled process water, and is pumped to a slurry feed tank.<sup>3</sup> The chemical reaction for slaking can be represented as:



In a limestone system (Figure 3b), limestone—usually 0.75 inch

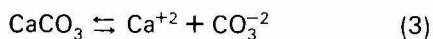
(1.9 cm) or less—is delivered by truck or rail, dumped into hoppers, and conveyed to a 30-day storage pile. The limestone is ground (usually to 70 percent minus 200 mesh) in wet ball mills, and is stored as a 60-percent (by weight) solids slurry in a slurry feed tank. Any dust resulting from limestone feed preparation must be controlled with dust collectors.<sup>3,4</sup>

Both slaked lime and limestone dissolve in the slurries to produce calcium ions. The reaction for slaked lime is:





For limestone the reaction is:



Slaked lime dissolves more readily than limestone, resulting in a higher pH for lime slurry than for limestone slurry. The typical operating pH range for a lime system is 7.0 to 8.5, compared with 5.0 to 6.5 for a limestone system.

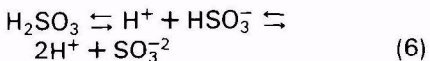
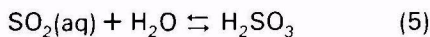
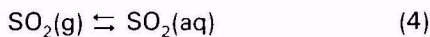
Carbide lime, an impure slaked lime byproduct of acetylene manufacturing, also has been used successfully as a feed material.

### Absorption

Absorption of  $\text{SO}_2$  takes place in a wet scrubber (Figure 4a). Flue gas enters the scrubber and, in most cases, flows countercurrent to a scrubbing slurry. As the circulating liquor makes contact with the flue gas, a pressure drop occurs across the scrubber and is overcome by the use of either induced- or forced-draft fans.

**Sulfite/Sulfate Reactions.** Sulfur dioxide is removed from flue gas by both absorption and reaction with the scrubbing slurry liquor. Reactions initiated in the scrubber are completed in an effluent holding tank. Specific details are still disputed;<sup>3,5</sup> however, the reactions in Equations 4 through 9 generalize the process.

The  $\text{SO}_2$  is absorbed in water, reacts with water to form sulfurous acid ( $\text{H}_2\text{SO}_3$ ), then dissociates to form sulfite ions ( $\text{SO}_3^{-2}$ ).

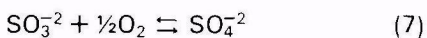


Dissolved lime or limestone (see Equations 2 and 3) and other alkaline species in the scrubbing liquor neutralize the absorbed  $\text{SO}_2$ , driving the reactions in Equations 4, 5, and 6 to completion.

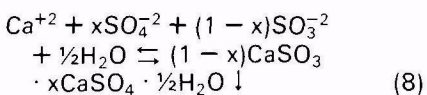


Interior of induced-draft booster fan

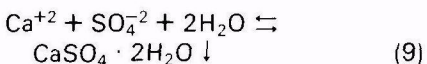
Some of the sulfite ions are oxidized in the system to sulfate ions ( $\text{SO}_4^{-2}$ ):



Some of the sulfate and most of the sulfite eventually coprecipitate with calcium as a solid solution:



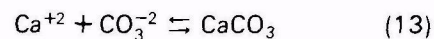
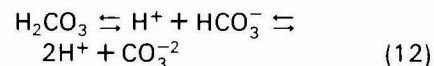
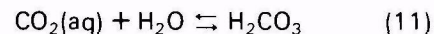
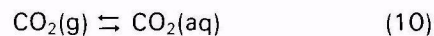
Excess sulfate eventually precipitates with calcium to form gypsum:



The mechanism of oxidation is not well understood; however, the rate is known to be a function of the ratio of  $\text{SO}_2$  and  $\text{O}_2$  concentrations in the flue gas and of scrubbing liquor pH. Levels of natural oxidation can range from near 0 to almost 40 percent for high sulfur coals. Oxidation as

high as 90 percent has been observed in systems treating dilute  $\text{SO}_2$  gas streams.<sup>6</sup> High concentrations of unprecipitated sulfate in the scrubber feed liquor increase the probability of scale formation in the scrubber.

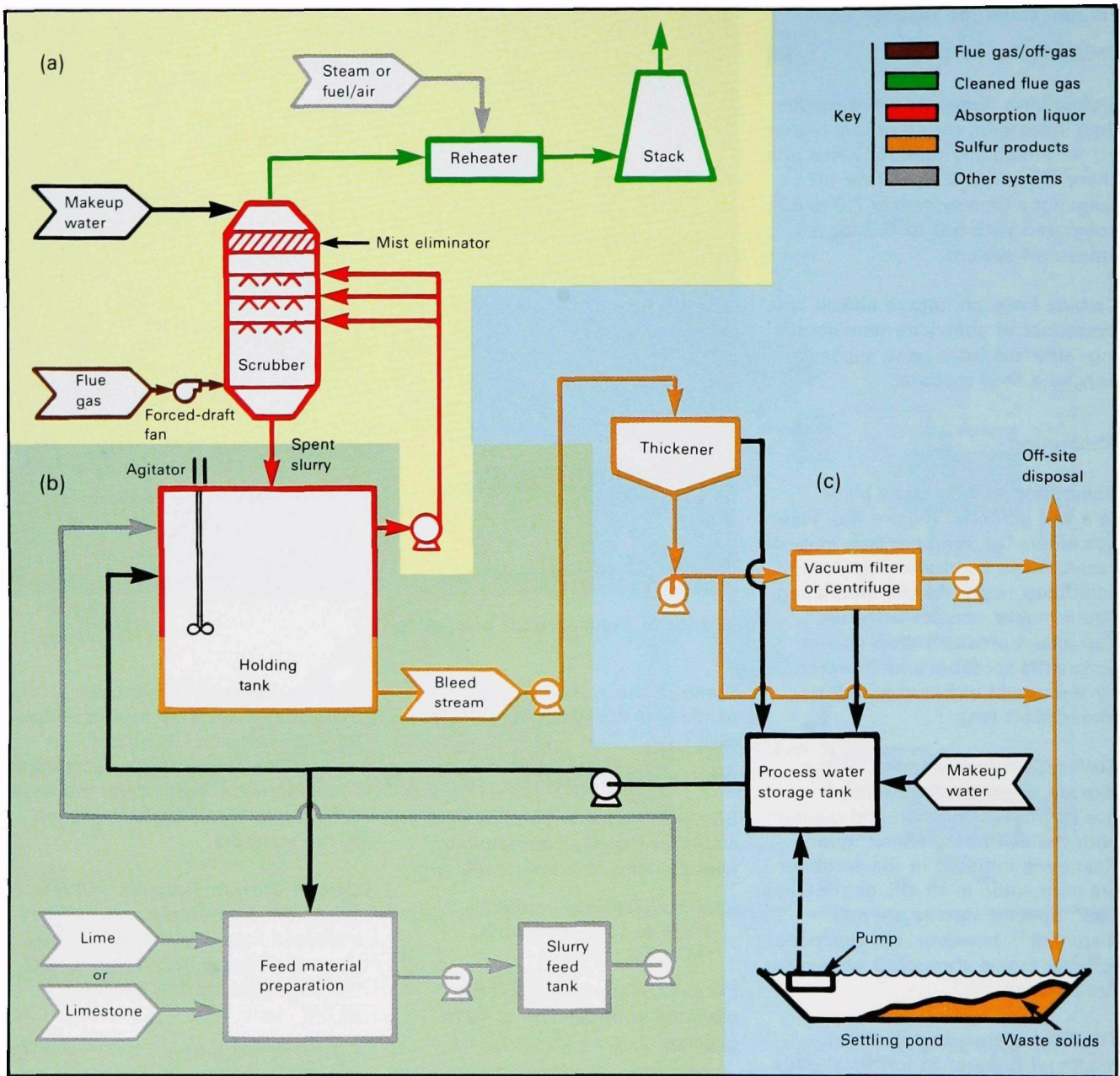
**Carbon Dioxide Transfer.** In lime scrubbers, carbon dioxide ( $\text{CO}_2$ ) absorbed from the flue gas can react with the slurry to form  $\text{CaCO}_3$ , thereby reducing the availability of  $\text{Ca}^{+2}$  ions.



Carbon dioxide absorption can be minimized by proper pH control.

In limestone scrubbers, carbon dioxide is liberated or desorbed. The reaction sequence is represented by the reverse reactions given in Equations 10 through 13.





**Figure 4.**

Lime/Limestone FGD Process: (a) Absorption, (b) Solids Precipitation, and (c) Concentration and Disposal

**Mist Elimination and Stack Gas Reheat.** All wet scrubbers require mist elimination, and most require reheat of the cleaned flue gas. As the flue gas exits the absorber, it passes through a mist eliminator where entrained liquid is removed.

After mist elimination, high pressure steam heat exchangers, direct fired reheaters, or indirect air or flue gas reheaters may be used to reheat the gas, which was cooled to saturation temperature in the absorber. Stack gas is reheated to:

- Eliminate condensation in downstream equipment

- Eliminate visible plume
- Provide enough plume buoyancy to minimize ground-level contaminant concentrations
- Prevent acid rain in the immediate vicinity of the stack

The amount of reheat needed is specific to the site.



## Solids Precipitation

Effluent holding tanks or precipitation vessels may be used, singly or in series, for solids precipitation, scrubber feed addition, and lime or limestone dissolution.

Slurry from the scrubber flows into the holding tank (Figure 4b). In the tank the slurry is mixed with recycled process water and system makeup water from the process water storage tank, and with fresh feed material from the slurry feed tank. An agitator keeps the slurry uniformly mixed. The slurry is recycled to the scrubber to be reused as scrubbing liquor. A bleed stream is drawn off simultaneously for dewatering, solids concentration, and disposal.

The holding tank is sized to provide sufficient residence time to complete the reactions (Equations 5 through 9) and to precipitate the reaction products. Seed crystals of coprecipitate (calcium sulfite/sulfate) and gypsum in the slurry provide nuclei for solids deposition and precipitation. Inadequate residence time in the holding tank can lead to nucleation of coprecipitate and gypsum in the scrubber, and scale may form as a result.

A material balance for the holding tank can be calculated by assuming that streams to and from the scrubber form a closed loop. Liquid-to-gas (L/G) ratio in the scrubber is varied by adjusting the liquid flow rate in the loop. The combined flow rates of the remaining incoming streams (feed material, makeup water, and recycled process water) match the flow rate of the bleed stream and compensate for water lost by evaporation in the scrubber and water added as mist eliminator wash. The ratio of feed material to water is adjusted to maintain a slurry concentration of 8 to 15 percent solids in the holding tank. It is important to maintain the solids concentration high enough to

provide sufficient seed crystals for precipitation, yet low enough to avoid erosion problems in the scrubber.

The incoming material/bleed stream flow rate is proportional to that at which  $\text{SO}_2$  is removed in the scrubber. In theory, 1 mole of calcium must be added for every mole of  $\text{SO}_2$  absorbed. In practice, however, more feed material is used, usually more in limestone systems than in lime systems because of the lower values of limestone utilization (moles  $\text{SO}_2$  removed per mole limestone added).

Recycled scrubbing slurry and the bleed stream contain solid and dissolved calcium sulfite/sulfate, gypsum, chlorides, unreacted lime or limestone, inerts, and possibly fly ash. Dissolved lime or limestone in the bleed stream is returned to the system as a part of the total dissolved solids in the recycled process water. Eventually, undissolved lime or limestone is disposed of with the waste solids.

## Solids Concentration and Disposal

One of the main disadvantages of the lime/limestone process, compared with regenerable processes, is the need for a waste pond, landfill, or other disposal area of sufficient size to receive the large quantity of waste solids produced. Dewatering and possibly stabilization may be desirable to minimize this need and to produce a more environmentally acceptable waste material. Specific methods vary depending on the application or the type of disposal.

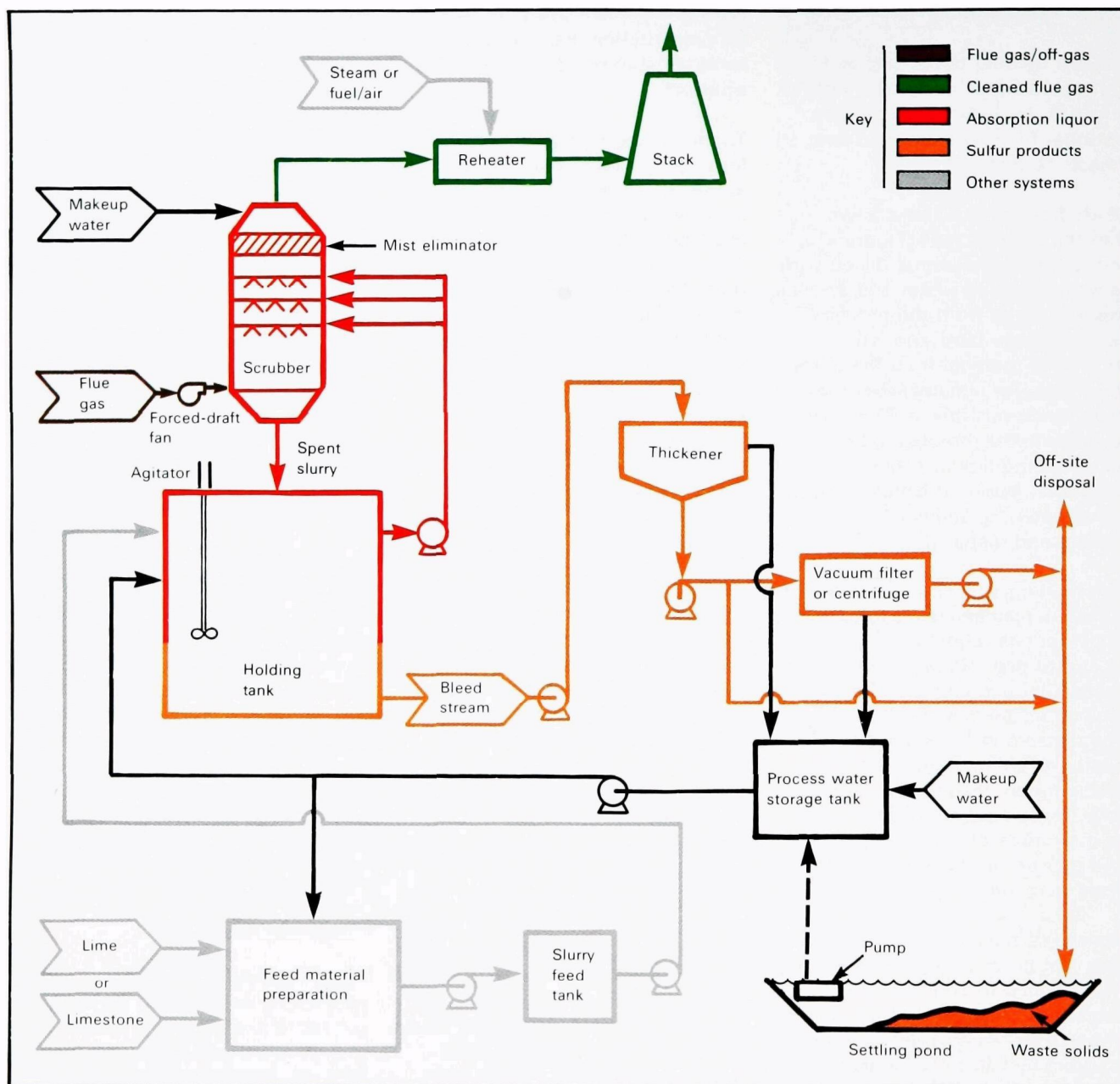
Several solids concentration and disposal systems may be used (Figure 4c). Usually a thickener is used for primary dewatering of the effluent holding tank bleed stream. Vacuum filtration or centrifugation can sometimes be used for further dewatering. Interim pond disposal is an alternative for secondary dewatering, although it is used infrequently.

Concentrated waste solids may be disposed of in an on-site pond, or they may be transported to a landfill area. Methods are available commercially for stabilizing waste solids to a structurally sound, leach resistant material, which can be disposed of in either a pond or a landfill area.

Clarified process water from the various solids concentration systems may be recycled to a process water storage tank. The water is pumped as needed from the storage tank to the effluent holding tank and to the feed-material-processing area. Makeup water may be added to the storage tank to compensate for system losses; however, fresh makeup water used for mist eliminator washing, pump seals, and lime slaking is usually sufficient.

## Integrated System

Figure 5 shows how the four processing areas—feed material preparation, absorption, solids precipitation, and solids concentration and disposal—are related to form the complete lime/limestone FGD process. Process design and operation are influenced strongly by the relationship of each process unit to the others. For example, solids precipitation in the holding tank affects the design and operation of the solids concentration and disposal subsystem.



**Figure 5.**

### Lime/Limestone FGD Process Flow



## Design Considerations

A complete discussion of the design considerations involved in the construction and operation of lime/limestone FGD systems is beyond the scope of a summary report. This section contains sufficient information on design considerations to permit a macroscopic analysis of the process, including details on:

- Feed material processing
- Absorption systems
- Scale control
- Mist elimination
- Solids dewatering and disposal
- Fly ash and chloride effects

### Feed Material Processing

As a rule the choice between lime and limestone as feed material is based on economics and availability. Among such factors as capital investment, operating costs, utilities requirements, land use, feed utilization, SO<sub>2</sub> removal efficiency, and reliability, the relationship is quite complex.<sup>7</sup> Although limestone is much less costly per unit weight than lime, limestone is usually less efficient than lime in SO<sub>2</sub> removal. This characteristic increases operating costs because more feed material must be added and more waste solids are produced. Operating costs for limestone systems are increased further because the feed material must be ground. Measures to improve utilization, therefore, are most important for the economics of limestone systems. Typically, lime systems have operated at around 90 percent utilization, although they can be designed to operate in the 95 to 100 percent range. Typical utilizations for limestone systems are 60 to 80 percent; however, more recent process designs can achieve utilizations as high as 85 to 95 percent.

Utilization is related to the solubility of the feed material. Limestone dissolves less completely than lime at pH levels appropriate for SO<sub>2</sub> absorption. It dissolves more com-

pletely at reduced pH levels, but SO<sub>2</sub> absorption efficiency is reduced.<sup>8</sup> A two-stage scrubber has provided a compromise; the first stage is operated at low pH for limestone solubility and the second at a higher pH for efficient SO<sub>2</sub> absorption.<sup>9,10</sup> In another compromise approach organic acids are added to the scrubber liquor to buffer the pH as an aid both to limestone dissolution and to SO<sub>2</sub> absorption. Benzoic and adipic acids have been especially successful.<sup>11,12</sup>

The following approaches also improve limestone utilization without decreasing SO<sub>2</sub> absorption efficiency:<sup>8,13</sup>

- Grinding to increase limestone surface area
- Using multiple holding tanks in series instead of a single tank
- Using two-stage forced oxidation for limestone systems

### Absorption Systems

Various absorption systems have been employed for lime/limestone FGD processes. Factors controlling selection of an appropriate system include flow rate and SO<sub>2</sub> content of the flue gas, desired efficiency of SO<sub>2</sub> removal, allowable pressure drop, turndown capability, and system reliability. The volume of flue gas to be treated, in part, determines the physical size of the scrubbing device. Because of size limitations for the various types used, however, a modular approach is usually taken. Spare modules may or may not be included, depending on the degree of conservatism.



Mobile bed sulfur dioxide scrubber system

Types of scrubbers that have been used successfully to remove  $\text{SO}_2$  include:

- Venturi scrubbers
- Spray towers (horizontal and vertical)
- Grid towers
- Mobile bed (turbulent contact) absorbers
- Packed towers
- Perforated plate towers

Each of these types will serve for both gas absorption and particle removal, but there are differences in  $\text{SO}_2$  and particle removal efficiency, gas velocity, L/G ratio, gas-side pressure drop, resistance to plugging,

and turndown capability. Performance characteristics are given in Table 1 for four scrubber types in a limestone system.<sup>6,14</sup>

Sulfur dioxide removal efficiency is based on both the scrubber type and the ability of the scrubbing slurry to absorb  $\text{SO}_2$ . Absorption efficiency may be improved by increasing:<sup>8,15</sup>

- Number of scrubber stages
- Contact area in each stage
- Scrubber L/G ratio
- Scrubber liquor pH
- Available alkali

Particles are removed by impingement. Turbulent flow and high gas-side pressure drop indicate good particle removal capability. A venturi scrubber exhibits both characteristics and commonly is used for primary particle removal in conjunction with a spray tower for improved  $\text{SO}_2$  absorption.

Minimum and maximum gas velocities vary widely among scrubber types. All but the venturi operate in a range of 5 to 25 ft/s (1.5 to 7.6 m/s). The extremely high gas velocities associated with the venturi, 125 to 300 ft/s (38 to 92 m/s), result from the small diameter of the venturi throat and do not



**Table 1.****Comparison of Scrubber Types for a Limestone Wet Scrubbing System**

Parameter	Scrubber type			
	Turbulent contact absorber	Venturi	Grid tower	Spray tower
SO <sub>2</sub> removal efficiency .....	Good	Fair	Good	Good
Particle removal efficiency .....	Good	Excellent	Good	Fair
Gas velocity (ft/s) .....	9 to 13	125 to 300	6 to 11	5 to 25
Typical liquid/gas ratio for SO <sub>2</sub> removal (gal/1,000 stdft <sup>3</sup> ) .....	50 to 75	20 to 50	50 to 100	70 to 110
Gas-side pressure drop for typical liquid/gas ratio (inches H <sub>2</sub> O) .....	6 to 8	8 to 20	1 to 7	1 to 3
Resistance to solids plugging .....	Good	Excellent	Good	Excellent

SOURCES: Robert H. Borgwardt, EPA, Research Triangle Park NC, personal communication, Jan. 1978. Ottmers, D. M., Jr., J. C. Dickerman, E. F. Aul, Jr., R. D. Delleney, G. D. Brown, G. C. Page, and D. O. Stuebner, *Evaluation of Regenerable Flue Gas Desulfurization Processes*, 2 vols., EPRI RP 535-1, Austin TX, Radian Corporation, July 1976.

necessarily imply a greater gas-volume-handling capability. The resulting shorter residence times reduce the SO<sub>2</sub> removal capabilities of the venturi.

The L/G values in Table 1 represent typical operating ranges for existing units. Turbulent contact absorbers provide greater surface area for transfer of SO<sub>2</sub> at lower L/G ratios than do spray towers. The L/G ratios are also limited because the scrubbers tend to flood if the liquid pumping rate is too high. This flooding occurs at different L/G ratios for the various scrubber types.

The volume of slurry circulated is critical and depends on the gas flow and the SO<sub>2</sub> content of the gas. In applications of low L/G ratio and high SO<sub>2</sub> concentrations, the slurry can absorb too much SO<sub>2</sub> per unit volume, resulting in high levels of supersaturation. Under these conditions, precipitation will take place in the scrubber as well as in the holding tank, causing scaling in the scrubber.

Slurry reactivity also influences the L/G ratio in the absorber. In general, L/G ratios must be higher in limestone systems than in lime systems to compensate for the lower reactivity of a limestone slurry.

Pressure drop across the scrubbers is a function of gas velocity, L/G ratio, scrubber design, and scrubber size. Gas pressure lost in the scrubber is compensated with forced- or induced-draft fans. In some applications, especially in retrofit installations, it may be desirable to design a system for low gas-side pressure drop to reduce the number of fans needed and, therefore, capital and operating costs.

Resistance to plugging is important in system reliability. The open configurations of the grid tower and the spray tower give a lower gas-side pressure drop and make these scrubbers less susceptible to plugging than are the turbulent contact absorber and the packed tower.

### Scale Control

In a lime/limestone scrubbing system, it is important to control gypsum and calcium sulfite/sulfate coprecipitate scale. If scaling conditions exist for significant amounts of time in any part of the system, chemical scale will be deposited on equipment and the system

eventually will have to be shut down for cleaning.

Gypsum presents a greater scaling problem than does the calcium sulfite/sulfate coprecipitate. Gypsum forms a hard scale that is difficult to remove. Sulfite/sulfate coprecipitate scale can be removed easily by a lowered pH, which causes the scale to dissolve.

If the scrubbing system can operate with less than 17 percent oxidation of sulfite to sulfate, most calcium sulfate coprecipitates from solution with calcium sulfite as  $(1 - x)\text{CaSO}_3 \cdot x\text{CaSO}_4 \cdot \frac{1}{2}\text{H}_2\text{O}$ . Under these conditions, gypsum concentrations are kept continually below saturation, and scaling problems are held to a minimum.<sup>5</sup>

Several approaches will reduce the probability of scale formation.<sup>6,14</sup>

The scrubber L/G ratio can be increased to prevent formation of more highly supersaturated calcium sulfite/sulfate solutions. Higher L/G ratios allow lower SO<sub>2</sub> pickup per unit volume of scrubber solution and, thus, lower supersaturations.

Sufficient gypsum and calcium sulfite/sulfate coprecipitate seed crystals should be recirculated in the slurry to provide surface area for precipitation. Most systems operate in the range of 8 to 15 percent solids by weight.

Holding tank volume should allow for adequate residence time for solids precipitation. The scrubbing liquor will then be sufficiently desupersaturated with calcium sulfite/sulfate. This variable is important in system design because changes in the holding tank volume usually represent expensive equipment modifications.

Use of magnesium or other additives may reduce the scaling tendency by reducing the relative concentration of calcium salts.<sup>16</sup>

## Mist Elimination

Reliable mist eliminator operation has been a major problem for limestone scrubbers. Mist eliminators have operated in lime scrubbers with more success.

All wet scrubbers introduce mist droplets in the gas. The mist must be collected and removed to prevent corrosion and scaling on downstream equipment. Mist elimination also reduces the energy requirement for flue gas reheat to evaporate excess moisture. Because mist droplets from the scrubber have relatively large diameters, usually 40  $\mu\text{m}$  or greater, they can be removed effectively by simple impingement devices such as baffle plates, chevron blades, or similar devices that alter the direction of the gas flow.

Problems with chevrons have included inefficient mist removal and plugging of the chevrons with soft deposits and scale. Mist elimination has been more efficient when chevrons are mounted in a slanted or vertical position instead of the usual horizontal position. This arrangement permits the liquor to drain off and prevents it from being reentrained in the gas.

Plugging and scaling of mist eliminators can be prevented by washing these components with a mixture of fresh water (usually about 35 percent) and clarified liquor, supplemented if necessary by intermittent washing with fresh water.<sup>14</sup> Scaling can be eliminated by operating the system at high  $\text{SO}_2$  removal efficiencies and high reagent utilizations. High scrubber  $\text{SO}_2$  removal efficiencies result in lower  $\text{SO}_2$  concentrations in the gas passing through the mist eliminator and, consequently, reduced  $\text{SO}_2$  absorption. Higher reagent utilizations result in lower reagent concentrations in the carryover. Both factors reduce scaling by reducing calcium sulfite/sulfate supersaturations in the mist

eliminator.<sup>4</sup> Plugging and scaling usually can be eliminated when systems are operated at utilization levels above 85 percent.<sup>8</sup>

Wash trays and wet electrostatic precipitators (ESP's) also have been used as components of mist elimination systems. A wash tray is placed under a horizontal chevron to remove solids in the entrained mist and to collect wash liquor flowing off the chevron. Wet ESP's remove both mist and residual dust in the flue gas leaving the absorber.

## Solids Dewatering and Disposal

Solids are dewatered to concentrate them for ease of handling and disposal and to lower transportation costs. Choice of the best dewatering method depends on the disposal method (i.e., wet disposal in ponds or dry disposal as landfill or for potential use as commercial gypsum); however, the composition of the solids and the availability of dry fly ash to supplement dewatering also are important.<sup>17</sup>

**Dewatering Methods.** Currently, thickening and vacuum filtration are used in lime/limestone solids dewatering on commercial-sized units, and interim ponding also has been used. Centrifugation was tested, but filtration was found more effective.

Clarifiers or thickeners are used commonly for primary dewatering of slurries with a low solids content (10 to 15 percent solids). Typically, these devices can achieve 30 to 40 percent solids. If solids dewaterability and ultimate disposal plans so warrant, solids content may be increased further using vacuum filters. These devices achieve 50 to 85 percent solids, depending on the system.

Solids dewaterability depends on the relative amounts of sulfites and sulfates that form in the desulfurization process. Generally, dewatering is improved by a higher ratio of sulfate to sulfite. Calcium sulfate can coprecipitate with calcium sulfite as  $(1 - x)\text{CaSO}_3 \cdot x\text{CaSO}_4 \cdot \frac{1}{2}\text{H}_2\text{O}$  or can precipitate as  $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$ . In forced-oxidation systems, however, only gypsum solids are formed because all of the sulfite reacts with the available oxygen. Coprecipitate solids are usually plate shaped, 0.5 to 2.0  $\mu\text{m}$  thick and 2 to 4  $\mu\text{m}$  long. Gypsum solids are usually large, bulky crystals 1 to 100  $\mu\text{m}$  or larger.<sup>18</sup>

Dewatering characteristics also are influenced by crystal size, which is affected by the precipitation conditions in the effluent holding tank and the amount of solids recirculated in the system.<sup>19,20</sup>

Solids from a forced-oxidation system, which contain essentially only calcium sulfate, can be dewatered to about 80 to 90 percent solids using filtration or centrifugation.<sup>13,21</sup> To obtain a better product for disposal, the Sherburne County FGD systems (of Northern States Power) have incorporated forced oxidation into the overall systems before clarification.<sup>22</sup>

**Stabilization Processes.** Solids stabilization is optional in system design. Stabilization lowers permeability, reduces leaching, and improves the structural stability of the solids. Untreated solids are difficult to handle and transport. Moreover, untreated solids disposal has caused concern about contamination of ground water with leachates and removal of large areas of land from productive use.

Solids from FGD processes usually contain some fly ash, a major source of trace elements in the leachate. Unstabilized solids high in calcium sulfite are also difficult to dewater, and are thixotropic. Unstabilized solids cannot be used as a load-bearing material because of their poor structural properties.



At least 16 vendor companies currently offer waste solids fixation processes, but only two processes—Dravo's Calcilox and IU Conversion System's (IUCS) POZ-O-TEC—have been developed and tested sufficiently to be commercially feasible for use with FGD waste solids.

In the Dravo process, Calcilox—a product derived from basic glassy blast furnace slag—is added to FGD solids. The only full-scale Dravo fixation operation is at Pennsylvania Power Company's Bruce Mansfield plant.<sup>1</sup>

The IUCS process employs vacuum filter dewatering of FGD solids, then adds lime, dry fly ash, and other substances to produce a dry product called POZ-O-TEC, which can be used as landfill. Four full-scale systems are currently in operation:<sup>1</sup>

- Columbus and Southern Ohio Electric Co., Conesville Plant
- Commonwealth Edison Co., Powerton Station
- Duquesne Light Co., Phillips Power Station
- Duquesne Light Co., Elrama Power Station

A definite increase in solids stability has been demonstrated when fixation processes are used. This improved stability allows the landfilled area to be used productively. The leaching of contaminants from the stabilized material is reduced but could still be an environmental problem.<sup>23</sup>

### Fly Ash and Chloride Effects

The fly ash content of the flue gas affects scrubbing system design. Unless fly ash and chlorides are eliminated upstream, they are removed by the SO<sub>2</sub> scrubber.

An important design decision for coal-fired system applications is whether to remove particles upstream of the scrubber. The current trend in the utility industry is to install a high-efficiency precipitator upstream. Low-efficiency precipitators (90 to 95 percent removal) or mechanical collectors may be considerably cheaper to operate, but the scrubber must still be designed to remove residual particles.

Some scrubber types (venturi or mobile bed) can control both particles and SO<sub>2</sub> effectively. Although the capital cost may be kept to a minimum, there are several significant disadvantages associated with removing particles in the FGD scrubber:<sup>24</sup>

- The extent to which dry fly ash is available as an additive for solids fixation is reduced. The importance of this factor depends on the solids disposal method.

- There is a consensus that ash causes erosion in the scrubber; on the other hand, some degree of erosivity may be desirable to keep the internal surfaces free of scale and deposits.
- Particulate emission regulations may not be met by the scrubber alone. And, if the scrubber is shut down, bypassing it may be impossible without exceeding the regulations.
- Fly ash cannot be marketed unless collected dry upstream of the scrubber.
- Particle scrubbing results in an increased pressure drop, which in turn increases power consumption and, consequently, operating costs.

The alkaline content (CaO, MgO) of some fly ashes (e.g., that from lignite) may be used for SO<sub>2</sub> removal. The behavior of magnesium content is similar to that of magnesium additives.<sup>16</sup>

Chlorine may be present in the flue gas as hydrogen chloride (HCl). Chlorides enter the SO<sub>2</sub> scrubbing liquor unless a prescrubber is used. Their presence in the slurry can cause corrosion and may alter system chemistry. Some of the chlorides are removed in the water disposed of with wastes, but there still may be a serious buildup, depending on the chloride content of the fuel combusted. An additional scrubbing liquor purge may help to alleviate this problem by producing a concentrated chloride stream for disposal.



1,250-horsepower pump for sulfur dioxide absorber

## Environmental Considerations

The ability of lime/limestone scrubbing systems to remove over 90 percent of the flue gas  $\text{SO}_2$  has been demonstrated successfully for brief periods at full-scale commercial installations. For example, the  $\text{SO}_2$  removal efficiency at the Louisville Gas and Electric Company, Paddy's Run Station, Boiler No. 6, has been greater than 90 percent when the boiler burns coal containing 3.7 percent sulfur. The unit uses a carbide/lime slurry. Sulfur dioxide removal efficiencies have been highest when the carbide/lime slurry contains significant amounts of magnesium.

High particle removal efficiency (99 percent and greater) can be obtained without major operational problems, as long as calcium sulfite/sulfate scaling control is not obstructed. Wet scrubbing of flue gas can reduce flue gas particle loadings to environmentally acceptable loads at reasonable L/G ratios.<sup>6</sup>

The major disadvantage of lime/limestone wet scrubbing is the large volume of solid waste produced. Scrubber waste can contain calcium sulfite/sulfate precipitate, gypsum, limestone in a limestone system, unreacted  $\text{CaO}$  in a lime system, chlorides, inerts, and fly ash. Usually the waste is disposed of in ponds or used as landfill after adequate dewatering, and leachates from these solids constitute a possible environmental problem. Therefore, an impervious liner, chemical fixation, or some other environmentally acceptable solution may be needed.

A limestone scrubber for a 500-MW boiler burning 3.5-percent-sulfur coal produces about 61 tons/h (55 Mg/h) of fly-ash-free waste after concentration to 50 percent solids by weight, assuming 79-percent limestone utilization and upstream particle removal. For a 5,260-h/yr loading, the waste stream would produce 320,000 tons/yr (290,000 Mg/yr),<sup>6</sup> requiring a disposal area of 73 acres (30 ha).<sup>25</sup>

A lime system operating under similar conditions produces 54 tons/h (49 Mg/h) of fly-ash-free solid waste, assuming 86-percent lime utilization. A plant operating 5,260 h/yr produces 283,000 tons/yr (257,000 Mg/yr) of waste,<sup>6</sup> requiring a disposal area of 53 acres (21 ha).<sup>25</sup>

The EPA has conducted a number of studies to determine the effectiveness of various FGD waste stabilization and disposal techniques. These studies examined leachate migration, run-off characteristics, and the physical stability of solid wastes. Stabilized and unstabilized solids are being tested both in ponds lined with clay and in those lined with synthetic materials. Research to date indicates that chemical stabilization increases physical stability and reduces permeability of solid waste, but that it does not eliminate the leaching of trace elements. When lined ponds are used for disposal, the migration of leachates is restricted.<sup>26</sup>

In Japan, land use considerations have resulted in process modifications to produce a more useful byproduct. Fly ash and chlorides are eliminated from the flue gas before it enters the absorber, and the bleed stream from the holding tank is oxidized to gypsum before concentration. Disposal problems are avoided because the purified gypsum is sold to the wallboard industry.<sup>27</sup>

A method of oxidation similar to that used in Japan has been demonstrated on solid wastes containing fly ash and chlorides. Currently, EPA is conducting research to study forced oxidation and fly-ash-free limestone scrubbing.<sup>10,13</sup>



## Status of Development

Lime/limestone scrubbing was used first about 40 years ago in England to control  $\text{SO}_2$  emissions from commercial boilers on a pilot scale. Success led to the construction of full-scale scrubbing plants that proved effective in removing  $\text{SO}_2$  and dust from stack gas. The process was also the first stack-gas desulfurization technology used in the United States. The trend toward lime/limestone scrubbing for  $\text{SO}_2$  removal is strong today owing to rapid progress in solving process problems and a clearer understanding of process chemistry.

As of June 1980, over 58,000 MW of electrical generating capacity in the United States had been committed to operating lime/limestone scrubbing systems. Fifty-eight facilities were in operation (Tables 2 and 3) and 71 were under construction or in the planning stage (Tables 4 and 5).<sup>1</sup> The proceedings from EPA's most recent FGD symposium<sup>28,29</sup> contains papers describing the performance of many of these operational U.S. installations and of foreign installations.

Problems in operating lime/limestone scrubber systems have been encountered in the following areas:

- Scrubber and pipe plugging
- Chemical scaling
- Erosion and corrosion
- Mist eliminator/reheater operation
- Solids disposal

Many of these problems have been solved or alleviated as a result of research and development efforts.<sup>6,28,29</sup>

In general, scrubber and pipe plugging has been eliminated by design simplification. Internal scrubber design has been refined. Incidence of pipe plugging has been reduced by eliminating unnecessary piping bends, valves other than gate valves, and obstacles in the piping system, and by maintaining high slurry velocity. Plugging is no longer considered a serious obstacle to process reliability.

Plugging, scaling, and corrosion have occurred frequently in mist eliminators. Studies at the EPA Alkali Scrubbing Test Facility—at the Tennessee Valley Authority's



Scrubber system, Cane Run No. 4

Table 2.

## Lime and Lime/Limestone FGD Systems Operating in U.S. Utilities as of June 1980

Process, utility, and station <sup>a</sup>	FGD units		Gas volume treated (1,000 stdft <sup>3</sup> /min)	Fuel		% SO <sub>2</sub> removal (design)	Startup date
	Size (MW)	No.		Type	% S		
Lime:							
Arizona Public Service:							
Four Corners 1 (R)*	175	2	350 <sup>b</sup>	Coal	0.75	67.5	1979
Four Corners 2 (R)*	175	2	350 <sup>b</sup>	Coal	0.75	67.5	1979
Four Corners 3 (R)*	229	2	458 <sup>b</sup>	Coal	0.75	67.5	1979
Big Rivers Electric: Green 1 (N)	242	2	484 <sup>b</sup>	Coal	3.75	90	1979
Columbus & Southern Ohio Electric:							
Conesville 5 (N)	411	2	882	Coal	4.67	89.5	1977
Conesville 6 (N)	411	2	882	Coal	4.67	89.5	1978
Cooperative Power Association: Coal Creek 1 (N)*	327	4	654 <sup>b</sup>	Lignite	0.63	90	1979
Duquesne Light:							
Elrama 1-4 (R)	510	5	1,840	Coal	2.20	83	1975
Phillips 1-6 (R)	408	5	1,778	Coal	1.92	83	1973
Kansas City Power & Light:							
Hawthorne 3 (R)	90	2	222	Coal	0.60	70	1972
Hawthorne 4 (R)	90	2	222	Coal	0.60	70	1972
Kentucky Utilities: Green River 1-3 (R)	64	1	256	Coal	4.00	80	1975
Louisville Gas & Electric:							
Cane Run 4 (R)	188	2	490	Coal	3.75	85	1976
Cane Run 5 (R)	200	2	431	Coal	3.75	85	1977
Mill Creek 3 (N)	442	4	1,232	Coal	3.75	85	1978
Paddy's Run 6 (R)	72	2	225	Coal	2.50	80	1973
Minnesota Power & Light: Clay Boswell 4 (N)*	475	NA	950 <sup>b</sup>	Coal	0.94	89	1980
Minnkota Power Coop.: Milton R. Young 2 (N)*	185	2	1,124	Lignite	0.70	75	1977
Monongahela Power: Pleasants 1 (N)	618	4	1,236 <sup>b</sup>	Coal	3.70	90	1979
Montana Power:							
Colstrip 1 (N)*	360	3	1,148	Coal	0.77	60	1975
Colstrip 2 (N)*	360	3	1,148	Coal	0.77	60	1976
Pennsylvania Power:							
Bruce Mansfield 1 (N)	917	6	2,267	Coal	3.00	92	1975
Bruce Mansfield 2 (N)	917	6	2,270	Coal	3.00	92	1977
Bruce Mansfield 3 (N)	917	6	2,270	Coal	3.00	92	1980
Utah Power & Light:							
Hunter 1 (N)	360	4	1,248	Coal	0.55	80	1979
Hunter 2 (N)	360	NA	720 <sup>b</sup>	Coal	0.55	80	1980
Huntington 1 (N)	366	4	1,248	Coal	0.55	80	1978
Lime/Limestone: Tennessee Valley Authority:							
Shawnee 10A (R)	10	1	24	Coal	2.90	( <sup>c</sup> )	1972
Shawnee 10B (R)	10	1	24	Coal	2.90	( <sup>c</sup> )	1972

<sup>a</sup>N = new. R = retrofit. Asterisk (\*) = lime/alkaline fly ash.

<sup>b</sup>Estimated: stdft<sup>3</sup>/min = 2,000 × MW rating.

<sup>c</sup>Experimentally controlled.

Note.—NA = data not available.

SOURCES: Smith, M., M. Melia, and N. Gregory, *EPA Utility FGD Survey: October-December 1979*, EPA 600/7-80-029a, NTIS No. Pb 80-176-811, Jan. 1980. Smith, M., et al., *EPA Utility FGD Survey: April-June 1980*, EPA 600/7-80-029c, July 1980.

(TVA) Shawnee steam plant—show that deposit formation was reduced significantly when feed utilization was increased above 85 percent in a limestone system.<sup>8</sup> Reduced gas velocity, increased spray droplet

size for spray towers, and increased distance between the scrubber and the mist eliminator decrease maintenance requirements by keeping to a minimum slurry carry-over from the scrubber. Reliability is also improved when the mist eliminator is oriented in a vertical

or sloped position so that captured mist and wash water can drain more effectively. With proper washing techniques and control of stoichiometry, mist eliminator plugging is no longer an obstacle.<sup>14</sup>

Table 3.

## Limestone FGD Systems Operating in U.S. Utilities as of June 1980

Process, utility, and station <sup>a</sup>	FGD units		Gas volume treated (1,000 stdft <sup>3</sup> /min)	Fuel		% SO <sub>2</sub> removal (design)	Startup date
	Size (MW)	No.		Type	% S		
Alabama Electric Coop.:							
Tombigbee 2 (N).....	179	2	476	Coal	1.15	85	1978
Tombigbee 3 (N).....	179	2	464	Coal	1.15	85	1979
Arizona Electric Power Coop.:							
Apache 2 (N).....	97.5	2	570	Coal	0.55	85	1978
Apache 3 (N).....	97.5	2	570	Coal	0.55	85	1979
Arizona Public Service:							
Cholla 1 (R).....	119	4	678	Coal	0.50	92	1973
Cholla 2 (N).....	264	4	1,401	Coal	0.50	75	1978
Central Illinois Light: Duck Creek 1 (N).....	416	4	1,002	Coal	3.30	85	1976
Colorado Ute Electric Association: Craig 2 (N).....	447	4	894 <sup>b</sup>	Coal	0.45	85	1979
Commonwealth Edison: Powerton 51 (R).....	450	3	900 <sup>b</sup>	Coal	3.53	74	1980
Indianapolis Power & Light: Petersburg 3 (N).....	532	4	1,350	Coal	3.25	85	1977
Kansas City Power & Light: La Cygne 1 (N).....	874	8	1,705	Coal	5.39	80	1973
Kansas Power & Light:							
Jeffrey 1 (N).....	540	6	1,080 <sup>b</sup>	Coal	0.32	50	1978
Jeffrey 2 (N).....	490	NA	980 <sup>b</sup>	Coal	0.30	NA	1980
Lawrence 4 (R).....	125	2	311	Coal	0.55	73	1976
Lawrence 5 (N).....	420	2	1,036	Coal	0.55	73	1971
Northern States Power:							
Sherburne 1 (N)*.....	740	12	2,115	Coal	0.80	50	1976
Sherburne 2 (N)*.....	740	12	2,115	Coal	0.80	50	1977
Salt River Project: Coronado 1 (N).....	280	2	560 <sup>b</sup>	Coal	1.00	82.5	1979
South Carolina Public Service:							
Winyah 2 (N).....	140	1	300	Coal	1.70	69	1977
Winyah 3 (N).....	280	NA	560 <sup>b</sup>	Coal	1.70	NA	1980
South Mississippi Electric Power:							
R. D. Morrow 1 (N).....	124	1	290	Coal	1.30	85	1978
R. D. Morrow 2 (N).....	124	1	290	Coal	1.30	85	1979
Southern Illinois Power Coop.: Marion 4 (N).....	184	2	523	Coal/refuse	3.50	89.4	1979
Springfield City Utilities: Southwest 1 (N).....	194	2	455	Coal	3.50	80	1977
Tennessee Valley Authority: Widows Creek 8 (R).....	550	4	1,100 <sup>b</sup>	Coal	3.70	80	1977
Texas Utilities:							
Martin Lake 1 (N).....	595	6	1,492	Lignite	0.90	70.5	1977
Martin Lake 2 (N).....	595	6	1,490	Lignite	0.90	70.5	1978
Martin Lake 3 (N).....	595	6	1,490	Lignite	0.90	70.5	1979
Monticello 3 (N).....	800	3	2,354	Lignite	1.50	74	1978

<sup>a</sup>N = new. R = retrofit. Asterisk (\*) = limestone/alkaline fly ash.

<sup>b</sup>Estimated: stdft<sup>3</sup>/min = 2,000 × MW rating.

Note.—NA = data not available.

SOURCES: Smith, M., M. Melia, and N. Gregory, *EPA Utility FGD Survey: October-December 1979*, EPA 600/7-80-029a, NTIS No. Pb 80-176-811, Jan. 1980. Smith, M., et al., *EPA Utility FGD Survey: April-June 1980*, EPA 600/7-80-029c, July 1980.

Much effort has been spent on development and design for scale prevention. High solids concentration in the circulating slurry (up to 15 percent), increased L/G ratios, and longer residence times in the scrubber holding tank have helped to alleviate scaling problems. A number of commercial-size installations have demonstrated scale-free service during continuous operation.<sup>1</sup>

A disadvantage of using high solids concentration to avoid scaling is the abrasive effect of the solids on spray nozzles, pumps, and piping. The current trend is to use stainless steel, Stellite, refractory, or other hardened materials for spray nozzle construction. Soft rubber or neoprene-lined carbon steel can be effective for pump and

piping material under abrasive conditions at temperatures up to 175° F (80° C). Erosion and significant weight loss of the spheres have been noted in turbulent contact absorbers.

To minimize erosion and corrosion, surfaces in the wet scrubbing system that come in contact with wet SO<sub>2</sub> or acid scrubber liquor must be constructed of acid- or abrasive-resistant materials. Stainless



**Table 4.**

Lime and Lime/Limestone FGD Systems Planned or Under Construction in U.S. Utilities as of June 1980

Process, utility, and station <sup>a</sup>	FGD units		Gas volume treated <sup>b</sup> (1,000 stdft <sup>3</sup> /min)	Fuel		% SO <sub>2</sub> removal (design)	Startup date
	Size (MW)	No.		Type	% S		
Lime:							
Arizona Public Service:							
Four Corners 4 (R).....	755	NA	1,510	Coal	0.75	NA	1982
Four Corners 5 (R).....	755	NA	1,510	Coal	0.75	NA	1982
Big Rivers Electric:							
D. B. Wilson 1 (N).....	440	NA	880	Coal	NA	NA	1984
D. B. Wilson 2 (N).....	440	NA	880	Coal	NA	NA	1985
Green 2 (N).....	242	2	484	Coal	3.75	90	1980
Cincinnati Gas & Electric: East Bend 2 (N).....	650	3	1,300	Coal	5.00	87	1980
Cooperative Power Association: Coal Creek 2 (N)*.....	327	4	654	Lignite	0.63	90	1980
East Kentucky Power Coop.: Spurlock 2 (N).....	500	NA	1,000	Coal	3.50	90	1981
Grand Haven Board of Light & Power: J. B. Sims 3 (N)....	65	2	130	Coal	2.75	NA	1983
Los Angeles Department of Water & Power:							
Intermountain 1 (N).....	820	NA	1,640	Coal	0.79	NA	1986
Intermountain 2 (N).....	820	NA	1,640	Coal	0.79	NA	1987
Intermountain 3 (N).....	820	NA	1,640	Coal	0.79	NA	1988
Intermountain 4 (N).....	820	NA	1,640	Coal	0.79	NA	1989
Louisville Gas & Electric:							
Mill Creek 1 (R).....	358	NA	716	Coal	3.75	NA	1980
Mill Creek 2 (R).....	350	NA	700	Coal	3.75	NA	1981
Mill Creek 4 (N).....	495	4	990	Coal	3.75	NA	1981
Monongahela Power: Pleasants 2 (N).....	618	4	1,236	Coal	4.50	90	1980
Montana Power:							
Colstrip 3 (N)*.....	700	NA	1,400	Coal	0.70	NA	1983
Colstrip 4 (N)*.....	700	NA	1,400	Coal	0.70	NA	1984
West Penn Power: Mitchell 33 (R).....	300	NA	600	Coal	2.80	95	1982
Lime/limestone: Tampa Electric: Big Bend 4 (N).....	475	NA	950	Coal	2.35	90	1984

<sup>a</sup>N = new. R = retrofit. Asterisk (\*) = lime/alkaline fly ash.<sup>b</sup>Estimated: stdft<sup>3</sup>/min = 2,000 × MW rating.

Note.—NA = data not available.

SOURCES: Smith, M., M. Melia, and N. Gregory, *EPA Utility FGD Survey: October-December 1979*, EPA 600/7-80-029a, NTIS No. Pb 80-176-811, Jan. 1980. Smith, M., et al., *EPA Utility FGD Survey: April-June 1980*, EPA 600/7-80-029c, July 1980.

steel or rubber-lined carbon steels are now being used for scrubber shells and internals, and glass flake epoxy-type materials have been used for scrubber shell and tank linings. Various other corrosion resistant materials have been used for scrubber pumps and piping.<sup>8,28,29</sup>

For many systems, reheating presents design problems. In cases where heat exchangers are placed in the duct, materials passing through the mist eliminator may plug, scale, or corrode the reheater surfaces. The problem may be kept

to a minimum by proper selection of materials and efficient mist removal. Direct-fired in-line reheaters exhibited poor combustion in the past because of the quenching effect of the cool gas stream. Recent design improvements such as external combustion chambers, however, make these systems operable.<sup>8</sup> Indirect reheaters (i.e., those that heat air externally for mixing with the flue gas) are probably the least troublesome and

most reliable; they may also be the most expensive.

Problems associated with solid waste disposal are receiving increased attention as problems more critical to system reliability are solved. Currently, waste solids are stored in ponds or stabilized and used as a landfill material. Both unstabilized and stabilized solids are susceptible to leaching of trace elements. Lining waste ponds prevents migration of leachates, but limits the dewatering capacity of the pond.<sup>30,31</sup>

Table 5.

Limestone FGD Systems Planned or Under Construction in U.S. Utilities as of June 1980

Process, utility, and station <sup>a</sup>	FGD units		Gas volume treated <sup>b</sup> (1,000 stdft <sup>3</sup> /min)	Fuel		% SO <sub>2</sub> removal (design)	Startup date
	Size (MW)	No.		Type	% S		
Arizona Public Service: Cholla 4 (N) . . . . .	126	NA	252	Coal	0.50	NA	1981
Associated Electric Coop.: Thomas Hill 3 (N) . . . . .	670	4	1,340	Coal	4.80	NA	1982
Basin Electric Power Coop.:							
Laramie River 1 (N) . . . . .	570	5	1,140	Coal	0.81	90	1980
Laramie River 2 (N) . . . . .	570	5	1,140	Coal	0.81	90	1981
Central Illinois Light: Duck Creek 2 (N) . . . . .	450	NA	900	Coal	3.30	NA	1986
Colorado Ute Electric Association: Craig 1 (N) . . . . .	447	4	894	Coal	0.45	85	1980
Deseret Generation & Transmission Coop.:							
Moon Lake 1 (N) . . . . .	410	NA	820	Coal	0.50	95	1984
Moon Lake 2 (N) . . . . .	410	NA	820	Coal	0.50	95	1988
Hoosier Energy:							
Merom 1 (N) . . . . .	441	1	882	Coal	3.50	90	1982
Merom 2 (N) . . . . .	441	1	882	Coal	3.50	90	1981
Houston Lighting & Power:							
Limestone 1 (N) . . . . .	750	NA	1,500	Lignite	1.08	NA	1985
Limestone 2 (N) . . . . .	750	NA	1,500	Lignite	1.08	NA	1986
W. A. Parish 8 (N) . . . . .	492	NA	984	Coal	0.60	82	1984
Indianapolis Power & Light:							
Patriot 1 (N) . . . . .	650	NA	1,300	Coal	3.50	NA	1987
Patriot 2 (N) . . . . .	650	NA	1,300	Coal	3.50	NA	1987
Patriot 3 (N) . . . . .	650	NA	1,300	Coal	3.50	NA	1987
Petersburg 4 (R) . . . . .	530	NA	1,060	Coal	3.50	NA	1984
Iowa Electric Light & Power: Guthrie 1 (N) . . . . .	720	NA	1,440	Coal	0.40	NA	1984
Jacksonville Electric Authority:							
New Project 1 (N) . . . . .	600	NA	1,200	Coal	3.00	NA	1985
New Project 2 (N) . . . . .	600	NA	1,200	Coal	3.00	NA	1987
Lakeland Utilities: McIntosh 3 (N) . . . . .	364	2	728	Coal	2.56	85	1981
Michigan South Central Power Agency: Project 1 (N) . . . . .	55	NA	110	Coal	2.25	NA	1982
Muscatine Power & Water: Muscatine 9 (N) . . . . .	166	2	332	Coal	3.00	94	1982
New York State Electric & Gas: Somerset 1 (N) . . . . .	870	NA	1,740	Coal	2.20	90	1984
Northern States Power: Sherburne 3 (N) . . . . .	860	NA	1,720	Coal	0.80	NA	1985
Pacific Gas & Electric:							
Montezuma 1 (N) . . . . .	800	NA	1,600	Coal	0.80	NA	1989
Montezuma 2 (N) . . . . .	800	NA	1,600	Coal	0.80	NA	1990
Plains Electric G&T Coop.: Plains Escalante 1 (N) . . . . .	233	NA	466	Coal	0.80	NA	1983



Table 5.

## Limestone FGD Systems Planned or Under Construction in U.S. Utilities as of June 1980—Concluded

Process, utility, and station <sup>a</sup>	FGD units		Gas volume treated <sup>b</sup> (1,000 stdft <sup>3</sup> /min)	Fuel		% SO <sub>2</sub> removal (design)	Startup date
	Size (MW)	No.		Type	% S		
Public Service Indiana: Gibson 5 (N) . . . . .	650	4	1,300	Coal	3.30	NA	1982
Salt River Project:							
Coronado 2 (N) . . . . .	280	2	560	Coal	1.00	82.5	1980
Coronado 3 (N) . . . . .	280	2	560	Coal	0.60	NA	1988
San Miguel Electric Coop.: San Miguel 1 (N) . . . . .	400	4	800	Lignite	1.70	86	1980
Seminole Electric:							
Seminole 1 (N) . . . . .	620	NA	1,240	Coal	2.75	NA	1983
Seminole 2 (N) . . . . .	620	NA	1,240	Coal	2.75	NA	1985
Sikeston Board of Municipal Utilities: Sikeston 1 (N) . . . . .	235	3	470	Coal	2.80	NA	1981
South Carolina Public Service:							
Cross 1 (N) . . . . .	500	NA	1,000	Coal	1.80	NA	1985
Cross 2 (N) . . . . .	500	NA	1,000	Coal	1.80	NA	1985
Winyah 4 (N) . . . . .	280	2	560	Coal	1.70	NA	1981
Southwestern Electric Power: Henry W. Pirkey 1 (N) . . . . .	720	4	1,440	Lignite	0.80	99	1984
Springfield Water, Light, & Power: Dallman 3 (N) . . . . .	205	2	410	Coal	3.30	95	1980
Tennessee Valley Authority:							
Paradise 1 (R) . . . . .	704	6	1,408	Coal	4.20	NA	1982
Paradise 2 (R) . . . . .	704	6	1,408	Coal	4.20	NA	1982
Widows Creek 7 (R) . . . . .	575	NA	1,150	Coal	3.70	NA	1981
Texas Municipal Power Agency: Gibbons Creek 1 (N) . . . . .	400	3	800	Lignite	1.06	NA	1982
Texas Power & Light:							
Sandow 4 (N) . . . . .	382	3	764	Lignite	1.60	75	1980
Twin Oaks 1 (N) . . . . .	750	NA	1,500	Lignite	0.70	NA	1984
Twin Oaks 2 (N) . . . . .	750	NA	1,500	Lignite	0.70	NA	1985
Texas Utilities: Martin Lake 4 (N) . . . . .	750	NA	1,500	Lignite	0.90	NA	1985
Utah Power & Light:							
Hunter 3 (N) . . . . .	400	NA	800	Coal	0.55	NA	1983
Hunter 4 (N) . . . . .	400	NA	800	Coal	0.55	NA	1985

<sup>a</sup>N = new. R = retrofit.<sup>b</sup>Estimated: stdft<sup>3</sup>/min = 2,000 × MW rating.

Note.—NA = data not available.

SOURCES: Smith, M., M. Melia, and N. Gregory, *EPA Utility FGD Survey: October-December 1979*, EPA 600/7-80-029a, NTIS No. Pb 80-176-811, Jan. 1980. Smith, M., et al., *EPA Utility FGD Survey: April-June 1980*, EPA 600/7-80-029c, July 1980.

## System Requirements

### Raw Materials and Utilities

Lime and limestone scrubbing systems have larger raw material requirements than do regenerable FGD processes, but, as a rule, for limestone systems the raw material cost is relatively low. Both lime and limestone FGD processes have low energy requirements compared with the regenerable processes.<sup>32</sup> These energy requirements include:

- Pumping energy to move the scrubbing slurry through the process equipment
- Electric power for flue gas booster blowers (forced- or induced-draft fans)
- Stack gas reheat (assumed to be indirect steam for this analysis)
- Electric power for auxiliary equipment, such as agitators, feed preparation equipment, and dewatering equipment

Table 6 shows system raw material and energy requirements of lime/limestone processes for three sizes of new coal-fired power plants, based on a recent TVA study.<sup>33</sup> Many

variables in system design and operating conditions affect these requirements, and must be considered before the information in Table 6 is applied to a specific installation. The table assumes that pebble lime is purchased in a form suitable for slaking; therefore, energy for calcining limestone to produce lime is not included in the lime system energy requirements. As plant size or coal sulfur content increase, however, the extra revenue requirements for lime with on-site calcination decrease. The break-even point for coal containing 3.5 percent sulfur is 1,150 MW. For coal containing 5 percent sulfur 750 MW is the break-even point for economically feasible on-site calcination.<sup>33</sup>

The large quantity of lime or limestone required for SO<sub>2</sub> removal and the associated disposal of the large volume of waste solids produced are major expense components for the process. Limestone systems usually require substantially more reagent than do lime systems because of limestone's lower reactivity.

**Table 6.**

Estimated Annual Raw Material and Utility Requirements for Lime/Limestone FGD Processes

Component	Boiler size (MW)		
	200	500	1,000
Lime scrubbing system:			
Raw materials: lime (1,000 tons) . . . . .	28.1	68.6	131.6
Utilities:			
Steam (10 <sup>9</sup> Btu) . . . . .	199.7	488.4	944.2
Process water (10 <sup>6</sup> gal) . . . . .	95.1	232.6	503.5
Electricity (10 <sup>6</sup> kWh) . . . . .	19.6	47.0	90.3
Limestone scrubbing system:			
Raw materials: limestone (1,000 tons) . . . . .	65.5	159.3	305.2
Utilities:			
Steam (10 <sup>9</sup> Btu) . . . . .	200.3	489.8	946.8
Process water (10 <sup>6</sup> gal) . . . . .	100.1	243.4	527.0
Electricity (10 <sup>6</sup> kWh) . . . . .	22.5	54.2	104.2

Note.—Midwest plant operating 7,000 h/yr. Stack gas reheat to 175° F. 3.5% sulfur coal. 79% SO<sub>2</sub> removal. Meets emission regulation of 1.2 lb SO<sub>2</sub> per 10<sup>6</sup> Btu. Pond disposal 1 mile from FGD facilities.

SOURCE: Anderson, K. D., J. W. Barrier, W. E. O'Brien, and S. V. Tomlinson, *Definitive SO<sub>x</sub> Control Process Evaluations: Limestone, Lime, and Magnesia FGD Processes*, EPA 600/7-80-001, NTIS No. Pb 80-196-314, Jan. 1980.



Lime systems usually operate at higher utilizations and, therefore, lose less reagent in the waste solids. The unreacted species in a fly-ash-free system represent 11 percent by weight of the lime solids and 15 percent by weight of the limestone solids. Limestone systems can be designed to obtain higher utilization by a number of procedures, and these techniques are the subject of continuing experimental work.<sup>13</sup>

Although lime utilization is higher than that of limestone, lime systems are usually more expensive to operate. Lower feed material requirements often are outweighed by the higher price of lime. But under conditions such as small plant size, low-sulfur coal, and low heat rates the lime process is more economical to operate than the limestone process. Slightly below the 200-MW power plant size, with 3.5-percent-sulfur coal, lime has lower annual revenue requirements. Lime also becomes more economical for a 500-MW power plant when coal contains less than 1.5 percent sulfur.<sup>33</sup>

The sum of the liquid-side energy requirement for pumps and the gas-side energy requirement for fans usually remains fairly uniform for most types of scrubbers. For example, fan power needed to overcome the high gas-side pressure drop in a packed-bed absorber (e.g., mobile bed absorber) is nearly twice the slurry pumping requirement. Scrubbers with an open configuration (e.g., spray towers) are characterized by lower gas-side pressure drops and higher liquid flow

rates, and therefore require less energy for fans and more energy for pumps.<sup>6</sup>

Pumping energy requirements for scrubbers are lower for lime systems than limestone systems. Operation at lower L/G ratios in lime systems reduces the slurry pumping requirement.

As a rule, pumping requirements are low for transporting waste solids from the scrubber area to the disposal area if on-site interim ponds are used for secondary dewatering. Systems with vacuum filters or centrifuges and those with more distant disposal sites require more energy.

### Installation Space and Land

Installation space and land requirements for lime/limestone FGD systems vary depending on site-specific factors: size of the plant, type of scrubber, number of effluent holding tanks, and type of solids-dewatering system. To compare lime and limestone systems, a typical installation for a new 500-MW boiler burning 3.5-percent-sulfur coal will be considered. Figures and dimensions have been adapted from a TVA study.<sup>3</sup>

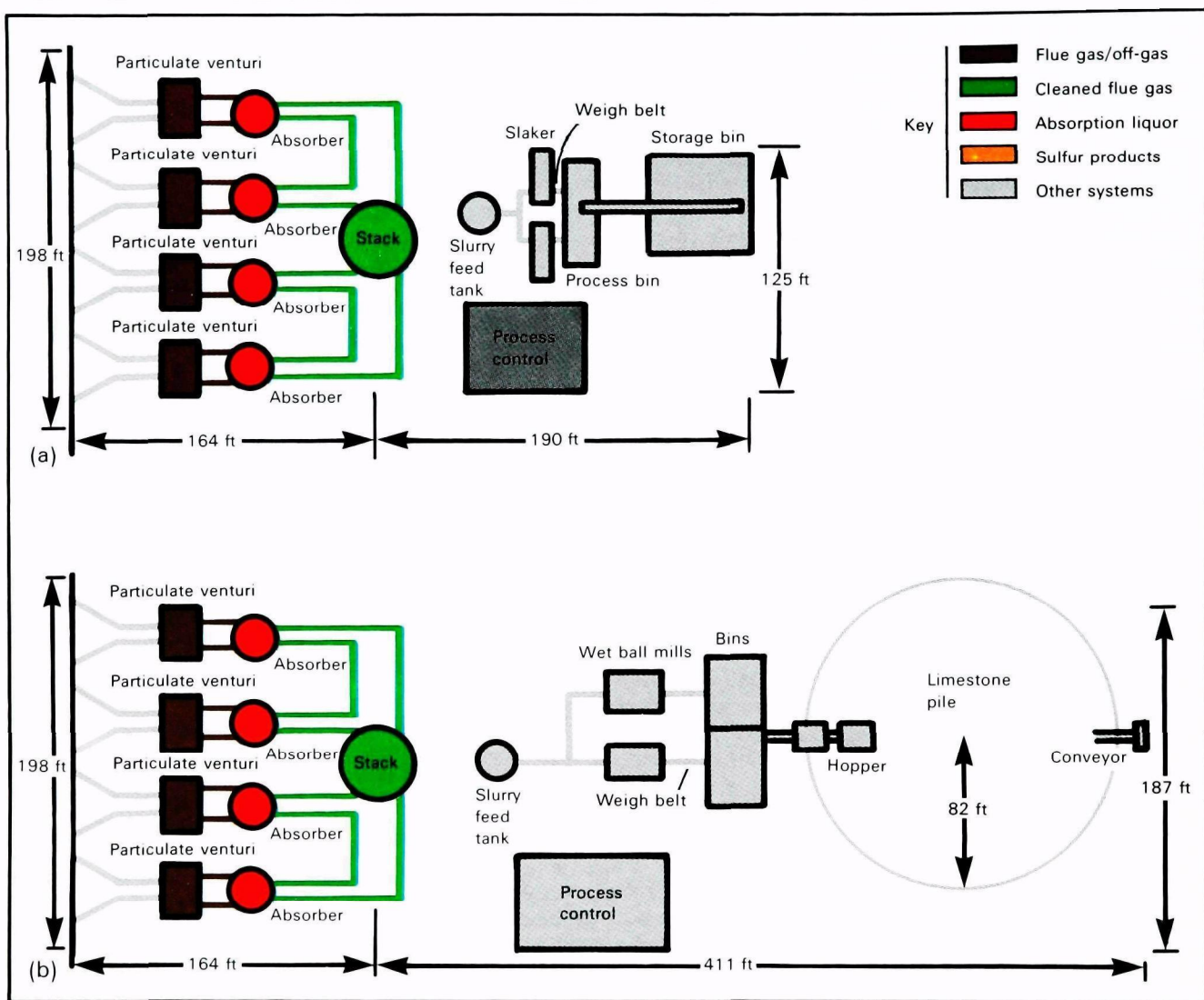
The same scrubbing system may be used with both FGD systems.

Figure 6a shows the total estimated land requirement for a 500-MW lime FGD system—1.04 acres (0.42 ha), of which the process control and storage area accounts for 0.54 acres (0.21 ha).

Figure 6b shows the total estimated land requirement for a typical limestone FGD system—2.5 acres (1.0 ha). Of this total, the storage and process control area accounts for 1.76 acres (0.71 ha).

Although the absorber systems for the two processes require the same area, the total area for the limestone system is twice that of lime. The difference results from the need to store limestone in greater quantities because of its lower utilization values in the absorber systems. An outside pile of pelletized limestone, approximately 165 ft (50 m) in diameter, is used along with a line of hoppers and conveyors (Figure 6b).

A large additional area is needed for waste solids disposal, on or off site. A lifetime pond (assuming a lifetime of 14.5 years or 127,500 operating hours) for a lime system would require an area of 188 acres (76 ha) with an initial depth of 40 ft (12 m). A limestone system would require a pond 40 ft deep (12 m) with an area of 206 acres (83 ha). Fly ash disposal in either scrubber system (or with no scrubber system) requires an additional pond area of 130 acres (53 ha).



**Figure 6.**

Land Requirements for FGD Systems (500-MW Boiler Size): (a) Lime and (b) Limestone

## Costs

Because full-scale lime/limestone scrubbing systems have been installed on a number of utility boilers, capital and operating costs can be calculated with reasonable accuracy for specific base cases. The estimated and actual costs of an FGD system can vary widely depending on the assumptions made, conditions of operation, options included, and degree of redundancy, among other factors. Cost estimates for lime and limestone FGD processes were prepared by TVA.<sup>3,33</sup>

Tables 7 and 8 present specific components of 1980 annual operating costs for a lime and a limestone FGD system, respectively. The

tabulations assume installation on a new 500-MW boiler burning 3.5-percent-sulfur coal, and providing 79 percent SO<sub>2</sub> removal. The annual operating costs for a lime system are about 6 percent higher than for a limestone system, primarily because of the higher raw material cost (0.823 mill/kWh for lime versus 0.319 mill/kWh for limestone). The raw material cost accounts for about 19 percent of the annual operating cost for a lime system and about 8 percent of that for a limestone system.

The requirement for 90 percent SO<sub>2</sub> removal, compared with the 79 percent removal assumed in Tables 7 and 8, has little effect on the annual

**Table 7.**

**Annual Operating Costs for a Lime FGD System on a New 500-MW Coal-Fired Boiler**

Component	Annual quantity	Costs		
		Unit (\$)	Annual operating (\$1,000)	Mills/kWh
Direct costs:				
Conversion costs:				
Operating labor and supervision.....	25,990 man-hours	12.50/man-hour	324.9	0.093
Utilities:				
Steam .....	488.4 × 10 <sup>9</sup> Btu	0.002/1,000 Btu	976.8	0.279
Process water.....	232.6 × 10 <sup>6</sup> gal	0.12/1,000 gal	27.9	0.008
Electricity .....	47.0 × 10 <sup>6</sup> kWh	0.029/kWh	1,363.2	0.389
Maintenance, labor and material .....			1,691.9	0.483
Analyses .....	3,760 man-hours	17.00/man-hour	63.9	0.018
Total conversion costs.....			4,448.6	1.270
Delivered raw materials: lime .....	68,600 tons	42.00/ton	2,881.2	0.823
Total direct costs .....			7,329.8	2.093
Indirect costs:				
Capital charges:				
Depreciation, interim replacements, and insurance at 6% of total depreciable investment .....			2,587.6	0.739
Average cost of capital and taxes at 8.6% of total capital investment . . .			3,897.4	1.113
Overhead:				
Plant, 50% of conversion costs less utilities.....			1,040.4	0.297
Administrative, 10% of operating labor.....			32.5	0.009
Total indirect costs .....			7,557.9	2.158
Total annual operating costs.....			14,887.7	4.251

Note.—Midwest plant, operating 7,000 h/yr. 1980 revenue requirements. 30-yr remaining plant life. 1.5 × 10<sup>6</sup> tons/yr coal burned, 9,000 Btu/kWh, 3.5% sulfur. Stack gas reheat to 175° F. Pond disposal 1 mile from plant. Investment and revenue requirement for fly ash removal and disposal excluded. Total direct investment, \$23,960,000; total depreciable investment, \$43,130,000; total capital investment, \$45,320,000.

SOURCE: Anderson, K. D., J. W. Barrier, W. E. O'Brien, and S. V. Tomlinson, *Definitive SO<sub>x</sub> Control Process Evaluations: Limestone, Lime, and Magnesia FGD Processes*, EPA 600/7-80-001, NTIS No. Pb 80-196-314, Jan. 1980.



**Table 8.****Annual Operating Costs for a Limestone FGD System on a New 500-MW Coal-Fired Boiler**

Component	Annual quantity	Costs		
		Unit (\$)	Annual operating (\$1,000)	Mills/kWh
Direct costs:				
Conversion costs:				
Operating labor and supervision.....	25,990 man-hours	12.50/man-hour	324.9	0.093
Utilities:				
Steam .....	489.8 × 10 <sup>9</sup> Btu	0.002/1,000 Btu	979.6	0.280
Process water.....	243.4 × 10 <sup>6</sup> gal	0.12/1,000 gal	29.2	0.008
Electricity .....	54.2 × 10 <sup>6</sup> kWh	0.029/kWh	1,571.5	0.449
Maintenance, labor and material .....			1,832.3	0.523
Analyses .....	3,760 man-hours	17.00/man-hour	63.9	0.018
Total conversion costs.....			4,801.4	1.371
Delivered raw materials: limestone .....	159,300 tons	7.00/ton	1,115.1	0.319
Total direct costs .....			5,916.5	1.690
Indirect costs:				
Capital charges:				
Depreciation, interim replacements, and insurance at 6% of total depreciable investment.....			2,813.9	0.804
Average cost of capital and taxes at 8.6% of total capital investment . . .			4,209.1	1.203
Overhead:				
Plant, 50% of conversion costs less utilities.....			1,110.6	0.317
Administrative, 10% of operating labor .....			32.5	0.009
Total indirect costs .....			8,166.1	2.333
Total annual operating costs.....			14,082.6	4.023

Note.—Midwest plant, operating 7,000 h/yr. 1980 revenue requirements. 30-yr remaining plant life.  $1.5 \times 10^6$  tons/yr coal burned, 9,000 Btu/kWh, 3.5% sulfur. Stack gas reheat to 175° F. Pond disposal 1 mile from plant. Investment and revenue requirement for fly ash removal and disposal excluded. Total direct investment, \$26,120,000; total depreciable investment, \$46,900,000; total capital investment, \$48,940,000.

SOURCE: Anderson, K. D., J. W. Barrier, W. E. O'Brien, and S. V. Tomlinson, *Definitive SO<sub>x</sub> Control Process Evaluations: Limestone, Lime, and Magnesia FGD Processes*, EPA 600/7-80-001, NTIS No. Pb 80-196-314, Jan. 1980.

operating costs for both processes. Limestone system annual operating costs are increased by 3 percent, while costs for the lime process, with its higher raw material cost, are increased by 5 percent.

Capital and annual operating costs for scrubbing systems vary depending on several site-specific factors such as application, fuel, plant life, and efficiency of SO<sub>2</sub> removal. Table 9 shows the effect of various combinations of these

parameters on the cost of lime and limestone FGD systems. Specific situations should be compared with the bases used to estimate the costs in Table 9. Some reevaluation will be required for each location.

Tables 7 through 9 assume absorber waste disposal in an earthen-diked, clay-lined pond 1 mile (1.6 km) from the FGD facilities. The waste settles to 40 percent solids, and the

supernatant is returned to the FGD system. If pond disposal of limestone slurry is not practical, fixation and landfill disposal can be used; however, this alternative would increase the annual operating costs by about 15 percent because of higher labor and materials costs.<sup>33</sup> Conventional limestone systems (not force-oxidized systems) produce more waste solids than do lime systems; therefore, the extra costs for fixation and landfill reduce the difference in annual operating costs.

**Table 9.****Estimated Capital and Operating Costs for Lime/Limestone FGD Processes**

System characteristics						Total capital investment <sup>a</sup>		Annual operating costs <sup>b</sup>	
Size (MW)	Application	Fuel		Plant life (yr)	% SO <sub>2</sub> removal <sup>c</sup>	\$10 <sup>6</sup>	\$/kW	\$10 <sup>6</sup>	Mills/kWh
		Type	% S						
Lime									
200	Existing	Coal	3.5	20	S	22.8	114	7.6	5.42
200	New	Coal	3.5	30	S	22.8	114	7.2	5.15
500	Existing	Coal	3.5	25	S	46.5	93	15.5	4.43
500	New	Coal	2.0	30	S	36.9	74	11.7	3.35
500	New	Coal	3.5	30	S	45.3	90	14.9	4.25
500	New	Coal	3.5	30	90	46.9	94		
500	New	Coal	5.0	30	S	50.3	101	17.4	4.96
500	Existing	Oil	2.5	25	R	35.8	72		
1,000	Existing	Coal	3.5	25	S	71.1	71	25.4	3.63
1,000	New	Coal	3.5	30	S	67.6	68	23.9	3.42
Limestone									
200	Existing	Coal	3.5	20	S	25.1	126	7.5	5.34
200	New	Coal	3.5	30	S	25.5	128	7.1	5.11
500	Existing	Coal	3.5	25	S	50.4	101	14.8	4.22
500	New	Coal	2.0	30	S	39.8	80	11.7	3.32
500	New	Coal	3.5	30	S	48.9	98	14.1	4.02
500	New	Coal	3.5	30	90	50.6	101	14.6	4.15
500	New	Coal	5.0	30	S	54.8	110	15.9	4.54
500	Existing	Oil	2.5	25	R	38.6	77	11.6	3.30
1,000	Existing	Coal	3.5	25	S	75.1	75	23.1	3.30
1,000	New	Coal	3.5	30	S	71.7	71	21.8	3.11

<sup>a</sup>Project beginning mid-1977, ending mid-1980. Average cost base for scaling, mid-1979. Minimum in-process storage; only pumps are spared. Pond disposal 1 mile from facility. FGD process investment estimate begins with common feed plenum downstream of electrostatic precipitator. No overtime pay.

<sup>b</sup>1980 revenue requirements. Power unit operating 7,000 h/yr.

<sup>c</sup>S = meets emission regulation of 1.2 lb SO<sub>2</sub> per 10<sup>6</sup> Btu. R = meets allowable emission of 0.8 lb SO<sub>2</sub> per 10<sup>6</sup> Btu.

Note.—Midwest plant. Stack gas reheat to 175° F. Investment and revenue requirement for fly ash removal excluded.

SOURCE: Anderson, K. D., J. W. Barrier, W. E. O'Brien, and S. V. Tomlinson, *Definitive SO<sub>x</sub> Control Process Evaluations: Limestone, Lime, and Magnesia FGD Processes*, EPA 600/7-80-001, NTIS No. Pb 80-196-314, Jan. 1980.

## References

- <sup>1</sup>Smith, M., M. Melia, and N. Gregory. *EPA Utility FGD Survey: April-June 1980*. EPA 600/7-80-029c. July 1980.
- <sup>2</sup>Ponder, T. C., Jr., et al. *Lime FGD Systems Data Book*. EPA 600/8-79-009, NTIS No. Pb 80-188-824. Apr. 1979.
- <sup>3</sup>McGlamery, G. G., R. L. Torstrick, W. J. Broadfoot, J. P. Simpson, L. J. Henson, S. V. Tomlinson, and J. F. Young. *Detailed Cost Estimates for Advanced Effluent Desulfurization Processes*. Final rep. EPA 600/2-75-006, NTIS No. Pb 242-541. Jan. 1975.
- <sup>4</sup>Merrill, Richard S., Radian Corporation, Austin TX, personal communication, July 1977.
- <sup>5</sup>Jones, Benjamin F., Philip S. Lowell, and Frank B. Meserole. *Experimental and Theoretical Studies of Solid Solution Formation in Lime and Limestone SO<sub>2</sub> Scrubbers*. Final rep. EPA 600/2-76-273a. Oct. 1976.
- <sup>6</sup>Ottmers, D. M., Jr., J. C. Dickerman, E. F. Aul, Jr., R. D. Delleney, G. D. Brown, G. C. Page, and D. O. Stuebner. *Evaluation of Regenerable Flue Gas Desulfurization Processes*. Rev. rep. 2 vols. EPRI RP 535-1. Austin TX, Radian Corporation, July 1976.
- <sup>7</sup>Barrier, J. W., H. L. Faucett, and L. J. Henson. *Economics of Disposal of Lime/Limestone Scrubbing Wastes: Untreated and Chemically Treated Wastes*. TVA Bull. Y-23, EPA 600/7-78-023a. Feb. 1978.
- <sup>8</sup>Bechtel Corporation, *EPA Alkali Scrubbing Test Facility: Advanced Program, Second Progress Report*. EPA 600/7-76-008. Sept. 1976.
- <sup>9</sup>Borgwardt, Robert H. "IERL-RTP Scrubber Studies Related to Forced Oxidation." In *Proceedings: Symposium on Flue Gas Desulfurization, New Orleans, March 1976*. Vol. I. EPA 600/2-76-136a, NTIS No. Pb 255-317. Pp. 117-144. May 1976.
- <sup>10</sup>Borgwardt, Robert H. "Effect of Forced Oxidation on Limestone/SO<sub>x</sub> Scrubber Performance." In *Proceedings: Symposium on Flue Gas Desulfurization, Hollywood, FL, November 1977*. Vol. I. EPA 600/7-78-058a. Pp. 205-228. Mar. 1978.
- <sup>11</sup>Hatfield, J. D., and J. M. Potts. "Removal of Sulfur Dioxide from Stack Gases by Scrubbing with Limestone Slurry: Use of Organic Acids." In *Proceedings: Second International Lime/Limestone Wet-Scrubbing Symposium*. Vol. I. APTD No. 1161. Pp. 263-283. Research Triangle Park NC, EPA, June 1972.
- <sup>12</sup>Rochelle, G. T., and C. J. King. "The Effect of Additives on Mass Transfer in CaCO<sub>3</sub> or CaO Slurry Scrubbing of SO<sub>2</sub> from Waste Gas." *Ind. Eng. Chem. Fund.*, 16:67-75, 1977.
- <sup>13</sup>Head, H. N., S. C. Wang, and R. T. Keen. "Results of Lime and Limestone Testing with Forced Oxidation at the EPA Alkali Scrubbing Test Facility." In *Proceedings: Symposium on Flue Gas Desulfurization, Hollywood, FL, November 1977*. Vol. I. EPA 600/7-78-058a. Pp. 170-204. Mar. 1978.
- <sup>14</sup>Borgwardt, Robert H., EPA, Research Triangle Park NC, personal communication, Jan. 1978.
- <sup>15</sup>Epstein, M. *EPA Alkali Scrubbing Test Facility: Summary of Testing Through October 1974*. EPA 650/2-75-047. June 1975.



- <sup>16</sup>Cronkright, Walter A., and William J. Leddy. "Improving Mass Transfer Characteristics of Limestone Slurries by Use of Magnesium Sulfate." *Env. Sci. Tech.*, 10(6):569-572, 1976.
- <sup>17</sup>Ottmers, D., Jr., J. Phillips, C. Burklin, W. Corbett, N. Phillips, and C. Shelton. *A Theoretical and Experimental Study of the Lime/Limestone Wet Scrubbing Process*. EPA 650/2-75-006. Dec. 1974.
- <sup>18</sup>Selmeczi, Joseph G., and Hameed A. Elmagher. "Properties and Stabilization of SO<sub>2</sub> Scrubbing Sludges." In *Coal Utilization Symposium—Focus on SO<sub>2</sub> Control, Louisville, KY, October 1974, Proceedings*. Monroeville PA, Bituminous Coal Research, 1974.
- <sup>19</sup>Lowell, Philip S. Removing Sulfur Dioxide from Gases. U.S. Patent No. 3,972,980. Aug. 1976.
- <sup>20</sup>Phillips, J. L., J. C. Terry, K. C. Wilde, G. P. Behrens, P. S. Lowell, J. L. Skloss, and K. W. Luke. *Development of a Mathematical Basis for Relating Sludge Properties to FGD-Scrubber Operating Variables*. EPA 600/7-78-072. Apr. 1978.
- <sup>21</sup>Gleason, Robert J. "Improved Flue Gas Desulfurization Process with Oxidation." In *Proceedings: The Second Pacific Chemical Engineering Congress (PACHEC '77)*. Vol. I. Pp. 371-377. New York NY, American Institute of Chemical Engineers, 1977.
- <sup>22</sup>Kruger, R. J. "Experience with Limestone Scrubbing Sherburne County Generating Plant, Northern States Power Company." In *Proceedings: Symposium on Flue Gas Desulfurization, Hollywood FL, November 1977*. Vol. I. EPA 600/7-78-058a. Pp. 292-319. Mar. 1978.
- <sup>23</sup>Stern, R. D., et al. *Interagency Flue Gas Desulfurization Evaluation*. Rev. draft rep. Vol. I. Austin TX, Radian Corporation, Nov. 1977.
- <sup>24</sup>Slack, A. V. "Lime-Limestone Scrubbing: Design Considerations." *CEP74*(2):71, 1978.
- <sup>25</sup>Princiotta, Frank T. *Sulfur Oxide Throw-away Sludge Evaluation Panel*. Vol. I. EPA 650/2-75-010a. 1975.
- <sup>26</sup>Leo, P. P., and J. Rossoff. *Control of Waste and Water Pollution from Power Plant Flue Gas Cleaning Systems: First Annual R and D Report*. EPA 600/7-76-018, NTIS No. Pb 259-211. Oct. 1976.
- <sup>27</sup>Ando, Jumpei. "Status of SO<sub>2</sub> and NO<sub>x</sub> Removal Systems in Japan." In *Proceedings: Symposium on Flue Gas Desulfurization, Hollywood, FL, November 1977*. Vol. I. EPA 600/7-78-058a. Pp. 59-79. Mar. 1978.
- <sup>28</sup>U.S. Environmental Protection Agency. *Proceedings: Symposium on Flue Gas Desulfurization, Las Vegas, NV, March 1979*. Vol. I. EPA 600/7-79-167a. July 1979.
- <sup>29</sup>U.S. Environmental Protection Agency. *Proceedings: Symposium on Flue Gas Desulfurization, Las Vegas, NV, March 1979*. Vol. II. EPA 600/7-79-167b. July 1979.
- <sup>30</sup>Fling, R. B., W. M. Groven, P. P. Leo, and J. Rossoff. *Disposal of Flue Gas Cleaning Wastes: EPA Shawnee Field Evaluation-Second Annual Report*. EPA 600/7-78-024. Feb. 1978.
- <sup>31</sup>Leo, P. P., R. B. Fling, and J. Rossoff. "Flue Gas Desulfurization Waste Disposal Study at the Shawnee Power Station." In *Proceedings: Symposium on Flue Gas Desulfurization, Hollywood, FL, November 1977*. Vol. II. EPA 600/7-78-058b. Pp. 496-536. Mar. 1978.
- <sup>32</sup>Ottmers, D. M., J. C. Dickerman, and D. H. Brown. "Raw Material and Utility Requirements for Flue Gas Desulfurization Processes." Paper presented at 84th National Meeting of American Institute of Chemical Engineers, Atlanta GA, Feb. 26-Mar. 1, 1978.
- <sup>33</sup>Anderson, K. D., J. W. Barrier, W. E. O'Brien, and S. V. Tomlinson. *Definitive SO<sub>x</sub> Control Process Evaluations: Limestone, Lime, and Magnesite FGD Processes*. EPA 600/7-80-001, NTIS No. Pb 80-196-314. Jan. 1980.

---

This summary report was prepared jointly by the Radian Corporation of Austin TX and the Centec Corporation of Reston VA. P. B. Hulman and J. M. Burke of Radian are the principal contributors. Michael A. Maxwell is the EPA Project Officer. Photographs were taken at Louisville Gas and Electric Company's Cane Run Power Plant.

Comments on or questions about this report or requests for information regarding EPA flue gas desulfurization programs should be addressed to:

Emissions/Effluent Technology Branch  
Utilities and Industrial Power Division  
IERL, USEPA (MD-61)  
Research Triangle Park NC 27711

This report has been reviewed by the Industrial Environmental Research Laboratory, U.S. Environmental Protection Agency, Research Triangle Park NC, and approved for publication. Approval does not signify that the contents necessarily reflect the views and policies of the U.S. Environmental Protection Agency, nor does mention of trade names or commercial products constitute endorsement or recommendation for use.

COVER PHOTOGRAPH: Reaction tank with additive feed tank in background