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Project Summary

Third Survey of Dry SO_2 Control Systems

Mary E. Kelly and S. A. Shareef

This report is the third in a series of reports on the status of dry flue gas desulfurization (FGD) processes in the United States. This updated assessment of dry FGD systems is based on a review of current and recently completed research, development, and commercial activities. Dry FGD systems covered include: (1) spray dryers with a fabric filter or an electrostatic precipitator (ESP), (2) dry injection of alkaline material into flue gas combined with particulate collection in an ESP or a fabric filter, and (3) combustion of coal/alkali fuel mixtures.

Spray drying continues to be the only commercially applied FGD process. Since the last survey was completed in the Fall of 1980, two new utility and two new industrial spray drying systems have been sold. All of these new systems use a lime sorbent and include a fabric filter for particulate collection. No new commercial systems have come on line since the last survey report, but the first utility system is scheduled to start up in the Spring of 1981.

A number of pilot-scale demonstration programs funded by vendors, utilities, and/or government agencies have been completed in the last few months and several similar programs are continuing currently. The Environmental Protection Agency is currently funding a spray drying demonstration program and a program for the development of a process for combustion of coal/limestone fuel pellets. In a program jointly funded by the EPA and the Department of Energy, the combustion of a pulverized coal/alkali fuel mixture in a low-NO_x burner is being investigated. The Department of Energy and a few vendors, as well as EPA, are continuing to investigate dry injection through pilot-scale demonstration programs. In addition, a substantial amount of work has begun in the area of dry FGD waste disposal. Waste disposal projects are being funded by the DOE, the Electric Power Research Institute (EPRI), and several vendors.

This Project Summary was developed by EPA's Industrial Environmental Research Laboratory, Research Triangle Park, NC, to announce key findings of the research project that is fully documented in a separate report of the same title (see Project Report ordering information at back).

Introduction

This report is the third in a series of reports on the status of dry flue gas desulfurization (FGD) processes in the United States for both utility and industrial applications. Throughout this report, dry FGD is defined as any process which involves contacting an SO_2-containing flue gas with an alkaline material and which results in a dry waste product for disposal. This definition includes (1) systems which use spray dryers for a contactor with subsequent baghouse or electrostatic precipitator (ESP) collection of waste products; (2) systems which involve dry injection of alkaline material into the flue gas with subsequent baghouse or ESP collection; and

(3) other varied dry systems which are concepts that primarily involve addition of alkaline material to a fuel prior to combustion. This definition of dry systems excludes several dry adsorption or "acceptance" processes, such as the Shell/UOP copper oxide process and the Bergbau-Forschung adsorptive char process. The status of these processes has been documented in previous EPA reports. Fluidized-bed combustion has also been excluded.

Also excluded was the regenerable Rockwell Aqueous Carbonate Process (ACP) which, although based on SO_2 removal with a spray dryer, does not fit the limitation of this study as being a "throwaway" system. However, the open loop, spray dryer contactor portion of the Rockwell process has been adapted for a "throwaway" system and, as such, has been included here.

The report is divided into four sections. The first section presents an introduction to the report and a general process description of each of the three types of dry scrubbing technology (spray drying, dry injection, and combustion of a coal/alkali fuel mixture). The second section contains an overview of the dry FGD systems and includes: (1) a discussion of the commercial and developmental activities for each type of process and (2) the highlights of the results of dry FGD test work completed recently.

Details of commercial, current, and recently completed research work, and demonstration programs are provided in the third section. The activities of each organization or vendor involved with dry FGD processes are discussed with respect to current and future research and development programs and commercial system sales.

The final section presents some of the findings of the research work in the area of dry FGD waste characterization and disposal. In addition, the scope of ongoing studies in this area and the current and planned disposal methods for commercial-sized dry FGD systems sold to date are presented.

Recent Developments

Spray drying continues to be the only commercially applied dry FGD technology. Since Fall 1980, two new industrial and two new utility systems have been sold, bringing the total number of commercial spray drying systems to 17: 11 utility and 6 industrial. (See Table 1 on pages 4, 5, 6, and 7.) At this time, only two commercial systems are operating and they are both applied to industrial boilers: at Celanese Fibers Co., in Cumberland, MD, and at Strathmore Paper, Inc., in Woronco, MA. No utility system is in commercial operation, although initial start-up procedures have begun at Otter Tail Power Co.'s Coyote Station in Beulah, ND.

Several spray drying demonstration programs have been completed or are nearing completion. It should be noted that none of these programs, which ranged in size from 1000 acfm to 120,000 acfm, were conducted on high sulfur coals. Two new demonstration programs are scheduled to begin soon. Northern States Power's Riverside Station is in start-up and the EPRI-sponsored spray drying demonstration program at Public Service of Colorado's Arapahoe Station is in the design and construction stage.

Dry injection development programs are continuing under DOE and EPRI funding, and Buell recently completed EPA-funded tests at the City of Colorado Springs' Martin Drake Station. Recently reported results have shown that a substantial degree of SO_2 removal (up to 90 percent) is achievable with nahcolite at stoichiometric ratios (moles Na_2O/mole inlet SO_2) of less than 2. But even with this improved performance, relative to earlier tests, the commercial application of dry injection has not occurred. Primary restrictions on the commercial development of this technology are sorbent cost and availability, relatively high stoichiometric requirements, and waste disposal concerns related to the undesirable solubility and leachability properties of the sodium-based waste solids.

Development of a process to reduce SO_2 and nitrogen oxides (NO_x) emissions through combustion of pulverized coal/alkali mixtures in a low-NO_x burner is continuing under a 5-year program jointly funded by the DOE and EPA. The primary emphasis of this program will be to assess the retrofit potential of the technology for existing boilers.

The EPA is also continuing to fund development of the coal/limestone pellets for control of SO_2 emissions from industrial stoker-fired boilers. However, a continuous 14-day test of the pellet, scheduled for November 1980, was cancelled due to inadequacies in the pellet production process.

Recent pilot-scale test work with both of the combustion technologies has shown that they are capable of achieving at least 50 percent SO_2 removal. Combustion of coal/alkali fuel mixtures offers a low cost alternative to scrubbing for industrial boilers, and interest in these technologies remains strong in the light of potential new source regulations for industrial boilers and the concern over acid rain. Much work remains, however, to fully characterize the impact of these technologies on boiler and particulate control system design and operation.

Current Status of Dry FGD Processes

Spray Drying

Eleven utility systems (totalling over 3200 MWe) and six industrial systems had been sold as of January 1981. Only two systems were fully operational at this writing: the Rockwell/Wheelabrator-Frye system at Celanese Fibers Company's Amcelle plant in Cumberland, MD, and the Mikropul system at Strathmore Paper, Inc. in Woronco, MA. The first utility system to become operational will likely be another Rockwell/Wheelabrator-Frye system, this one at the Coyote Station of Otter Tail Power Company. Initial start-up procedures at Coyote began in January 1981. Construction on several other utility systems, including Antelope Valley Unit 1 (Basin Electric Power Cooperative), Laramie River (also Basin Electric), and Colorado Ute Power Company's Craig Station, is reportedly on schedule.

The two new utility spray drying systems will both be applied to low-sulfur coal-fired boilers. Basin Electric has awarded Joy/Niro a contract for the utility's 430 MWe Antelope Valley Unit 2. The North Dakota lignite-fired boiler and lime-based spray dryer/fabric filter system will essentially be a duplicate of the Antelope Valley Unit 1 system. The second new utility system has been awarded to the Buell/Anhydro joint venture. The Marquette (MI) Board of Light and Power has purchased the system to treat flue gas from a 44 MWe coal-fired boiler located at Marquette's Shiras Municipal Power Plant. This system will also use a lime sorbent and include a fabric filter for collection of fly ash and waste solids. Both new utility system designs will have provisions for recycle of the waste solids.

A new industrial system was recently awarded to Joy/Niro by the Department of Energy's Argonne National Laboratories in Argonne, IL. Argonne is converting an existing boiler to fire a nominal 3.5 percent sulfur Illinois bituminous coal. This system will be the first commercial application of spray drying to a boiler firing coal with a sulfur content of greater than 3 percent. (However, the Mikropul system at Strathmore Paper, Inc. is scheduled to undergo compliance/performance testing in February 1981 while the boiler is firing a 3 percent sulfur coal.) Sulfur dioxide emissions from the Argonne unit are to be reduced by about 80 percent to meet an SO_2 emission limit of 1.2 lb/million Btu thermal input. Ecolaire Systems, Inc. has sold a lime-based spray dryer/fabric filter system to Container Corporation. The system will treat flue gas from a 170,000 lb steam/hr coal-fired boiler at Container Corporation's facility in Philadelphia, PA.

Contracts for at least two new industrial systems (one for a high sulfur coal-fired boiler) and one utility system are expected to be awarded soon. Also, at least five utilities have specified only dry FGD or are considering both dry and wet FGD for new units that will go on-line before the end of the decade.

Part of the reason for the increasing commercial application of dry FGD is the potential cost savings the technology offers when compared with conventional wet lime/limestone scrubbing. Results of a recent EPA-funded TVA conceptual cost study support this premise. The study compared the capital and annual costs of a lime spray dryer/fabric filter system with that of a wet limestone scrubbing system for a new 500 MWe power plant. Costs were developed for three fuels: low sulfur western coal, low sulfur eastern coal, and high sulfur eastern coal. The spray dryer designs were based on vendor information, while the limestone scrubbing design (which includes an ESP upstream of the scrubber) was based on information from the EPA Shawnee test facility and general industry information. Table 2 shows the results of the cost comparison. Lime spray drying is reported to be less expensive on a capital and annual cost basis for all three coals. The higher absorbent cost associated with the spray dryer process, particularly for the high sulfur coal case, is offset by the lower spray dryer equipment costs. Note that the spray drying operating costs are based on limited data and may change as more experience is gained with commercial utility systems.

Another EPA-funded conceptual economic study was performed to estimate the cost of retrofitting a spray drying system to a northeastern utility power station. The costs were assumed to be associated with conversion to low sulfur coal-firing from oil-firing. The cost estimates were based on vendor budgetary quotes. The total installed costs for the spray dryer/fabric filter system ranged from $89/kW to $118/kW for a generalized northeastern location.

Table 2. Comparison of Capital Costs and Annual Revenue Requirements for Wet and Dry FGD Systems for a New 500 MW Power Plant[a]

	Capital Cost ($/kW)	*Levelized Annual Revenue Requirements (mills/kWhr)*
Low Sulfur Western Coal		
Lime spray drying[b]	*144 to 152*	*8.7 to 9.1*
Limestone wet scrubbing[c]	*168 to 176*	*10.5 to 10.9*
Low Sulfur Eastern Coal		
Lime spray drying[b]	*144 to 152*	*8.4 to 8.7*
Limestone wet scrubbing[c]	*180 to 188*	*11.3 to 11.6*
High Sulfur Eastern Coal		
Lime spray drying[b]	*180 to 188*	*14.5 to 14.9*
Limestone wet scrubbing[c]	*236 to 234*	*16.4 to 16.7*

[a]*Source: Burnett, T.A., et al. Spray Dryer FGD: Technical Review and Economic Assessment. (Presented at EPA's Sixth FGD Symposium. Houston, TX. October 28-31.) Tennessee Valley Authority. Muscle Shoals, AL.*
[b]*Includes fabric filter.*
[c]*Includes ESP upstream of scrubber.*

Developments in spray dryer system design include increased use of off-product recycle and closer approaches to the adiabatic saturation temperature at the dryer outlet. Reslurrying and recycling of dry fly ash/product solids mixture has been shown to significantly increase SO_2 removal for a given stoichiometric ratio of fresh sorbent to inlet SO_2 and to reduce fresh sorbent consumption for a given SO_2 removal efficiency. However, recent tests have shown conflicting results with respect to the role of fly ash alkalinity in the improved system performance observed with recycle.

Recent tests have also shown that a 20°F approach to saturation at the dryer outlet appears to be the optimum control point in spray dryer system design. This approach has been shown to significantly increase SO_2 removal relative to a 30 or 40°F approach, while still allowing for an adequate margin of safety to protect the downstream control device from moisture condensation and also maintaining dry free-flowing product solids.

These and other, more subtle, refinements of spray drying technology have occurred partly as a result of several recent demonstration programs. A number of the programs are now complete, and it appears that future testing may be somewhat limited to high sulfur coal applications. However, at least five demonstration programs, of varying size and focus, will be conducted during 1981. Buell/Anhydro is continuing tests at the City of Colorado Springs' Martin Drake Station, and Joy/Niro has begun a 2- to 3-year large-scale demonstration program at Northern States Power Company's Riverside Station. Also, Combustion Engineering, Inc. recently started tests on a 100,000 acfm unit at the Gadsden Station of Alabama Power Company. DOE's Pittsburgh Energy Technology Center (PETC) will soon begin pilot-scale tests to evaluate the performance of a spray dryer/fabric filter system treating flue gas from a high-sulfur coal-fired test furnace. Finally, the Electric Power Research Institute (EPRI) has contracted with Stearns-Roger for demonstration tests at Public Service of Colorado's Arapahoe Station.

The demonstration programs also involve evaluation of sorbents other than lime. In an effort to evaluate the viability of less expensive limestone for the spray drying process, Buell/Anhydro has run tests using a pulverized limestone slurry with adipic acid addition. Adipic acid appears to benefit the reaction between $CaCO_3$ and SO_2, but the maximum SO_2 removal achieved on a straight-through basis was less than 40 percent at an inlet SO_2 concentration of 1000 ppm. Buell/Anhydro has also run tests with trona, which exhibited better SO_2 removal and sorbent utilization

Table 1. *Key Features of Commercial Spray Drying Systems Sold to Date*

System Purchaser/Vendor Utility	Location/Size	System Description	Coal	SO_2 Removal Guarantee
Otter Tail Power Co./ Rockwell/Wheelabrator-Frye	Coyote Station, Beulah, ND/ Unit 1, 410 MW (1,890,000 acfm)	Four parallel spray dryers, with 3 centrifugal atomizers each, followed by fabric filter with Dacron bags. Will initially use commercial soda ash. Sorbent utilization guarantee of 80%.	North Dakota lignite; 0.78% S average; 7050 Btu/lb; 7% ash.	70% for all fuels.
Basin Electric Power Coop/ Joy-Niro	Antelope Valley, Beulah, ND/ Unit 1, 430 MW (2,200,000 acfm)	Five parallel spray dryers (one spare), single rotary atomizer per dryer, followed by fabric filter with Teflon-coated fiberglass bags. Lime sorbent with partial recycle of solids. Ball mill slaker.	North Dakota lignite; 0.68% S average; 1.22% S maximum.	62% for average S coal; 78% for maximum S coal.
Basin Electric Power Coop/ Babcock & Wilcox	Laramie River, Wheatland, WY/Unit 3, 500 MW (2,810,000 acfm)	Four parallel reactors (one spare) with 12 fluid nozzles each. Each reactor followed by an ESP. Lime sorbent, no solids recycle.	Wyoming subbituminous, 0.54% S average; 0.81% S maximum; 8140 Btu/lb; 8% ash.	82% for average S coal; 90% for maximum S coal.
Basin Electric Power Coop/ Joy-Niro	Antelope Valley, Beulah, ND/Unit 2, 430 MW (2,200,000 afcm)	Design identical to Antelope Valley Unit 1 (see above).	North Dakota lignite; 0.68% S average; 1.22% S maximum.	62% for average S coal; 78% for maximum S coal.
Marquette Board of Light and Power/Buell-Anhydro	Shiras Municipal Power Plant, Marquette, MI/ 44 MW (226,000 acfm)	Single spray dryer with rotary atomizer. Reverse-air fabric filter. Lime sorbent. Solids recycle.	1.5% S western subbituminous 15% ash. 7700 Btu/lb.	80% design efficiency.
Tucson Electric/ Joy-Niro (2)	Springerville Station/ Units 1 and 2; 350 MW each	Spray dryer/fabric filter design. Lime sorbent. Rotary atomization.	New Mexico coal; 0.69% S.	61%.
United Power Association/ Research-Cottrell	Stanton Station, Stanton, ND/65 MW	Spray dryer/fabric filter rotary atomizers, possibly multiple atomizers per dryer. Lime sorbent.	Low and intermediate sulfur subbituminous Montana coal.	Not available.
Platte River Power Authority/ Joy-Niro	Rawhide Station/Unit 1 250 MW	Spray dryer/fabric filter design. Rotary atomizers. Lime Sorbent.	Western subbituminous coal; 1.3% S.	80%.
Colorado-Ute Association/ Babcock & Wilcox	Craig Station/Unit 3 450 MW	Horizontal spray dryers with nozzle atomizers, followed by fabric filter. Solids recycle. Ball mill slaker for lime sorbent.	0.70% S, 8950 Btu/lb, 14% ash design coal; 0.40% S, 10250 Btu/lb.	87% for design coal.
Sunflower Electric Coop/ Joy-Niro	Holcombe Station/Unit 1 310 MW	Spray dryer/fabric filter. Rotary atomization. Lime sorbent.	Western subbituminous coal.	80%.
Industrial				
Celanese Fibers Co./ Rockwell/Wheelabrator-Frye	Amcelle plant, Cumberland, MD/65,000 acfm (110,000 lb steam/hr)	Spray dryer with single rotary atomizer followed by fabric filter with felt/ fiberglass bags. Paste slaker for lime sorbent. No solids recycle.	1.5% S and 2 to 2.5% S eastern coals.	70% for 1.5% S coal, 87% for 2.0% S coal.
Strathmore Paper Co./ Mikropul, Inc.	Woronco, MA/ 40,000 acfm (85,000 lb steam/hr)	Spray dryer with four two-fluid nozzles, followed by fabric filter with specially finished acrylic bags.	2.3 to 3% S eastern coal.	75%.
University of Minnesota/ Kennecott Development Co. (Environmental Products Division)	Univ of Minnesota/2 units at 120,000 acfm each	Two spray dryers-one with single, other with multiple rotary atomizers-followed by fabric filter with fiberglass bags. Lime sorbent.	Subbituminous coal; 0.6 to 0.7% S.	70%.

Reported Capital Cost	Reported Operating Cost	Status
$32,000,000 ($78/kW)[a].	*$6,580,000 ($2.5 mills/kWh)[a]. Does not include waste disposal.*	*Start-up scheduled for mid-1981.*
$49,665,100 ($113/kW)[b].	*$2,270,834/yr ($0.8 mills/kWh)[b]. Lime cost - $1,102,500 ($60/ton). Does not include waste disposal.*	*Start-up scheduled for April 1982.*
$49,807,000 (83/dW)[b].	*$2,571,000/yr ($0.7 mills/kWh)[b]. Lime cost - $1,396,570 ($60/ton). Does not include waste disposal costs.*	*Start-up scheduled for Spring 1982.*
$54,000,000[c]. ($126/kW)	*Same as Antelope Valley Unit 1 (see above).*	*Start-up scheduled for 1985.*
Not available.	*Not available.*	*Start-up scheduled for Fall 1982.*
Not available.	*Not available.*	*Unit 1 scheduled to start up in late 1984; Unit 2 in 1986.*
$5,000,000 ($77/kW).	*Not available.*	*Start-up scheduled for 1981.*
Not available.	*Not available.*	*Start-up scheduled for 1983.*
($100/kW)	*Not available.*	*Initial operation in November 1982. Commercial operation in April 1983.*
Not available.	*Not available.*	*Start-up scheduled for 1983.*
$1,250,000[d].	*Not available.*	*Operational. Passed Maryland state compliance tests in February 1980. Has achieved guaranteed removal.*
$1,400,000[d,e].	*$600/day.*	*Operational. Now achieving removal guarantee.*
$3,300,000[d,g].	*Not available.*	*Commercial operation in Fall 1981.*

than lime. However, the soluble nature of the waste products and the cost and/or availability of trona may restrict the use of this sorbent in commercial systems.

The current focus of on-going and planned demonstration programs appears to be toward higher inlet SO_2 concentrations and obtaining a better definition of spray dryer performance limits. And, of course, many of the programs will evaluate more subtle refinements to the technology such as lime quality, slaking technique, and recycle methods. Another area of emphasis will likely be development of more sophisticated process control techniques to improve system reliability and reduce sorbent-related operating costs.

Table 3 shows the status of eight major spray drying demonstration programs. Results from three of these programs, Buell/Anhydro at Martin Drake, Research-Cottrell at Comanche, and Babcock & Wilcox at Jim Bridger, were presented at the recent EPA-sponsored FGD Symposium. Also, Flakt, Inc. has recently published some results of its Jim Bridger tests. Many of these results are presented in detail in the full report.

Dry Injection

Presently, there are no plans for the construction of any commercial dry injection systems. However, several demonstration programs are being conducted. Demonstration-scale dry injection systems have been or are being operated through funding by the Department of Energy (DOE), the Environmental Protection Agency (EPA), and the Electrical Power Research Institute (EPRI). The current status of several demonstration programs is presented in Table 4.

Investigations with a number of sorbents have shown that only sodium-based sorbents, such as sodium bicarbonate, nahcolite, and trona ores, provide satisfactory SO_2 removal. However, nahcolite appears to be the most reactive sorbent. Removal efficiencies of up to 90 percent have been reported with a nahcolite sorbent. Many important variables influence SO_2 removal during dry injection. These include: stoichiometric ratio, injection temperature, sorbent pretreatment, sorbent particle size, and the mode of injection.

Buell, a division of Envirotech Corpo-

Table 1. Key Features of Commercial Spray Drying Systems Sold to Date

System Purchaser/Vendor Utility	Location/Size	System Description	Coal	SO_2 Removal Guarantee
Calgon/Niro-Joy	57,000 acfm	Spray dryer/fabric filter. Rotary atomizer. Soda ash sorbent. Removing SO_2 and HCl from 1700°F gases. Solids recycle.	1 to 2% S coal, 6000-8000 ppm SO_2, 8000 ppm halides.	75% SO_2; 90% HCl.
Argonne National Labs/ Niro-Joy	Argonne, IL/ 170,000 lb steam/hr	Single spray dryer with rotary atomizer followed by pulse-jet fabric filter. Lime sorbent, solids recycle.	3.5% S Illinois bituminous coal.	78.8% SO_2 removal (1.2 lb/10^6 Btu).
Container Corporation/ Ecolaire Systems	Philadelphia, PA/ 170,000 lb steam/hr	Spray dryer with single rotary atomizer followed by pulse-jet fabric filter. Lime sorbent, solids recycle.	1% S coal.	Not available.

[a]Capital cost for turnkey installation from air preheater outlet to stock connection, excluding I.D. fans (1977$). Source: Johnson, O.B. et al. "Coyote Station, First Commercial Dry FGD System." (Presented at 41st Annual American Power Conference, Chicago, IL. April 23-25, 1979.)
[b]Based on 35-year plant life, 75% capacity factor (1981$). Source: Janssen, K.E. and R.L. Eriksen. "Basin Electric's Involvement with Dry Flue Gas Desulfurization." In Proceedings; Symposium on Flue Gas Desulfurization - Las Vegas, NV, March 1979; Volume II. EPA- 600/7-79-167b (NTIS PB 80-133176). July 1979. pp 629-653.
[c](1980$)
[d]Stern, J.L. "Dry Scrubbing for Industrial Flue Gas Desulfurization: State-of-the Art, 1980." (Presented at the 89th National Meeting of AIChE. Portland, OR. August 17-20, 1980.)
[e]From "ground-up." (1979$)
[f]Kelly, M.E. and S.A. Shareef. Meeting notes at Babcock & Wilcox. Barberton, OH. June 1980.
[g]"Straight-through system." (1980$)

Table 3. Major Spray Drying Demonstration Activities[a,b]

Vendor/Agency	Location	Size	Comments
Babcock & Wilcox[c]	Pacific Power & Light's Jim Bridger Station	120,000 acfm	Testing completed.
Buell/Anhydro[c]	Colorado Springs-Martin Drake Station	20,000 afcm	EPA-funded testing still in progress. Bulk of program has been completed.
Flakt, Inc.	Pacific Power & Light's Jim Bridger Station	15,000 acfm	Testing completed.
Combustion Engineering	Alabama Power's Gadsden Station	100,000 acfm	Testing has begun and is expected to run for remainder of 1981.
Ecolaire Systems, Inc.	Nebraska Power's Gerald Gentleman Station	10,000 acfm mobile pilot plant	Testing near completion.
Research-Cottrell[c] (Cottrell Environmental Sciences)	Public Service of Colorado's Comanche Station	10,000 acfm	Testing completed in January 1981.
Electric Power Research Industry (EPRI) (Stearns-Roger will conduct the tests)	Public Service of Colorado's Arapahoe Station	2.5 MWe equivalent of flue gas	System in design and construction phase. (Spray dryer and associated equipment will be supplied by Stork-Bowen.)
Joy-Niro	Northern States Power's Riverside Station	680,000 acfm	In start-up.

[a]More information on each of these programs can be found in Section 3 of full report.
[b]Several other smaller demonstration tests are also being conducted by private firms, and the Department of Energy's Pittsburgh Energy Technology Center will begin tests soon on a 2500 acfm unit.
[c]Results presented in FGD Symposium - related papers.

Reported Capital Cost	Reported Operating Cost	Status
$1,600,000[c,d].	*Not available.*	*Under construction.*
Not available.	*Not available.*	*Start-up scheduled for Winter of 1981-82.*
Not available.	*Not available.*	*Construction scheduled for April 1981, start-up in October 1981.*

ration, recently completed EPA-funded dry injection testing at the City of Colorado Springs' Martin Drake Station. The tests were begun in late October 1979 and completed in May 1980. Experiments with three sorbents, nahcolite, raw trona, and refined trona, were conducted on the 4500 acfm dry injection baghouse system. The sorbents were ground to less than 74 μm in diameter before being injected into the duct leading to the fabric filter. These tests were performed in an attempt to characterize the effects of sorbent type, stoichiometric ratio, temperature, and air-to-cloth ratio on SO_2 removal.

The results of these parametric tests showed that nahcolite provided the best SO_2 removal, followed by refined trona. Raw trona exhibited the weakest SO_2 removal capability. It was also found that an increase in the stoichiometric ratio caused SO_2 removal to increase. However, removal began to level off at stoichiometric ratios between 1.5 and 1.75 for these sodium sorbents. The effects of changes in temperature were also characterized. It was found that SO_2 removal decreased with increasing temperature for both nahcolite and refined trona. However, removal with raw trona increased with increasing temperature. Results of tests characterizing the effect of air-to-cloth ratio have shown that variation of the air-to-cloth ratio from 1.5 to 3.0 ft/min had no noticeable effect on SO_2 removal.

The DOE has conducted research on dry injection systems at both the Grand Forks Energy Technology Center (GFETC) and Pittsburgh Energy Technology Center (PETC). These tests were performed to characterize several process parameters, such as sorbent type, inlet SO_2 concentration, inlet gas temperature, bag materials, and air-to-cloth ratios.

Work conducted at GFETC with a 200-scfm dry injection system has shown that up to 90 percent utilization (based on NO_x and SO_2) has been obtained with trona and nahcolite sorbents. Low sulfur western coals were used in these tests, which resulted in inlet SO_2 concentrations of 650 to 1100 ppm. The results reported here are preliminary; a final report on these tests has not been published.

GFETC has just completed the installation of a new 130-scfm pulse jet baghouse. This baghouse will be used exclusively for dry injection studies (the present baghouse was also used for particulate characterization studies). Parametric tests with both nahcolite and trona will be conducted.

Dry injection work at the Pittsburgh Energy Technology Center (PETC) was completed in the Fall of 1980. A final report on the dry injection studies, which evaluated the performance of nahcolite, trona, and commercial sodium bicarbonate, is in preparation. The average baghouse temperature for the dry injection tests was 400°F. The fabric filter was equipped with Nomex bags and was operated at an air-to-cloth ratio of 4 ft/min. In general, the tests indicated that nahcolite showed the greatest SO_2 removal capability of the three sorbents evaluated.

In tests conducted with 1.1, 1.6, and 3.5 percent sulfur coals, dry injection of nahcolite resulted in SO_2 removals of up to 95 percent with a stoichiometric ratio of 1.5 moles Na_2O per mole of inlet sulfur. The tests also indicated that SO_2 removal decreased as inlet SO_2 concentration increased. However, 90 percent SO_2 removal was reportedly achieved with a stoichiometric ratio of 1.5, even when 3.5 percent sulfur coal was burned.

EPRI's Air Quality Control Program involves research on the technical aspects of a dry injection/baghouse system. Detailed laboratory scale tests have been completed. The results of these tests were summarized in the Second Survey of Dry SO_2 Control Systems. EPRI has been conducting large-scale dry injection tests at the Public Service of Colorado's Cameo Station since the Fall of 1980. These tests are being performed by KVB, Inc. on the 22 MWe Unit 1 boiler at Cameo using the existing fabric filter. Although no results are currently available for

Table 4. *Current Dry Injection Programs*

Vendor	*Location*	*Size*	*Comments*
EPA/Buell-Envirotech	*Colorado Springs - Martin Drake Station*	*4500 acfm*	*Testing completed in May 1980. EPA funded.*
DOE/Grand Forks Energy Technology Center	*GFETC Labs*	*200 acfm*	*Testing completed. Report is being prepared.*
DOE/Pittsburgh Energy Technology Center	*PETC Labs*	*500 lb coal/hr furnace*	*Testing completed. Report is being prepared.*
EPRI/KVB	*Public Service Company of Colorado - Cameo Station*	*20 MWe*	*Testing in progress. Report on initial testing is expected in June 1981.*

publication, the first phase testing with nahcolite has been completed and a final report is scheduled for June. Further testing will continue through the end of 1981.

Combustion of Coal/Alkali Fuel Mixtures

Currently, two processes are being developed, based on the combustion of coal/alkali fuel mixtures to control SO_2 emissions: combustion of coal/limestone pellets in an industrial stoker-fired boiler, and combustion of a pulverized coal/alkali fuel mixture in a low-NO_x burner.

Recent large-scale tests with a 3.5:1 calcium-to-sulfur molar ratio coal/limestone pellet demonstrated that 50 percent SO_2 removal was achievable with this technology. Although earlier laboratory tests had indicated that SO_2 removals of up to 75 percent were possible, the higher, less controllable bed temperatures in the full-size industrial test unit (60,000 lb steam/hr) resulted in lower removal efficiencies. Inadequacies in the pellet production process have hampered development and progress in recent months, but EPA hopes to resolve these problems in the near future. Meanwhile, Battelle-Columbus Laboratories is continuing to test the properties and SO_2 removal capabilities of the pellets on a smaller scale (25,000 lb steam/hr boiler).

The DOE and EPA have proposed a jointly funded 5-year development program to further investigate the concept of firing a coal/alkali fuel mixture in a low-NO_x burner. SO_2 removals of 50 percent and greater have been demonstrated in small-scale tests.

Reasons for the accelerated development of both these technologies include the potential cost savings offered by reduced equipment requirements relative to conventional wet FGD and the retrofit potential of the technology for existing boilers.

Dry FGD Waste Disposal

The collective experience of U.S. utilities and industries in operating wet scrubbers and disposing of scrubber waste (sludge, fly ash) has been studied and documented fairly extensively. Studies have been aimed at (1) developing a data base on sludge and ash handling procedures, (2) providing independent evaluations of the sludge fixation processes, (3) quantifying variables affecting the solubility of trace elements and potentially toxic species from solid waste by-products, and (4) establishing guidelines for the construction of sludge disposal facilities.

Similar efforts directed at characterization, disposal, and utilization of waste from dry SO_2 control systems are only now getting underway. As more commercial dry FGD systems begin to operate, these efforts can be expected to gain momentum, and a broader data base should begin to emerge. The results of some of the studies are summarized below:

(1) Chemico, a division of Envirotech Corporation, has conducted studies to determine various physical and chemical properties of the dry waste solids mixed with varying amounts of water. A mixture of 80 percent solids and 20 percent water displayed the most desirable properties in terms of disposal requirements. The unconfined compressive strength of the mixture was found to be about 12,000 lb/ft^2, and the permeability was less than 10^{-5} cm/sec. These values are similar to those for conventional fly-ash-stabilized FGD sludges. The leachability of heavy metallic compounds, as determined in laboratory tests, was found to be well within the limits set by EPA as guidelines for definition of a hazardous waste.

(2) Battelle-Columbus Laboratories, under a contract to Buell's Emission Control Division, has conducted a technical and economic feasibility study of the Sinterna* process for disposal of dry FGD wastes. Laboratory-scale studies were conducted on the powdered solid waste that was generated during nahcolite dry injection tests conducted by Buell at Colorado Springs' Martin Drake Station.

Sodium-based wastes present a disposal problem because of their high leaching potential. Untreated sodium-based dry FGD wastes are not considered suitable for disposal by conventional landfill methods. The Sinterna process produces stabilized pellets from the untreated wastes. These pellets are considered suitable for landfill disposal because of reduced leaching potential.

Laboratory tests showed that the sulfate leaching could be reduced from the 60 percent typical of a dried unsintered pellet to about 20 percent after sintering. The amount of leaching is measured by placing the pellets in a continuously stirred beaker of water and sampling the water at predetermined intervals, with the analysis at 100 hours used as the standard for comparing sintered and unsintered pellets. Using this method, it was observed that pellets (dried at 105°C) showed 60 percent sulfate leachability after 100 hours, while the comparable figure for pellets sintered at 1000°C was about 20 percent, and about 30 percent of the sulfur was converted to SO_2. Reducing the sintering temperature to 925°C reduced the conversion of sulfur to SO_2 to about 10 percent, while 65 percent of the sulfate was found to have leached out of the pellet (at 100 hours). A sintering temperature of 1000°C was found to provide the best balance between reduced sulfate leaching and conversion of sulfur to SO_2.

Although the Sinterna process appears to be technically feasible, and the sintered pellets have properties more suitable for landfill than untreated waste or dried pellets, it does not appear to be economically feasible. The estimated annualized cost (including capital charges for pelletizing, drying, and sintering equipment) is $100/ton of dry waste. The capital cost of the process for a conceptual 500 MWe plant (producing about 20 tons/hour of nahcolite-based dry injection wastes) was estimated to be about $20 million.

(3) Research-Cottrell has evaluated the characteristics of the spray dryer waste generated at Public Service Company of Colorado's Comanche Station. The Comanche fly ash is highly cementitious and has a high reactive CaO content. Results of the preliminary tests indicate that the dry wastes (from tests with lime) are similar to wet FGD sludge/fly ash mixtures. Initial permeabilities of the laboratory samples were in the 10^{-5} cm/sec range, but after 28 days of curing at ambient conditions, permeability dropped to the 10^{-7} cm/sec range.

(4) Niro Atomizer, Inc. has also conducted research on disposal of wastes from dry FGD systems. The properties of dry wastes have been investigated and alternatives for disposal, depending on the properties of the specific waste material, have been developed. The composition of the wastes was found to vary with coal composition and process conditions in the scrubber. For low sulfur western coals, fly ash dominates the waste material and its characteristics are, therefore, very important.

*The Patent for the Sinterna process is held by Industrial Resources, Inc.

Fly ash from western coals has pozzolanic properties. (A pozzolan is a material containing silicon or aluminum and silicon compounds. Alone it has no hardening qualities, but exposed to water at normal temperatures it reacts with calcium hydroxide to form a cement-like material.)

The critical parameters for a landfill material are density, compressive strength, permeability, and the composition of the leachate and run-off generated. Niro claims that 80 to 90 percent of the laboratory-measured dry density and compressive strength can be obtained in a landfill. High density is desirable in that it permits more material to be disposed of in a given amount of land. Compressive strength is important in that the landfill must support its own weight, sometimes in a thickness of 50 to 100 ft, and should allow trucks and earth-moving equipment to move on its surface without getting stuck. Low permeability reduces the risk that rain water will leach through the landfill and contaminate the groundwater underneath with soluble salts.

Niro has found that the addition of sufficient water to lubricate the grains of dry material will allow a greater final density for the same amount of compactive effort. Once the material is wetted and compacted into the landfill, it undergoes several chemical reactions that bind the individual particles together and fill the remaining void space with impermeable reaction products. The first reactions to take place are hydrations. The fly ash contains considerable calcium oxide which combines rapidly (in a few minutes) with water to form calcium hydroxide. Calcium sulfate hemihydrate combines with water somewhat more slowly to form the dihydrate. Much slower reactions form calcium-silicon-aluminates and sulfoaluminates over a period of days and months. Much of the ultimate strength of the cured product comes from these compounds.

The compressive strength of the landfilled material, as reported by Niro, is normally 100 to 150 psi, permeability is 10^{-6} cm/sec or less, and density is 100 lb/ft^3. (A permeability of 10^{-6} cm/sec equals 1 ft/year and a density of 100 lb/ft^3 is a normal value for compacted soil.)

Niro concludes that the outcome of landfill disposal is a block of solidified waste 50 to 100 ft deep. It is essentially inert and impermeable, may be covered with soil and revegetated, is strong enough to support light construction, and may be excavated or drilled like soft rock or hard soil.

An alternative method of dry FGD waste disposal, that may have less impact on the environment and could result in lower disposal costs, is also being developed by Niro, Inc. If the powder is exposed to a higher degree of compression at lower water content, it is possible to form pellets of high strength suitable for commercial uses. The "synthetic gravel" is produced by adding 10 to 20 percent water to dry FGD waste and compressing it to between 2.5 and 3.0 times its loose density. This is reported to result in a cured density of about 120 lb/ft^3 and a compressive strength of over 10,000 psi.

The gravel reaches 50 percent of its strength in 2 days and 90 percent in 10 days. The pellets are reportedly not affected by water, ordinary heat, freeze, thaw, or mechanical handling. Cold weather as well as excessive dryness does slow the curing process. However, the return of heat or moisture is reported to permit curing to continue. Therefore, Niro claims that the gravel may be silo cured a few days before use or may be stock-piled outdoors for years.

Niro has estimated the capital cost of a dry FGD waste disposal system to be about $9/kW and the operating cost to be about 0.8 mills/kWh. These estimates compare favorably with TVA's estimate for wet FGD (lime/limestone) waste disposal costs of about $17/kW for capital cost and 1.08 mills/kWh for operating cost. According to Niro, the difference in the costs is primarily due to the elimination of the thickening and filtration modules for a dry system.

Scope of On-going Waste Disposal Studies

In addition to the EPA-sponsored study being conducted by Cottrell Environmental Services, Inc., two other major studies aimed at characterizing dry FGD wastes are currently underway. The scope of these studies is briefly described below.

(1) EPRI has recently begun a study to characterize the physical and chemical properties of solid waste from spray drying and dry injection system. A total of 30 solid samples will be used to identify those parameters which impact the handling and disposal of dry FGD wastes. The parameters will also provide comparative data concerning the effects of system design and coal type on the physical and chemical make-up of the solids.

(2) DOE's Grand Forks Energy Technology Center (GFETC) is characterizing the chemical and physical properties of waste material produced by the combustion of low-rank coals. This will include waste from dry FGD systems as well as wet systems and coal fly ash. The waste material will be characterized chemically and physically through the following analyses:

- Collection of the waste materials.
- Fixation of FGD sludges.
- Chemical and physical analysis of all the waste materials, including FGD sludges before and after fixation.
- Extraction and column leaching of the various waste materials.
- Evaluation of current disposal techniques and future disposal requirements.
- Assessment of the GFETC column leaching program results.

Current and Planned Disposal Methods for Commercial Units

The studies performed by most dry FGD system vendors to date have not shown any special treatment requirements for disposal of dry FGD wastes. Consequently, the current and planned disposal methods for dry FGD commercial systems are not much different from the established disposal methods for wet FGD systems. At present there are only two commercial dry FGD systems in operation. Wastes from both the Strathmore Paper Company system at Woronco, MA, and the Celanese Fibers Company System at Cumberland, MD are being trucked to landfills.

Tentative waste disposal plans by utilities with contracts for commercial systems range from dry landfill to ponding of wetted solids. Eight of the 10 utilities report the following disposal plans:

Natural clay-lined landfill (1).
PVC-lined landfill (1).
Wetted transport to landfill (2).
Landfill with fixation (1).
Clay-lined ponding of wetted solids (1).
Unspecified landfills (2).

Mary E. Kelly and S. A. Shareef are with Radian Corporation, 3024 Pickett Road, Durham, NC 27705.
***Theodore G. Brna** is the EPA Project Officer (see below).*
The complete report, entitled "Third Survey of Dry SO_2 Control Systems," (Order No. PB 81-218 976; Cost: $11.00, subject to change) will be available only from:
National Technical Information Service
5285 Port Royal Road
Springfield, VA 22161
Telephone: 703-487-4650
The EPA Project Officer can be contacted at:
Industrial Environmental Research Laboratory
U.S. Environmental Protection Agency
Research Triangle Park, NC 27711

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