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Technology Transfer

Capsule Report

Bahco Flue Gas Desulfurization and Particulate Removal System

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July 1979

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

Scrubber circulating pump and piping

1. Introduction and Summary

This capsule report has been prepared as an aid in solving one of today's vitally important technological concerns the selection and use of fuel for industrial-size steam generating units and other fuel-burning equipment. Reduced availability of natural gas supplies, increased cost of low sulfur oil, and pollution problems generally associated with coal currently present operators of boiler installations with a question: What is the best technique for compliance with particulate and sulfur dioxide regulations? The flue gas desulfurization (FGD) technology described herein permits any fuel, including high sulfur oil or coal, to be burned in conventional equipment in a manner that is both cost effective and environmentally acceptable.

In September 1974, the U.S. Air Force (USAF) awarded a contract to Research-Cottrell (R-C) to erect an SO_2 and particulate emission control system at the central heat plant of Rickenbacker Air Force Base (RAFB) near Columbus, Ohio. The equipment chosen was an R-C/Bahco scrubber (module size 50) based on technology developed by A B Bahco in Sweden. This unit accomplishes both SO_2 and particulate removal

The R-C/Bahco system has been used on many foreign oil-fired industrial boilers since 1969. The installation at the Rickenbacker facility is the first application of the system on a coal-fired industrial boiler.

A second contract, sponsored by the U.S. Environmental Protection Agency (EPA), was awarded to Research-Cottrell in April 1975. The key provision of this program was to characterize the R-C/Bahco scrubbing system installed at RAFB in terms of its performance, reliability, and economics for SO_2 and particulate control on industrial coal-fired plants. The R-C/Bahco system was started up in March 1976; the Characterization Program was started a month later and was completed in June 1977. Final acceptance of the system by the USAF followed in September 1977, at the end of a 1-year operating cost guarantee period.

The Characterization Program demonstrated that the R-C/Bahco scrubbing system is capable of controlling both particulate and sulfur dioxide emissions from the combustion of high sulfur (2 to 4 percent) midwestern coal. The following salient data were obtained during the program:

- Particulate emissions were reduced to as low as 0.15 lb/10^6 Btu (0.27 g/10^6 cal).
- Sulfur dioxide emissions were reduced to as low as 0.1 lb/10^6 Btu (0.18 g/10^6 cal) with lime reagent, and as low as 0.6 lb/10^6 Btu (1.1 g/10^6 cal) with limestone.
- Operating costs, exclusive of capital charges, were $5.28/ton of coal burned when using lime, including $0.21 maintenance costs.
- Waste product properties relative to dewatering, handling, and disposal were found to be similar to those measured for other FGD waste products.
- Operation of the system required less than 2,000 man-hours per year. System availability above 95 percent is projected.
- No significant buildup of scale or solids occurred in the scrubbing system during the test program.

Bin activator, feeder, and lime slaker

2. The FGD System

The R-C/Bahco facility operating at RAFB is a calcium-based throwaway FGD and particulate removal system. Either pebble lime (CaO) or ground limestone ($CaCO_3$) can be used for SO_2 removal to produce mixtures containing calcium sulfite ($CaSO_3$), gypsum ($CaSO_4$), and fly ash. The overall chemical reactions for the respective reagents are shown in Table 1.

The scrubbing system comprises the following major components:

- Flue-gas-handling equipment
- R-C/Bahco scrubber
- Reagent-handling and -storage equipment
- Sludge disposal equipment

The entire FGD system (Figure 1) is served by a centrally located control room and is operated, part time, by heat plant personnel.

Flue-Gas-Handling Equipment

The flue-gas-handling equipment includes a flue gas header, bypass stack, mechanical collector, and booster fan. Flue gas from as many as eight stoker-fired hot water generators—up to 108,000 actual ft^3/min ($51\ m^3/s$)—passes into the header and mechanical collector where coarse particulate matter is removed before it enters the booster fan and scrubber. Removing particulate minimizes erosion of the fan and other scrubber components and reduces the amount of wet solids handled by the scrubbing system. The ash is disposed of via the existing ash-handling system. A bypass stack in the carbon steel flue gas header serves two purposes: it serves as a fail-safe emergency bypass, and it permits air to enter the system at low loads to maintain gas velocity through the mechanical collector and scrubber to maximize collection efficiency.

Gas Flow

As shown in Figure 2, the R-C/Bahco scrubber, which is fabricated from 316L stainless steel, is a two-stage inverted venturi unit specifically designed to operate with slurries containing calcium sulfite, calcium sulfate (gypsum), calcium carbonate, calcium hydroxide, and fly ash. All of the internal gas flow passages are large, unobstructed, and well irrigated with circulating slurry or makeup water to essentially eliminate the possibility of serious plugging problems.

Hot flue gas from the booster fan enters the first stage, where it impinges on the surface of the slurry, creating a cascade of droplets that it carries into the throat of the lower venturi. The droplets, containing SO_2 scrubbing reagent, cool the gas to its saturation temperature, absorb sulfur dioxide, and trap particulate

Table 1.

Chemical Reactions for Lime and Limestone in SO_2 Removal

Reagent	Reaction
Lime	
Lime slaking	$CaO + H_2O \longrightarrow Ca(OH)_2$
SO_2 absorption	$Ca(OH)_2 + SO_2 \longrightarrow CaSO_3 + H_2O$
Sulfite oxidation	$CaSO_3 + \frac{1}{2}O_2 \longrightarrow CaSO_4$ (gypsum)
Limestone	
SO_2 absorption	$CaCO_3 + SO_2 \longrightarrow CaSO_3 + CO_2$
Sulfite oxidation	$CaSO_3 + \frac{1}{2}O_2 \longrightarrow CaSO_4$ (gypsum)

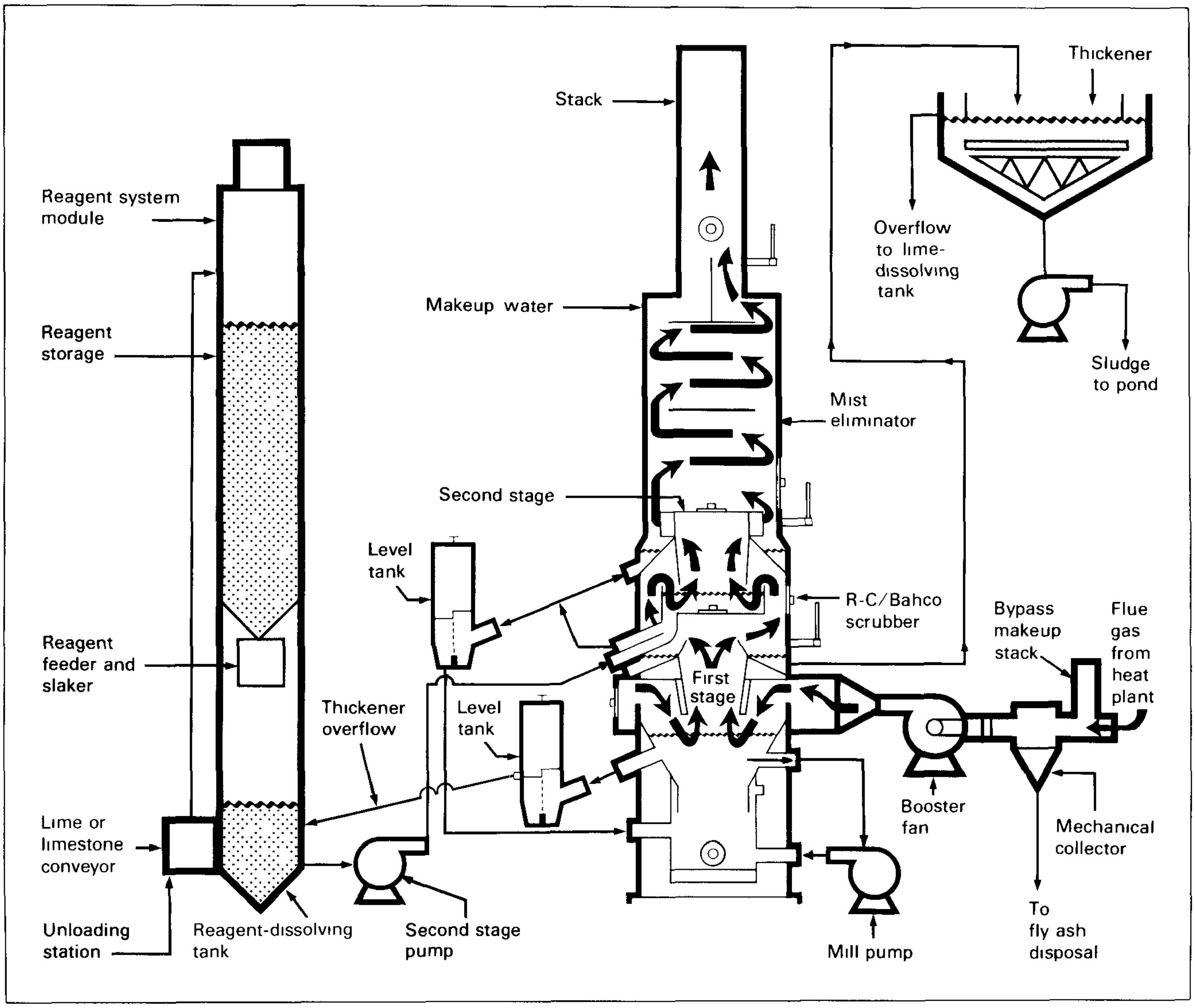


Figure 1.

R-C/Bahco Scrubber System

matter. Above the first venturi, the gas stream is turned downward by the bottom of the pan in the second stage venturi causing most of the droplets to fall out. In the second stage, or upper venturi, the process of impinging the gas stream on the surface of a slurry is repeated. Here the gas/droplet mixture passes up through the throat of the upper venturi where final SO_2 absorption and particulate removal are accomplished. A cyclonic mist eliminator above the upper venturi imparts a spinning motion to the gas stream, causing the droplets to move toward the wall where they coalesce and drain from the scrubber. From the mist eliminator, clean gas, which is not reheated, enters the surrounding atmosphere via the stack.

Slurry Flow

Two techniques of handling slurry flow in the system are used to eliminate or minimize the plugging and erosion problems often associated with calcium-based FGD systems: maintaining essentially constant slurry flow rates through the scrubber, and eliminating turndown in slurry bleed streams by operating in an

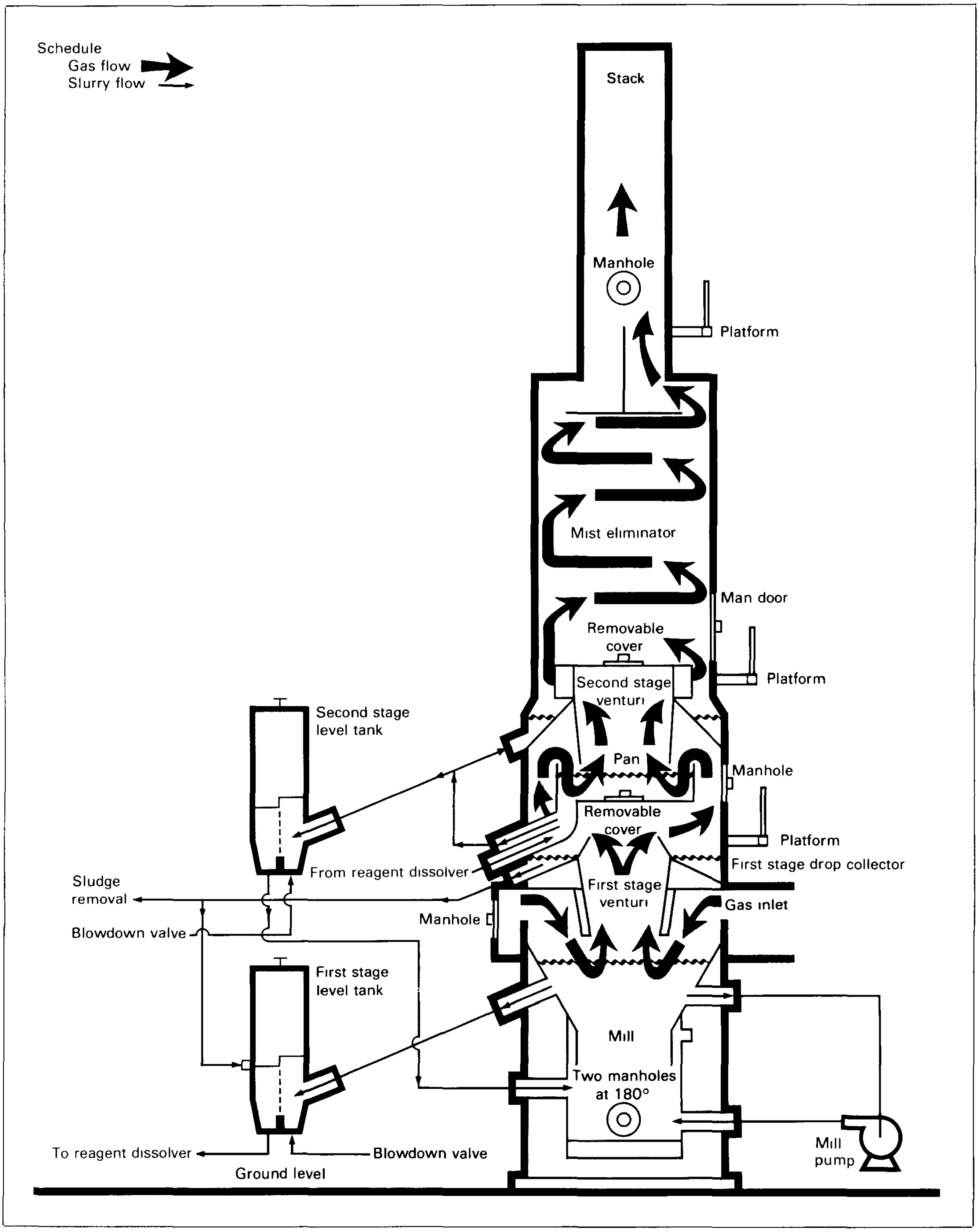


Figure 2.

R-C/Bahco Scrubber

on-and-off mode with water flushing after slurry flow is interrupted.

Slurry flows by gravity from top to bottom in the scrubber, counter-current to the gas flow. Slurry from the reagent dissolver (which is also of 316L stainless steel) contains makeup reagent—either lime or ground limestone. The slurry enters the pan in the upper venturi. Slurry level in the pan determines the upper venturi pressure drop; the level is set by adjusting a weir in the level tank located outside the scrubber.

Slurry streams from the mist eliminator and the pan are combined in the level tank before flowing by gravity to the mill under the lower venturi, where another level tank is used to set the pressure drop in the lower venturi. Part of the slurry collected in the area between the upper and lower venturis, the part that has contacted the gas stream twice, flows by gravity to the sludge disposal system. In the first-stage level tank this slurry is combined with overflow from the mill and is returned to the reagent dissolver. More reagent is added in the dissolver before the slurry is recycled to the upper venturi. The fluid mill is powered by an external pump and is used to grind coarse limestone or other large particles in the system.

First-stage venturi, showing gas inlets and makeup water spray manifolds

Reagent-Handling and -Storage Equipment

The reagent system installed at RAFB is capable of handling both 0.75-inch (1.9-cm) pebble lime and 200-mesh ground limestone. Primary components include truck-unloading equipment, a steel silo with 3 weeks' storage capacity at winter load conditions, a weigh belt feeder, and a lime slaker. The silo, feeder, slaker, and reagent-dissolving tank are integrated into a single module to minimize materials handling, supports, and space requirements. Lime or limestone drops directly out of the silo into the feeder-slaker and overflows into the reagent-dissolving tank directly under the slaker.

Sludge Disposal Equipment

Calcium sulfite, gypsum, and fly ash collected in the scrubber are concentrated from 10 percent to approximately 40 percent solids (by weight) in a thickener. The overflow from the thickener is returned by gravity to the reagent-dissolving tank. The underflow from the thickener is pumped underground to a hypalon-lined storage pond.

3. The Test Program

The R-C/Bahco FGD system test program, carried out at RAFB between March 1976 and June 1977, incorporated the following categories:

- Material balance
- Lime reagent process variable
- Lime reagent verification
- Particulate collection efficiency
- Limestone reagent process variable
- Sludge characterization
- Scrubber reliability monitoring

Material balance tests were conducted to establish the range of operating conditions over which the R-C/Bahco scrubber could be operated and to verify performance at design conditions by completing material balances. Maximum and minimum gas flow rates, pressure drops, and slurry circulation rates were determined and preliminary SO_2 and the particulate performance data at the limits of the system's capabilities were obtained. The system was operated at the design gas rate of 50,000 stdft^3/min (25 normal m^3/s) and complete material balances on calcium, sulfur, and total solids were performed.

Statistically designed lime process variable tests helped to establish the quantitative effect of the following process variables on SO_2 removal: gas flow rate, first- and second-stage pressure drops, mill and second-stage slurry rates, lime.SO_2 stoichiometric ratio, slurry inventory, and slurry solids concentration.

Lime reagent verification tests were undertaken to verify the results obtained in the lime process variable tests, and to determine the effect of very dilute scrubber slurry (2 percent solids) on system performance.

Particulate collection efficiency tests were a continuation of the particulate tests initiated during the earlier sampling phase. Relationships were determined between system variables, including particle size distribution and particulate removal efficiency.

Limestone process variable tests were completed using the same statistically designed test plan used for lime. The effect of system variables on SO_2 removal efficiency and reagent use was determined.

Sludge samples generated at RAFB were tested to determine dewatering, transport, and disposal characteristics (sludge characterization). Samples of sludge from lime as well as limestone scrubbing were tested.

The R-C/Bahco system was monitored from March 1976 to June 1977, to document its operating and maintenance history and to obtain data for a cost analysis. Data were gathered on reagent, coal, water, and power consumption as well as on operating and maintenance labor requirements.

Throughout the test program samples were taken of slurry, flue gas, lime, limestone, and coal, often in duplicate, for chemical analyses, particulate loading, and particle size distribution. A field analytical laboratory was established, and especially developed and highly efficient test methods using thermogravimetric analysis were employed extensively.

4. Test Results

Capacity/Material Balance Tests

Performance of the size 50 R-C/Bahco scrubber at RAFB is measured by its ability to handle variations in system operating parameters while reducing SO_2 and particulate emissions to the limits allowed by the applicable regulations, without exceeding the capacity of the system. Regulations applicable to RAFB limit SO_2 emissions to 2.2 lb/10^6 Btu (3.96 g/10^6 cal) and particulate to 0.16 lb/10^6 Btu (0.29 g/10^6 cal). Table 2 lists maximum, minimum, and optimum operating levels determined for the system at RAFB. The cost of reducing emissions to meet requirements will be minimized at optimum operating levels.

Lime Tests

The SO_2 removal capabilities of the R-C/Bahco system using pebble lime were characterized in two steps. First, a series of screening tests determined the effects of slurry rates, gas rate, venturi pressure drops, slurry density, system volume, and lime stoichiometry on SO_2 removal.

Tests results indicated that lime stoichiometry—the ratio of lime feed in the system to SO_2 in the flue gas—was the only variable controlling SO_2 removal as long as the system was operated within the limits outlined in Table 2.

A second group of tests, in which the effects of the gas flow, slurry rates and slurry density were determined, confirmed the initial findings that stoichiometry alone controlled SO_2 removal.

Results of these verification tests are shown in Figure 3 The figure also shows that lime use is essentially 100 percent—that is, no excess lime is needed—up to 90 percent SO_2 removal. Figure 4 illustrates system performance when SO_2 removal is above 90 percent—that is, when SO_2 emissions at RAFB were reduced below 0.6 lb/10^6 Btu (1.08 g/10^6 cal). The figure indicates that over 98 percent of the SO_2 corresponding to 0.1 lb SO_2/10^6 Btu (0.18 g SO_2/10^6 cal), can be

Table 2.

R-C/Bahco Scrubber Operating Levels

Variable	Minimum	Maximum	Optimum
Gas rate (actual ft^3/min)	35,000	55,000	40,000-50,000
Slurry circulation rate (gal/min)	1,500	3,000	2,300
Venturi pressure drop for each stage (inches H_2O)	6	12	7-10
Slurry concentration (wt % solids)	2	25	10
Reagent.SO_2 stoichiometry (moles reagent moles SO_2, based on inlet SO_2 levels)			
Lime	0 45	1 05	0 7
Limestone	0 55	1 2	0 75
SO_2 removal efficiency (percent)			
Lime	45	98+	70
Limestone	40	85	70
SO_2 emission (lb/10^6 Btu)			
Lime	3.7	0 1	2 0
Limestone	4 0	1 0	2 0
Particulate emission (lb/10^6 Btu)	0 2-0 3	0 14	0 16

achieved with a stoichiometry of 1.1—that is, 10 percent excess lime. The SO_2 emission rates shown in Figure 4 are well below the required 2.2 lb/10^6 Btu (3.96 g/10^6 cal) and the guarantee level of 1.0 lb/10^6 Btu (1 8 g/10^6 cal).

From the lime tests it is concluded that lime:SO_2 stoichiometry is the controlling factor in determining SO_2 removal efficiency. Virtually any desired SO_2 removal efficiency can be achieved when lime is used in the R-C/Bahco scrubber, simply by adjusting the lime:SO_2 stoichiometry. Lime use approaches 100 percent at stoichiometric ratios up to about 0.9. At stoichiometric ratios up to 1.1, producing up to 99 percent removal, lime use is above 90 percent. Because most SO_2 regulations for industrial boilers permit emissions in the range of 1.0 to 2.0 lb/10^6 Btu (1.8 to 3.6 g/10^6 cal), lime, with its high removal capabilities, can be used to obtain offset credits in a nonattainment area to apply toward an expansion or new facility. No further capital expenditure need be made, because the R-C/Bahco system normally would be designed to handle lime as well as limestone, and switching from limestone to lime will increase the annual operating costs only by about 15 percent.

Limestone Tests

System performance with ground limestone was determined in a series of screening tests very similar to those used for pebble lime. These tests indicated that slurry circulation in addition to limestone stoichiometry controls SO_2 removal efficiency.

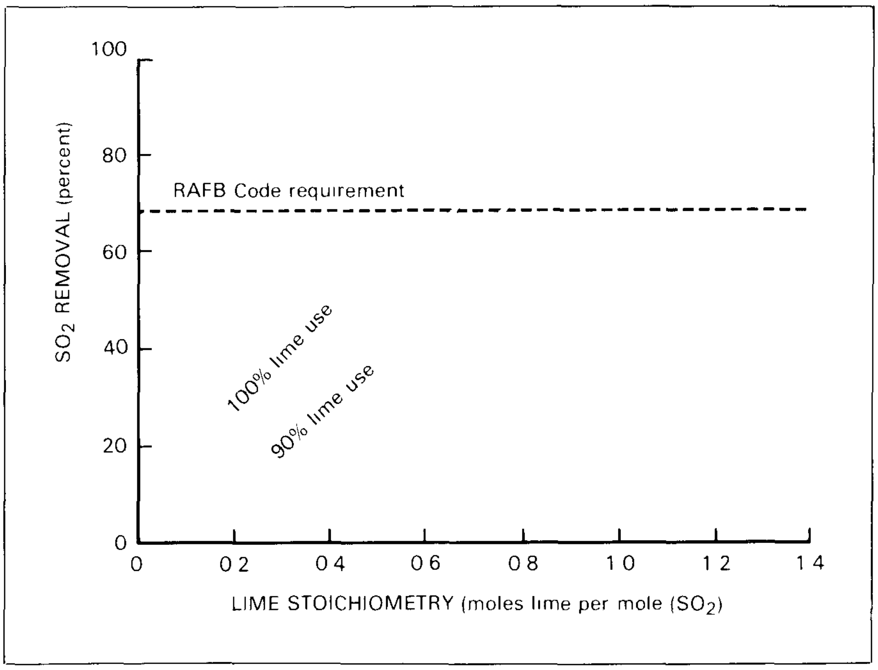
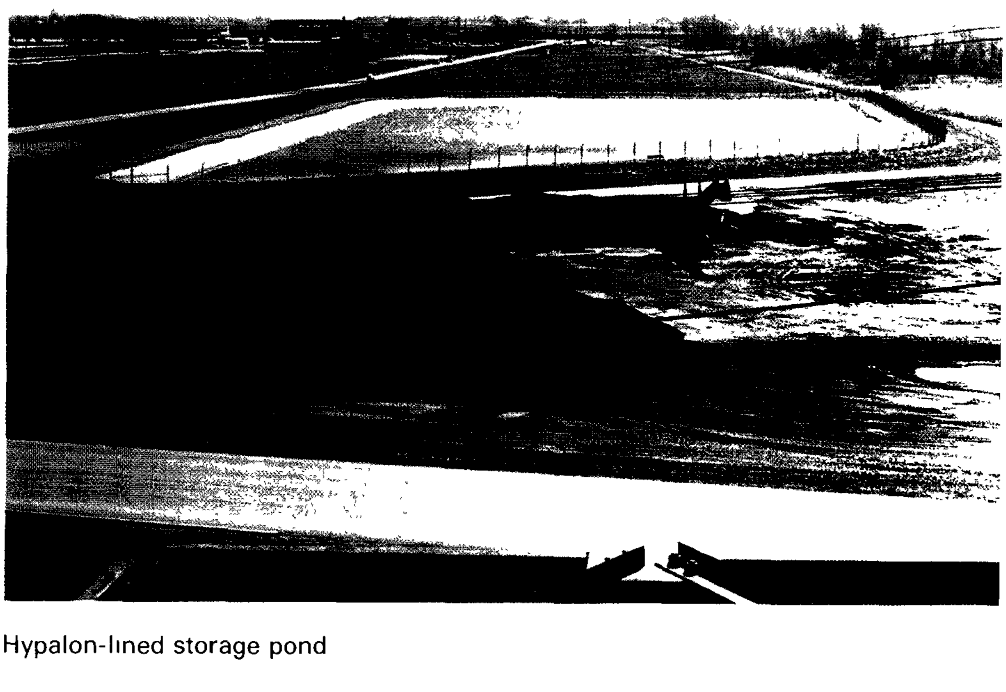


Figure 3.

SO_2 Removal Efficiency as a Function of Lime Stoichiometry



Hypalon-lined storage pond

Figure 5 shows the results of the tests and gives limestone use data. At a stoichiometry of 1.0 and slurry circulation of 2,300 gal/min (0.14 m^3/s), slightly over 80 percent SO_2 removal is possible with 80 percent limestone use. A practical limit for limestone is 80 percent SO_2 removal, because higher removals result in substantial reductions in limestone use.

Operation with limestone at RAFB produced sludge that contained much more gypsum than did operation with lime. That is, there was more oxidation of $CaSO_3$ to $CaSO_4$. Table 3 shows an average gypsum ($CaSO_4 \cdot 2H_2O$) and calcium sulfite ($CaSO_3 \cdot ½H_2O$) content of 33 and 55 percent, respectively, when lime was used. The limestone slurry was almost completely oxidized and contained 78 percent sulfate and less than 1 percent sulfite. The comparison of average lime and limestone slurry analyses during similar boiler load periods listed in Table 3 indicates that the oxidation trend is probably attributable to the lower slurry pH encountered when using limestone, because all other operating conditions were essentially the same.

Particulate Removal Efficiency

Particulate Removal Tests. Initial particulate removal tests on the R-C/Bahco scrubber, performed in March, April, and May of 1976, revealed the presence of substantial amounts of soot in the stack gas. The average particulate emission rate for these tests was 0.23 lb/10^6 Btu (0.42 g/10^6 cal).

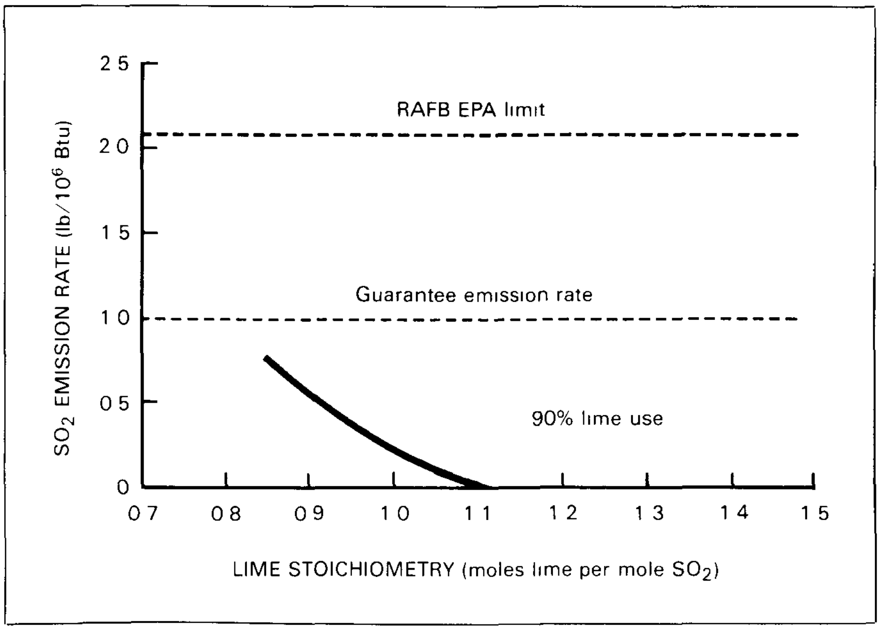


Figure 4.

Relationship Between SO_2 Emission Rates and Lime:SO_2 Stoichiometry

Overall particulate removal averaged 93 to 94 percent. Ohio emission standards require an overall removal efficiency of 96 percent at a particulate inlet loading of 1.5 gr/stdft ^{3} dry (3.4 g/normal m^3 dry) to achieve an emission rate of 0.16 lb/10^6 Btu (0.29 g/10^6 cal). Venturi pressure drops were increased to nearly double the design value of 7 inches (18 cm) H_2O to reduce these emissions. Below approximately 18 inches (46 cm) H_2O total pressure drop, particulate emissions increased rapidly. The amount of soot present in the flue gas at RAFB is higher than in other stoker-fired generators similar to the Rickenbacker boiler.

The Air Force has undertaken an extensive program to upgrade the heat plant at RAFB. Data obtained during this test program contributed substantially to information used to plan the upgrading program, and so far the following modifications have been completed:

- Installation of a new 60-Btu/h (18-Watt) generator to replace the two old units
- Replacement of hot water distribution piping
- Installation of flue gas oxygen monitoring equipment
- Repair of firing air distribution equipment and fire box pressure controls in the generators

- Rebuilding mechanical collectors and induced draft fans on the generators
- Replacement of burned out ledge plates, which regulate combustion air flow around the grates
- Repair of traveling grates

The problem with soot at RAFB points up a critical aspect of a successful emission control project—namely, that proper operation of all equipment, boilers as well as the scrubber, is essential to maintain satisfactory emission levels. Inadequate combustion or inadequate air can be as detrimental to emission control as improper scrubber operation.

Slurry Entrainment and Gas Bypassing. During the particulate tests, two phenomena were observed when the system was operated above its capacity limits. The first, called entrainment, occurs at very low venturi pressure drops—that is, under 6 inches (15 cm) H_2O involves small droplets of slurry carrying through the second-stage mist eliminator and out the stack. The second, called bypassing, is characterized by pulsations in the gas flow through the scrubber; the result is low collection efficiency in all particle size ranges. The second phenomenon takes place when relatively high pressure drops—that is, 12 inches (30 cm) H_2O or more in either venturi—are coupled with slurry flows under 150 gal/min (0.01 m^3/s) to the scrubber.

Conclusion. The particulate removal efficiency of the R-C/Bahco scrubber is comparable to that of low energy venturi scrubbers for particles larger than 1 μm, and appears to be better for particles smaller than 1 μm. In an R-C/Bahco scrubber, the second stage is the primary collector of fine particles. Slurry carryover and

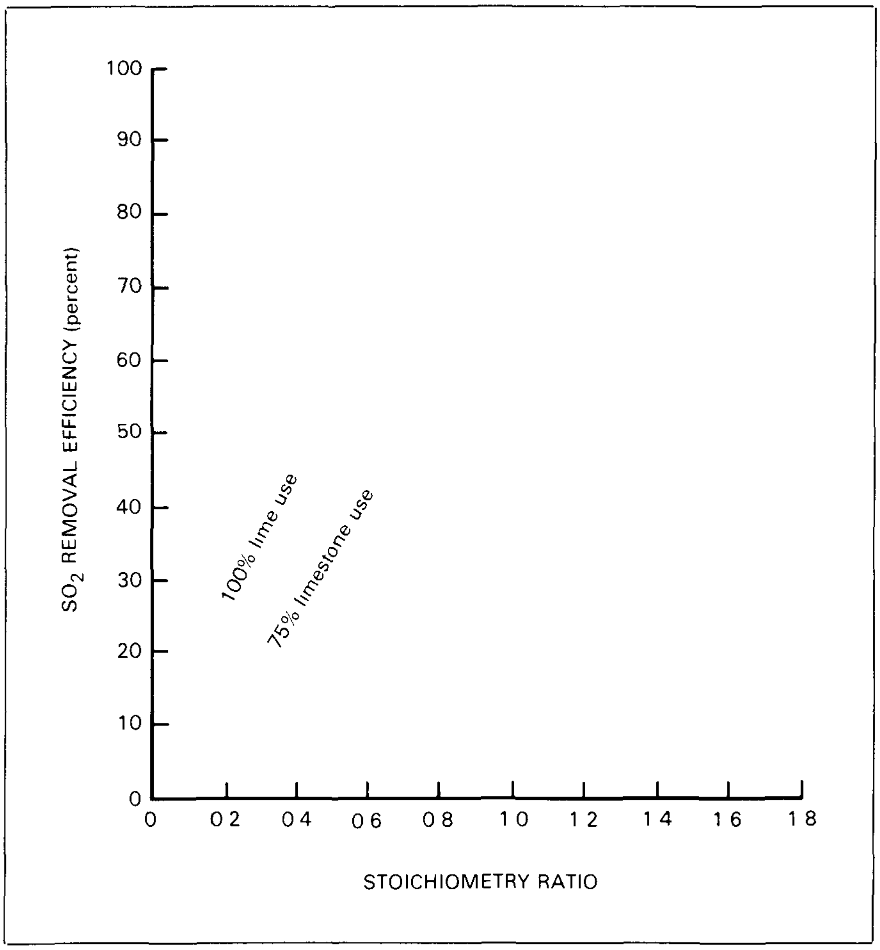


Figure 5.

SO_2 Removal Efficiency as a Function of Limestone:SO_2 Stoichiometry

Table 3.

Lime and Limestone Slurry Analyses

Slurry solids	Lime slurry (wt%)	Limestone slurry (wt%)
$CaSO_4 \cdot 2H_2O$	33.4	77.5
$CaSO_3 \cdot ½H_2O$	54.5	1.0
$CaCO_3$	3 7	17.3
$MgCO_3$	—	0 8
Acid insolubles	4.6	3 4
Total	96 2	100 0

gas bypassing limit particulate collection in an R-C/Bahco scrubber operated outside the levels shown in Table 1. Particulate emissions from stoker-fired coal-burning equipment can be reduced to levels required by regulatory agencies if excessive soot formation is prevented.

Sludge Characterization

A series of scrubber sludge characterization tests was carried out at the Research-Cottrell laboratories to:

- Determine scrubber sludge dewatering characteristics
- Evaluate transportability of dewatered sludge
- Determine physical/structural properties of dewatered sludge
- Measure sludge leachate properties

Slurry Dewatering. A series of settling, centrifuge, and filter leaf tests was run on lime and limestone slurry samples. The results are summarized in Table 4.

The settling tests showed that limestone slurries settle more rapidly and produce denser settled layer than lime slurries. Flocculation improved the settling of limestone slurries, but not that of lime slurries.

Table 4.

Dewatering Test Results

Test	Slurry type	Feed solids (wt%)	Final solids (wt%)	Rate at 35 percent solids
Settling	Lime	16 2	44	22 lb/d/ft^2
	Limestone	16 7	58	164 lb/d/ft^2
	Limestone[a]	16 7	58	578 lb/d/ft^2
Centrifuge	Lime	26 3	51	—
	Lime	38 4	56	—
	Limestone	37 4	65	—
Filter leaf	Lime	24 6	58	70 lb/h/ft^2
	Lime	41 5	59	124 lb/h/ft^2
	Limestone	37 4	74	64 lb/h/ft^2

[a]With 5 ppm flocculant

Table 5.

Sludge Leachate Analysis

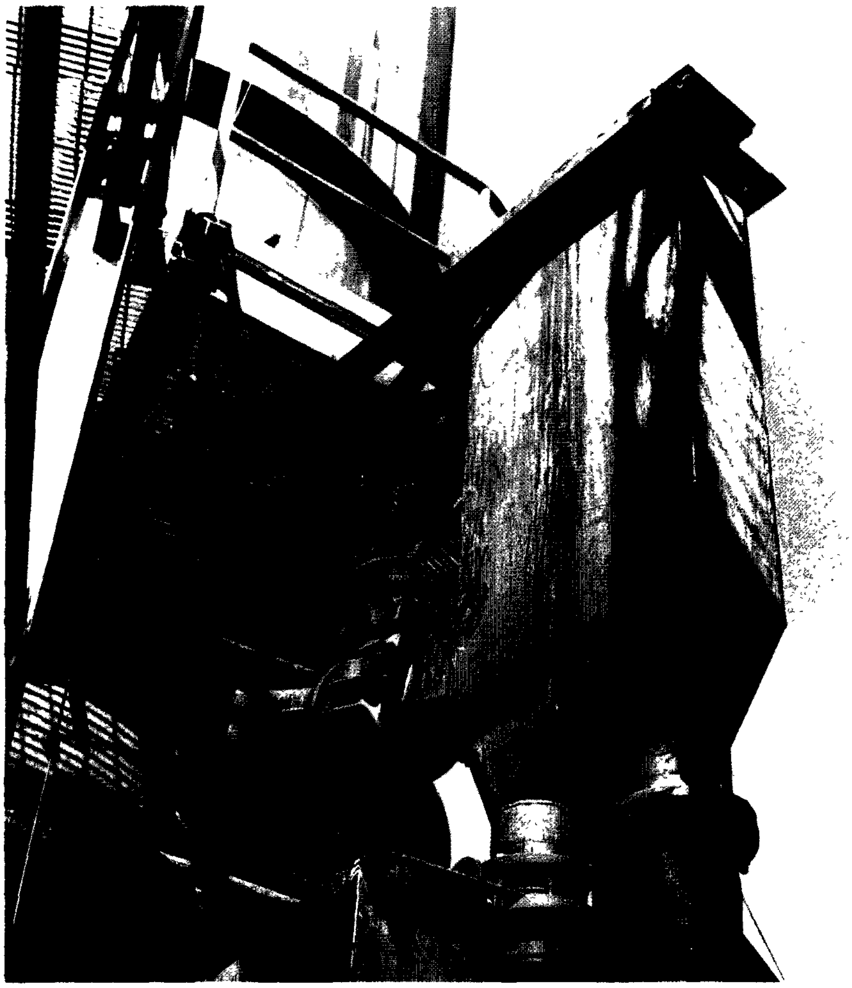
Analysis	Lime leachate	Limestone leachate
TDS (mg/l)	2,960	2,760
SO_4 (mg/l)	1,810 6	1,613 1
COD (mg/l)	8 4	6 8
Cl (mg/l)	72 52	48 04
Pb (ppb)	<100	<100
Cd (ppb)	<10	<10
Cr (ppb)	50	50
Hg (ppb)	<25	<25

The centrifuge tests indicated that final cake density increased as the solids concentration in the feed was increased, and that limestone slurries produced higher cake densities than did lime slurries.

Filter leaf tests showed that limestone slurry filtration rates were significantly lower than lime slurry rates. However, limestone again produced a denser cake.

Leachate Tests. Leachate tests were performed on samples of lime and limestone sludges. The results are listed in Table 5.

Leachate compositions from lime and limestone sludges are essentially the same. Total dissolved solids (TDS) in the range of 2,500 to 3,000 mg/l and sulfate levels of 1,600 to 1,800 mg/l indicate that the leachates were saturated with respect to $CaSO_4$. Both sulfites in the sludge and organic matter in the fly ash contribute to the chemical oxygen demand (COD) levels observed. Although the chloride level in the lime leachate is somewhat higher than the limestone leachate, the other trace elements are present in similar concentrations in both leachates. The constituents found in these leachates are similar in type and concentration to those reported in other studies. If a disposal site is placed so as to avoid infiltration of leachate into ground water, and if sludge and soil cover are placed properly to avoid excessive contamination of runoff, leachate from these sludges will not present an environmentally unacceptable disposal problem.



First-stage level tank

5. Operating Experience

Since startup in March 1976, the R-C/Bahco system has performed well in all areas essential to successful FGD, including:

- SO_2 removal
- Particulate removal
- Scrubber reliability
- Minimal routine maintenance
- Moderate operating costs
- Ease of operation

During the test period of about 11,000 hours, the scrubbing system operated for 6,194 hours. The operation is summarized in Figure 6. It is of interest that from December 1976 to February 1977 (when severe winter weather was encountered), no outages resulted from failure of auxiliary equipment. There were a few brief shutdowns caused by frozen air and water lines during this period, but system availability was over 95 percent.

Downtime is summarized in Table 6. This table shows the amount of time required to obtain parts as well as the actual time for repair work. Spare parts were not kept on hand during the test period, and this resulted in substantial unnecessary downtime. Since completion of the test program, a full supply of spares has been procured. Table 6 also shows that booster fan repair time accounted for 90 percent of the downtime caused by repairs. The booster fan operates on the inlet side of the scrubber, downstream from the mechanical collector, and handles only hot dry flue gas with moderate amounts of fine fly ash. Modifications to the fan wheel and bearings, completed in May 1977, have eliminated the recurring failures associated with this piece of equipment.

Total downtime, exclusive of fan repairs and procurement, was 1,845 hours, or 17 percent of the test period. During routine operation, the system availability should be over 95 percent, based on the factors observed during the test program.

Scrubber inspections were an integral part of the program to monitor scrubber performance. A thorough internal inspection was made in April 1976, approximately 1 month after startup. A followup inspection was made 2 months later, with subsequent inspections during outages up to the end of the test program in June 1977. These inspections confirmed the effectiveness of the water makeup system in keeping key areas of the scrubber clean.

Accumulations of solids were detected at seven locations within the scrubber (Figure 7). Accumulations in four areas—1, 5, 6, and 7—had no impact on scrubber performance. Problems of solids buildup in Areas 2, 3, and 4 were easily corrected, as follows:

In the first few months after startup, the first-stage venturi overflowed into the inlet manifold, Area 2, resulting in an accumulation of dried slurry in the bottom of that area. Subsequent investigation revealed that operation of the first-stage at pressure drops above 12 inches (30 cm) H_2O coupled with a second-stage slurry pumping rate more than 50 percent higher than the design rate of 2,600 gal/min (0.16 m^3/s), caused flooding when the gas flow was reduced below 35,000 stdft^3/min (17 normal m^3/s) or the booster fan was shut down. This problem was eliminated by decreasing the speed of the slurry pump to reduce the flow to design levels, and by adding an interlock to stop the pump when the booster fan is shut down. The accumulated material was removed during subsequent heat plant outages.

Areas 3 and 4 were affected twice during the test by accumulations of a coarse sandy material. The first incident, which occurred shortly after startup, was caused by inadequate removal of grit from the lime slaker. The material in the pan was removed and the slaker was readjusted to eliminate the problem. The second accumulation took place during the winter of 1976-77 when the air lines, which activated the blowdown valves on the first- and second-stage level tanks, froze and rendered these valves inoperative.

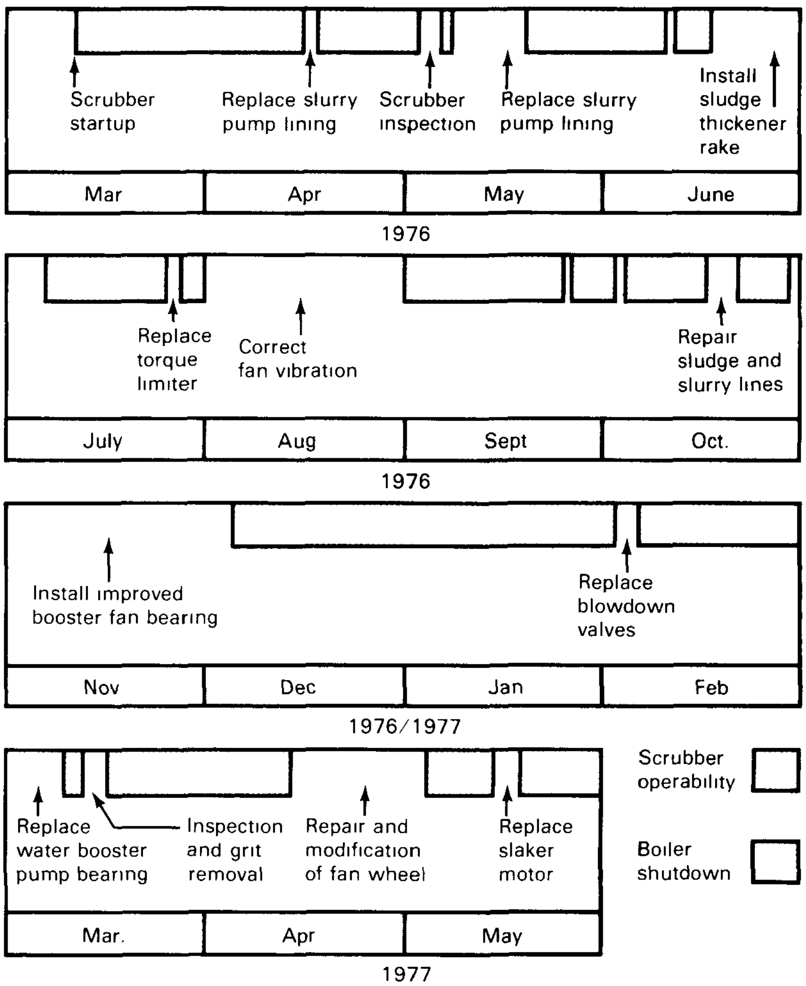


Figure 6.

Downtime Related to Auxiliary Equipment

Table 6.

Downtime Summary

Item	Hours			Percent of test period
	Procurement	Repairs	Downtime	
Booster fan	514	2,252	2,766	25 1
Thickener	471	8	479	4 4
Slurry pump	252	18	270	2 5
Water booster pump	190	16	206	1 9
Lime slaker	122	11	133	1 2
Modifications	—	—	388	3 5
Routine maintenance	—	—	139	1 3
Loss of utilities	—	—	116	1 1
Miscellaneous	56	58	114	0 9
Total	1,605	2,363	4,611	41 9

The results of this part of the test program demonstrated that there are situations that can result in deterioration of scrubber performance, including:

- Infiltration of grit into the system through the lime slaker
- Inadequate operation of the scrubber blowdown valves
- Slow accumulation of solids in the straightening vanes in the stack

The infiltration of grit can be kept to a minimum by paying close attention to the operation of the lime slaker grit removal circuit.

The blowdown valves should be operated two to four times a shift, depending on scrubber load, to avoid accumulations of solids in the slurry outlets.

The straightening vanes at the base of the stack, which serve only to minimize spin in the gas stream leaving the scrubber, may accumulate some material and should be checked twice a year. The possibility of accumulations taking place can be minimized by operating the scrubber within the limits outlined in Section 3 to avoid slurry carryover. Obviously, elimination of the vanes would prevent the problem entirely, but accurate outlet particulate sampling would then be difficult.

The RAFB operating experience indicates that there are no significant problems related to the accumulation of solids in the R-C/Bahco system. The scrubber can tolerate substantial accumulations of solids resulting from external operating problems before performance is adversely affected. Any deterioration in performance that does occur is gradual and can be rectified at a convenient time.

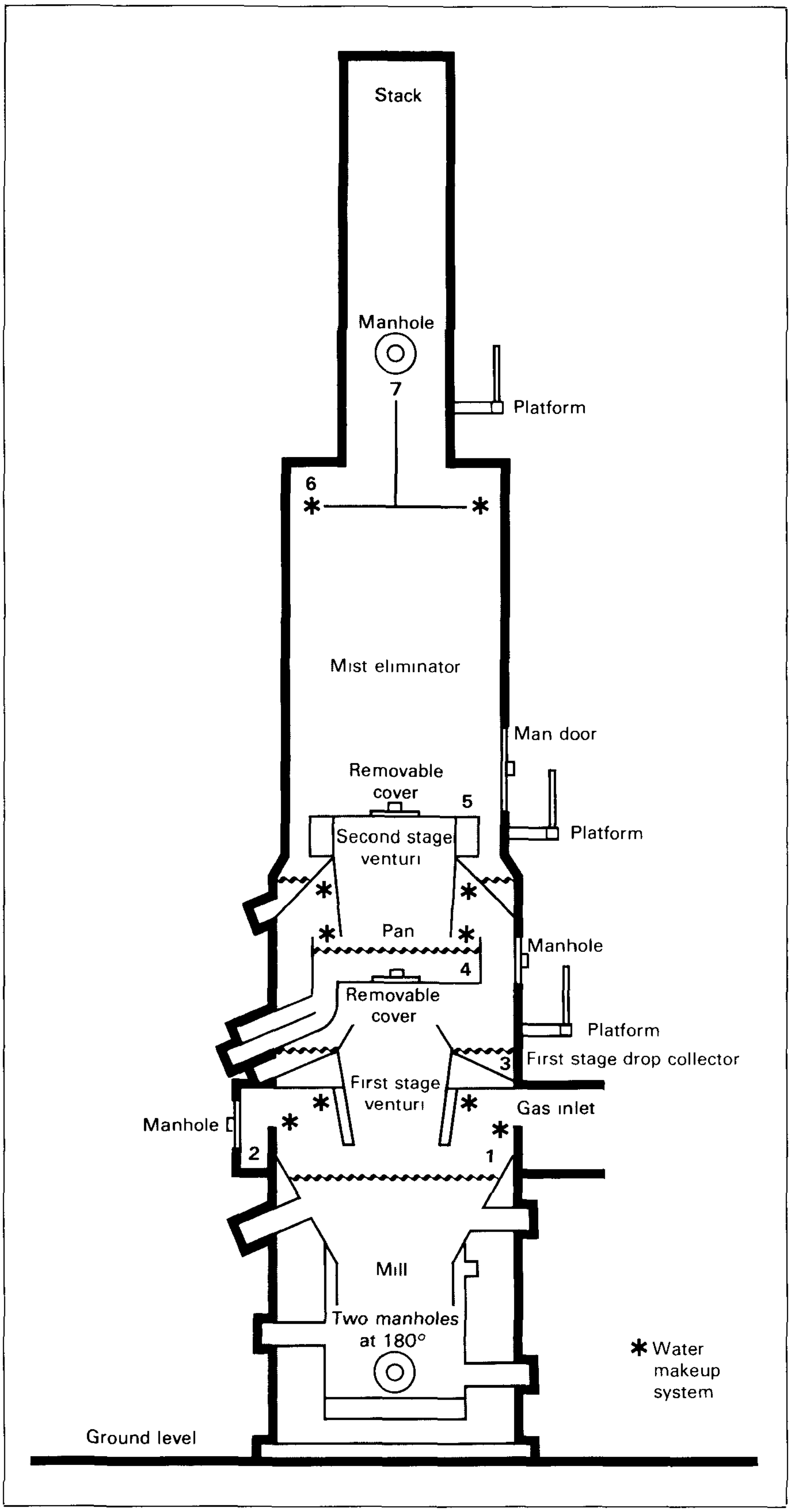
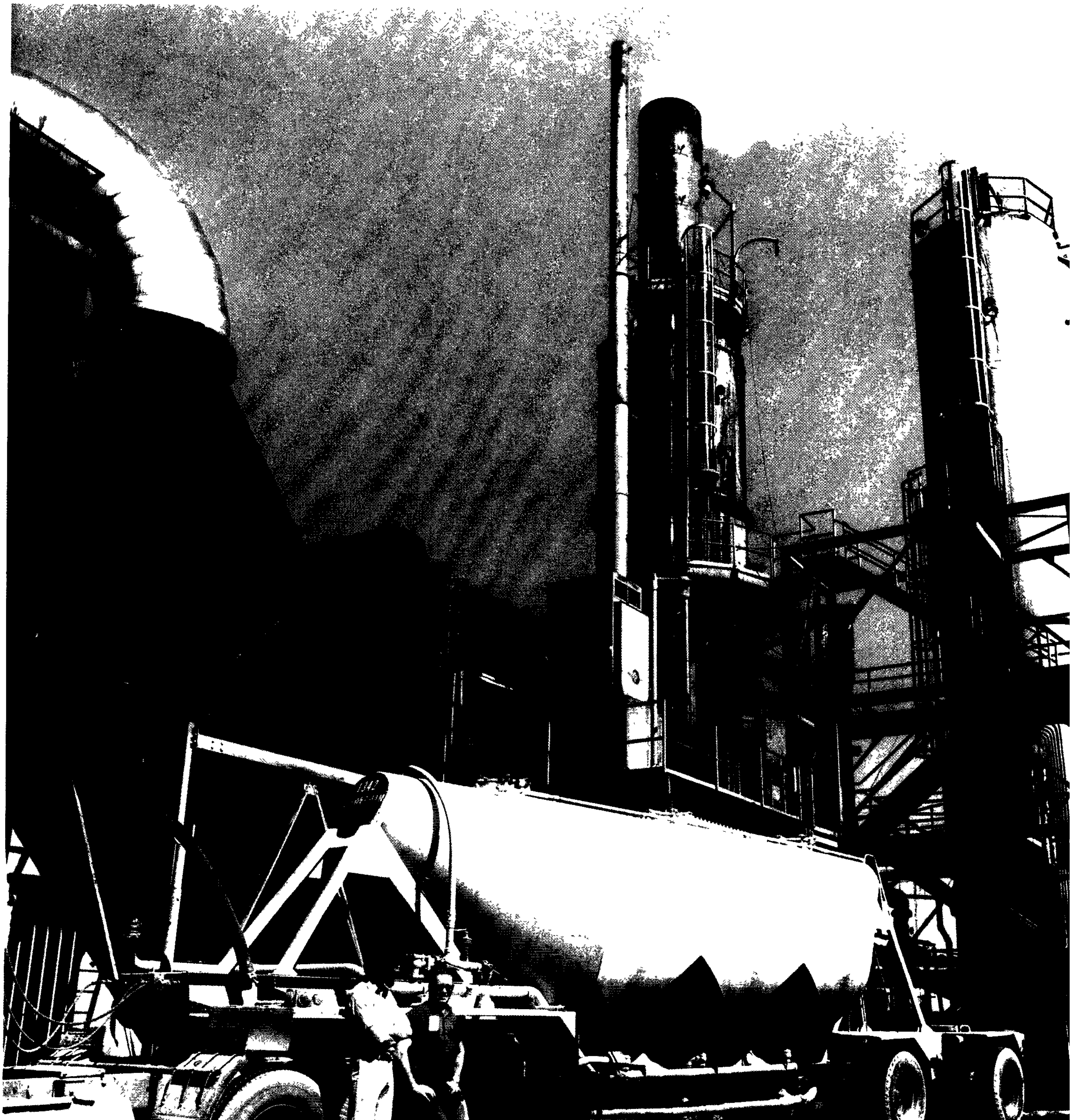


Figure 7.

R-C/Bahco Scrubber Module



Lime delivery truck with R-C/Bahco scrubber and lime bin in background

6. Economics

Compliance with air pollution control regulations can be achieved in several ways. The one frequently chosen today is switching to a fuel such as low sulfur oil that does not require emission control equipment. This choice is often based on an economic evaluation that proves it cost-effective. Table 7 summarizes data gathered on costs during the test program at RAFB[a].

During the 14-month test period, flue gas from the combustion of 27,216 tons (24,742 Mg) of coal, which averaged 2.5 percent sulfur, was treated by the scrubbing system. The total operating cost—including utilities, chemicals, and labor—was $5.07/ton of coal burned. Maintenance costs were $0.21/ton including labor and materials.

Sludge disposal cost is $0.45/ton of coal burned, calculated in terms of the installed cost of the pond and an anticipated 10-year life.

The turnkey cost of the RAFB installation was $2.25 million, including a new substation and additional equipment, controls, and instrumentation necessary for the EPA test program. Current costs for R-C/Bahco turnkey systems (Figure 8) are $1.3 million to $3.7 million. Figure 9 illustrates the capacities of the various size systems. The system installed at RAFB is capable of treating flue gas from a 180,000-lb/h (23-kg/s) steam boiler.

Table 8, based on the cost data collected at RAFB, summarizes the annual operating costs including normal overheads and capital charges for an industrial 180,000-lb/h (23-kg/s) steam plant operating at 75 percent of capacity.

The 1979 cost of low sulfur oil is approximately $20 to $22/barrel, or about $87 to $96 for energy equivalent to that contained in 1 ton (0.91 Mg) of coal: 25 Btu × 10^6 (26.4 kJ × 10^6). In the case outlined in Table 8, there would be an annual fuel saving of between $3,400,000 and $4,000,000, which could be applied to coal-handling and emission control equipment if coal at $30/ton were burned instead of low sulfur oil.

The R-C/Bahco system is designed specifically for industrial-size fossil-fuel-burning applications that require combined SO_2 and particulate removal. The system at RAFB handles SO_2 and particulate from the combustion of midwestern high sulfur coal, 12,200 Btu/lb (28,377 kJ/kg), 6 percent ash, 3.5 percent sulfur. Other units, listed in Table 9, have been operating successfully since 1969 on oil-fired boilers with SO_2 concentrations up to 4,000 ppm.

Basically, the R-C/Bahco system can economically reduce SO_2 particulate emissions from the combustion of coal and high sulfur oil, or emissions from certain other sources, to levels low enough to satisfy applicable environmental regulations. The R-C/Bahco system can be used successfully for emission control for almost any installation, where the SO_2 concentration does not exceed 6,000 ppm and most of the particulate to be collected is above 1 μm.

[a]1978 is the base year for costs unless otherwise indicated.

Table 7.

RAFB Operatıng Cost Summary

Item	Units	Cost ($)	
		Per unıt	Total
Power			
Booster fan	3,065,000 kWh	0 024/kWh	73,560
Auxılıary equıpment	602,500 kWh	0 024/kWh	14,460
Water			
Potable water	4,448,120 gal	0 36/1,000 gal	1,601
Well water	1,768,700 gal	—	—
Chemıcals			
Lıme	721 tons	40 35/ton	29,092
Lımestone	130 tons	12 72/ton	1,654
Labor			
Operatıng labor	1,860 man-hours	7 52/man-hour	13,987
Supervısıon (25% of operatıng labor estımate)	—	—	3,497
Total			137,851

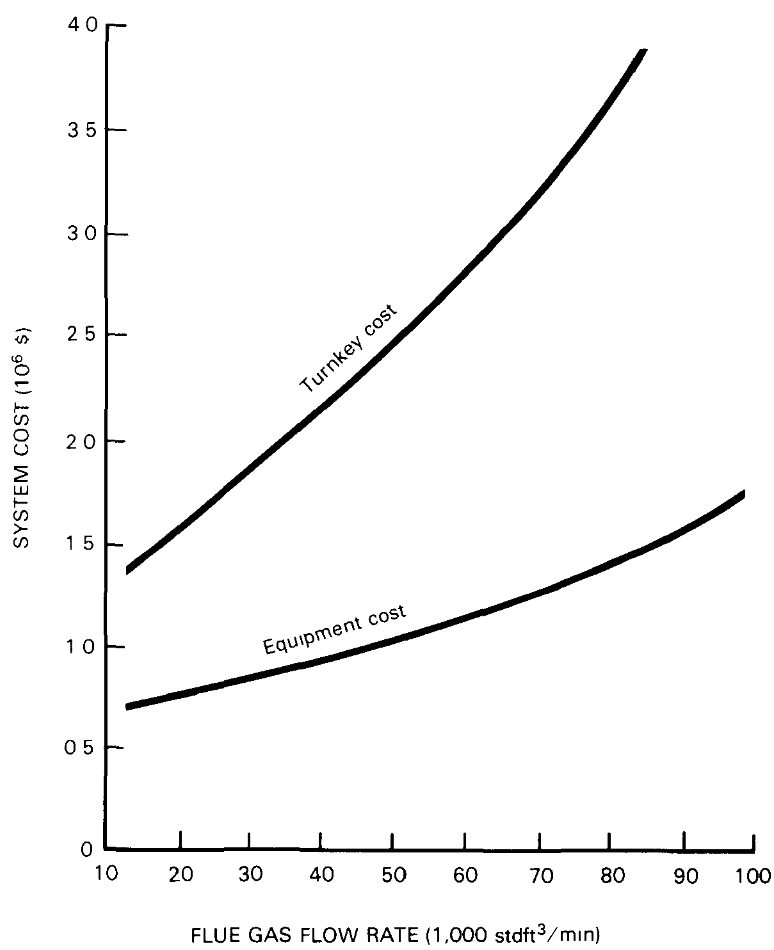


Figure 8.

R-C/Bahco Capital Costs

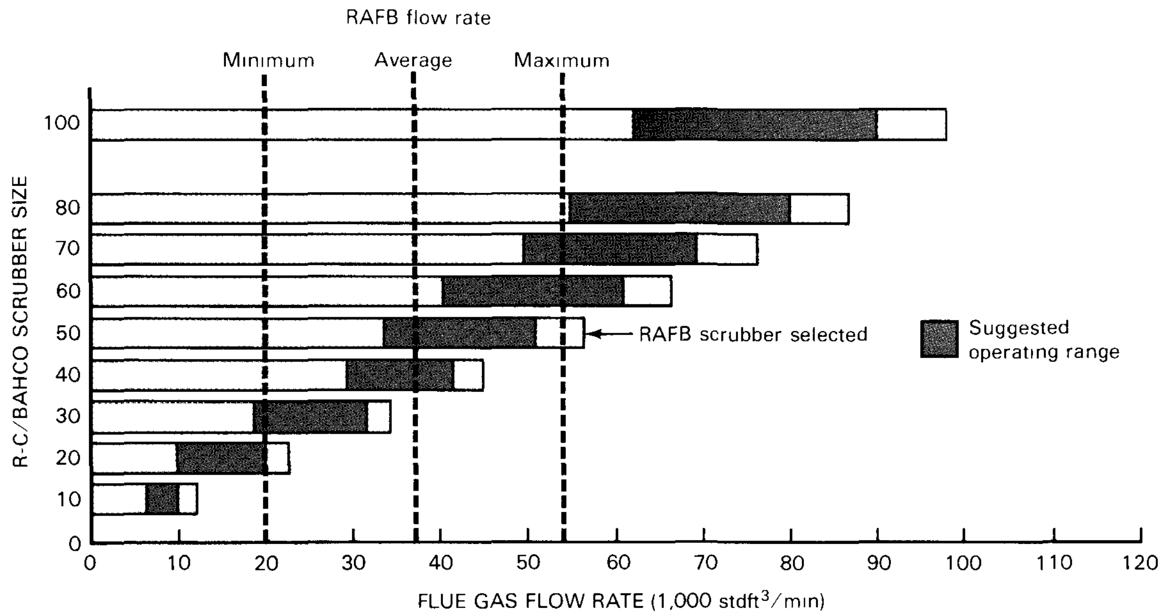


Figure 9.

R-C/Bahco Scrubber Capacities

Table 8.

Annual Operating Costs

Item	Units	Cost ($)	
		Per unit	Total
Power	3 5 million kWh	0 024/kWh	84,000
Water	6 million gal	0 36/1,000 gal	2,160
Chemical (limestone)	4,440 tons	12 72/ton	56,480
Sludge dewatering[a]	—	—	—
Operating labor	2,200 man-hours	8 00/man-hour	17,600
Supervision of labor	500 man-hours	10 00/man-hour	5,000
Maintenance labor and materials	—	—	12,600
General overhead (75% of labor man-hour costs)	—	—	17,300
Depreciation (10-year straight line)	—	—	225,000
Taxes and insurance	—	—	45,000
Total			465,140

[a] Included in other costs

Note —Installed cost = $2 25 million Coal consumption = 60,000 tons at 3 percent sulfur + 70 percent SO_2 removal Cost per ton of coal = $7 50

Table 9.

R-C/Bahco Particulate/SO_2 Removal Systems

Company and location	No of units	Unit capacity (stdft^3/min at 32° F)	Service	Scrubbing reagent
Rickenbacker Air Force Base *Columbus OH*	1	50,000	Coal-fired boiler	CaO and $CaCO_3$ dust
Kino Ura Utility Japan	1	75,000	Oil-fired boiler	NaOH
Kanegafuchi Chemical *Takasago, Japan*	2	159,000	Oil-fired boiler	NaOH
Stora Kopparberg Grycksbo, Sweden	1	17,700	Black liquor boiler	CaO and $CaCO_3$ dust
Osaka City Osaka, Japan	1	10,000	Secondary sludge incinerator	NaOH
Central Glass Company Sakai, Japan	1	31,300	Glass furnace	NaOH
Taio Paper Company Iyomishima, Japan	1 1	83,000 66,400	Oil-fired boiler Oil-fired boiler	NaOH NaOH
Yahagi Iron Works Nagoya, Japan	1	48,300	Sintering plant	$Ca(OH)_2$ waste carbide sludge
Hiroshima City Hiroshima, Japan	1	10,000	Secondary sludge incinerator	NaOH
Daishowa Seishi Yoshinaga, Japan	5	44,200	Oil-fired boiler	NaOH
Daishowa Seishi Suzukawa, Japan	1	14,700	Oil-fired boiler	NaOH
Sodersjukhuset Stockholm, Sweden	3	17,700	Oil-fired boiler	$Ca(OH)_2$

Table 9.

R-C/Bahco Particulate/SO_2 Removal Systems—Concluded

Company and location	Inlet SO_2 concentration (ppm)	SO_2 removal efficiency (percent)	Date on line
Rickenbacker Air Force Base Columbus OH	400-2,000	70-90[a]	Mar 1976
Kino Ura Utility Japan	1,500	—	Sept 1974
Kanegafuchi Chemical Takasago, Japan	1,400-1,530	95-98	Apr 1973
Stora Kopparberg Grycksbo, Sweden	4,000-6,000	70[a]	Sept 1972
Osaka City Osaka, Japan	70-80	50[a]	Mar 1971
Central Glass Company Sakai, Japan	1,200[b]	98	Mar 1971
Taio Paper Company Iyomishima, Japan	1,000-1,500 1,000-1,500	98 98	Jan 1971 Jan 1971
Yahagi Iron Works Nagoya, Japan	2,500-4,000	90-95	Dec 1970
Hiroshima City Hiroshima, Japan	—	—	Dec 1970
Daishowa Seishi Yoshinaga, Japan	900-1,000	97 5	Aug 3, 1970 July 2, 1972
Daishowa Seishi Suzukawa, Japan	900-1,200	97-99	July 1970
Sodersjukhuset Stockholm, Sweden	800-1,500	97-99	Nov 1969 Apr 1970 Nov 1970

[a] Sufficient to meet local code

[b] 25 percent SO_3

Environmental research and development of flue gas desulfurization programs is the responsibility of the Industrial Environmental Research Laboratory in Research Triangle Park NC. Mr. John Williams of the Emissions/Effluent Technology Branch is the Project Officer. Mr. Robert J. Ferb, of Research-Cottrell, is the principal contributor. EPA wishes to thank officials of the Rickenbacker Air Force Base, Columbus OH, for their cooperation and technical assistance.