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Design Guidelines for an Optimum Scrubber System

Interagency Energy/Environment R&D Program Report

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EPA REVIEW NOTICE

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Design Guidelines for an Optimum Scrubber System

by

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ABSTRACT

The U.S. Environmental Protection Agency, Industrial Environmental Research Laboratory, Research Triangle Park, North Carolina, is considering a demonstration of an optimum wet scrubber system for use on a coal-fired utility boiler. The optimum wet scrubber system has such design goals as maximum particulate collection, low power consumption, and low maintenance. In this study, the performance and operating experiences of existing utility scrubber systems and the state-of-the-art in design of scrubber components are reviewed. Based on this review, guidelines are given for the design of the optimum wet scrubber system.

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CONVERSION TABLE

To Convert From	To	Multiply By
Btu/lb	nm^3/hr (0°C)	2.324
scfm (60°F)	m^3/hr	1.61
cfm	m^3/hr	1.70
°F	°C	(°F-32)/1.8
ft	m	0.305
gal/mcf	l/m^3	0.134
gpm	l/min	3.79
gr/scf	gm/m^3	2.29
hp	kW	0.746
in.	cm	2.54
in. W.G.	mm Hg	1.87
lb	gm	454
psia	kilopascal	6.895
1 ton (short)	metric ton	0.907

1.0 INTRODUCTION

1.1 PURPOSE OF THE REPORT

The U. S. Environmental Protection Agency has been considering lowering its New Source Performance Standard for particulate emissions from coal-fired boilers to 0.03 lbs of particulate/million Btu. In the case of power plants which require a scrubber system to meet SO_2 emission standards, it is economically advantageous to also collect the particulate matter with the scrubber system. But existing utility scrubber systems either would require relatively large power consumptions to meet the standard, or would be incapable of meeting it at all. Hence it is desirable to design an optimum wet scrubber system which would have maximum collection efficiency at the lowest possible energy requirements.

The purpose of this report then is to summarize performance data and operating experiences of existing scrubber systems and to provide background information for use in the design of an optimum wet scrubber system for coal-fired utility boilers.

1.2 SCOPE OF THE REPORT

Section 2.0 presents recommendations regarding the best materials, component designs, and scrubber type to use in the optimum wet scrubber system.

Section 3.0 of this report indicates the tremendous variability in emissions among power plants. Such properties as flyash size distribution, flyash composition, and flue gas composition are considered.

Section 4.0 summarizes the scrubber types that have been used on utility boilers. The performance of these systems is correlated with power consumption. Two novel scrubbers are also discussed.

Section 5.0 summarizes utility operating experiences and design considerations for various components of a scrubber system. Particulate removal represents only one aspect of a scrubber system: such factors as mist elimination, reheat, and corrosion must also be considered.

2.0 CONCLUSIONS AND RECOMMENDATIONS

Design of the optimum wet scrubber system for use on coal-fired utility boilers is a two-step process consisting of characterizing the inlet gas stream, and then choosing the best designs for the various scrubber components based on operating experiences and research studies.

Characterization of the inlet flue gas stream is essential, but too frequently, neglected. The following properties should be determined.

Flyash Size Distribution. Flyash size distributions vary greatly among power plants, depending on boiler and coal types. For a particular scrubber, particle collection efficiency is determined by the inlet size distribution.

There may be some merit in using a mini-scrubber rather than an impactor to characterize the size distribution. Whereas a mini-scrubber does not actually determine the distribution, weight percent versus diameter, it will generally perform with the same efficiency as the full-scale unit. Impactor data, on the other hand, are subject to considerable error.

Flyash Composition. The chemical composition of the flyash is important. If the flyash contains substantial quantities of alkalis, calcium and magnesium oxides, it will scrub some SO_2 from the flue gas, leading to scale formation. Flyash may also contain chlorides which can cause stress corrosion in stainless steels.

Flue Gas Composition. The concentration of SO_3 (or H_2SO_4) should be determined because of its corrosiveness. Flue gas may also contain hydrogen chloride which poses another corrosion problem.

Once the inlet gas stream has been characterized, it is necessary to select the best scrubber components to obtain maximum performance. The choice of components should be based on past operating experiences and research studies. Unfortunately, operating experiences do not always present a consistent picture, making it difficult to formulate hard-fast rules. It should also be borne in mind that scrubber design technology has not advanced far enough to prevent problems from arising after construction. Hence the best overall designs are those that are flexible enough to permit easy replacement of damaged parts.

Recommendations for the various scrubber components based on this study are as follows.

Particulate Scrubber and SO_2 Absorber. Current practice suggests the use of simpler designs for both the particulate scrubber and SO_2 absorber. Hence, of the conventional particulate scrubber types, a gas-atomized scrubber, such as a venturi or rod scrubber, is recommended. Other types are less efficient or have more operating problems. Also, spray towers are preferable for use as the SO_2 absorber.

Based on a correlation of scrubber performance against energy requirements, a pressure drop of 17±2 in. W.G. would be necessary to meet the proposed New Source Performance Standard of 0.03 lbs particulate/million Btu[1] in a conventional scrubber. When fan losses and pressure drops across the absorber, ductwork, and mist eliminator are taken into account, total system pressure drop may run as high as 30 in. W.G. If this energy requirement is deemed too high, a novel particulate scrubber should be chosen. Of the novel scrubbers tested by EPA to date, the electrostatically augmented scrubbers appear to be the most suitable for use on coal-fired utility boilers. Pilot units have shown good collection efficiency of flyash, coke oven battery emissions and steel mill electric arc furnace emissions.

Mist Eliminator. Horizontal mist eliminators have greater capacities than vertical types, but space requirements are also greater. Vertical mist eliminators are best designed with sharp angled baffles to promote good drainage.

Reheaters. Operating experience with reheaters militates against the use of in-line reheaters because of combined acid and chloride stress corrosion. The two other types of commonly used reheaters, direct combustion and indirect hot air reheaters, are recommended and should be designed with interlocks to prevent heated gas from damaging ductwork when flue gas is not present. Adequate mixing is sometimes a problem with these types of reheaters.

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[1]To conform with present practices, English units are used throughout this report. See Conversion Table, pg. vi.

Materials of Construction. The most common construction material for scrubbers is 316 stainless steel. At points of high abrasion, wear plates, brick linings, or high grade nickel alloys are recommended. The higher grade alloys are also recommended in areas subject to chloride attack.

The best material for in-line reheaters appears to be the higher grade alloys--Inconel and Hastelloy have worked well at Colstrip (Montana Power). Carbon steel and lower grade stainless steels have worked at some plants but have failed at others.

Plastic is the best material for mist eliminators because of low cost, light weight, and reduced corrosion potential.

Waste Disposal. Disposal of collected flyash from a particulate scrubber is readily controlled, typically being disposed of along with bottom ash. With a dual-function particulate-SO_2 scrubber system, waste disposal is problematic because of the thixotropic nature of the sludge. Ponding is the most common and least expensive method of disposal, but creates a large unreclaimable area. Landfill is a better method of disposal, but the sludge requires greater dewatering as well as stabilization. In some site-specific cases, it may be possible to use less common methods, such as a dry lake (arid regions) or a mine.

3.0 THE POWER PLANT AS A SOURCE OF POLLUTION

The purpose of this report is to summarize data and provide useful information in the design of an optimum wet scrubber system for use on a coal-fired utility boiler. For a complete understanding of the problem, the source of pollutant emissions must be considered as well as the collection device. A brief description of a coal-fired electric generating plant and its effluents follows with emphasis on aspects relevant to a scrubber system.

3.1 OVERALL PROCESS DESCRIPTION

Modern coal-fired, electric generating plants consist of boilers, generators, condensers, coal handling equipment, dust collection and disposal equipment, water handling and treatment facilities, heat recovery systems (such as economizers and air heaters), and possibly flue gas desulfurization systems. A flow diagram of a single unit, emphasizing sources of pollution, is shown in Figure 3-1.

Boiler types in use include cyclone, pulverized, and stoker units, but nearly 90 percent are pulverized coal boilers (Sitig, 1977). Pulverized coal boilers are commonly classified as either wet bottom or dry bottom depending on whether the slag in the furnace is molten.

Two condensing cooling systems are used by the electric utility industry: the once-through system and the recirculatory system. In the once-through system, all the cooling water is discharged to a heat sink, such as a river or lake. In recirculating systems, cooling devices, such as cooling towers or spray ponds, permit the use of recirculated water.

As indicated in Figure 3-1, wet scrubbing systems in coal-fired electric generating plants may be used to collect particulate matter and/or to scrub SO_2 from the flue gas. In any case, a wet scrubbing system increases both the solid and wastewater disposal problems of the plant.

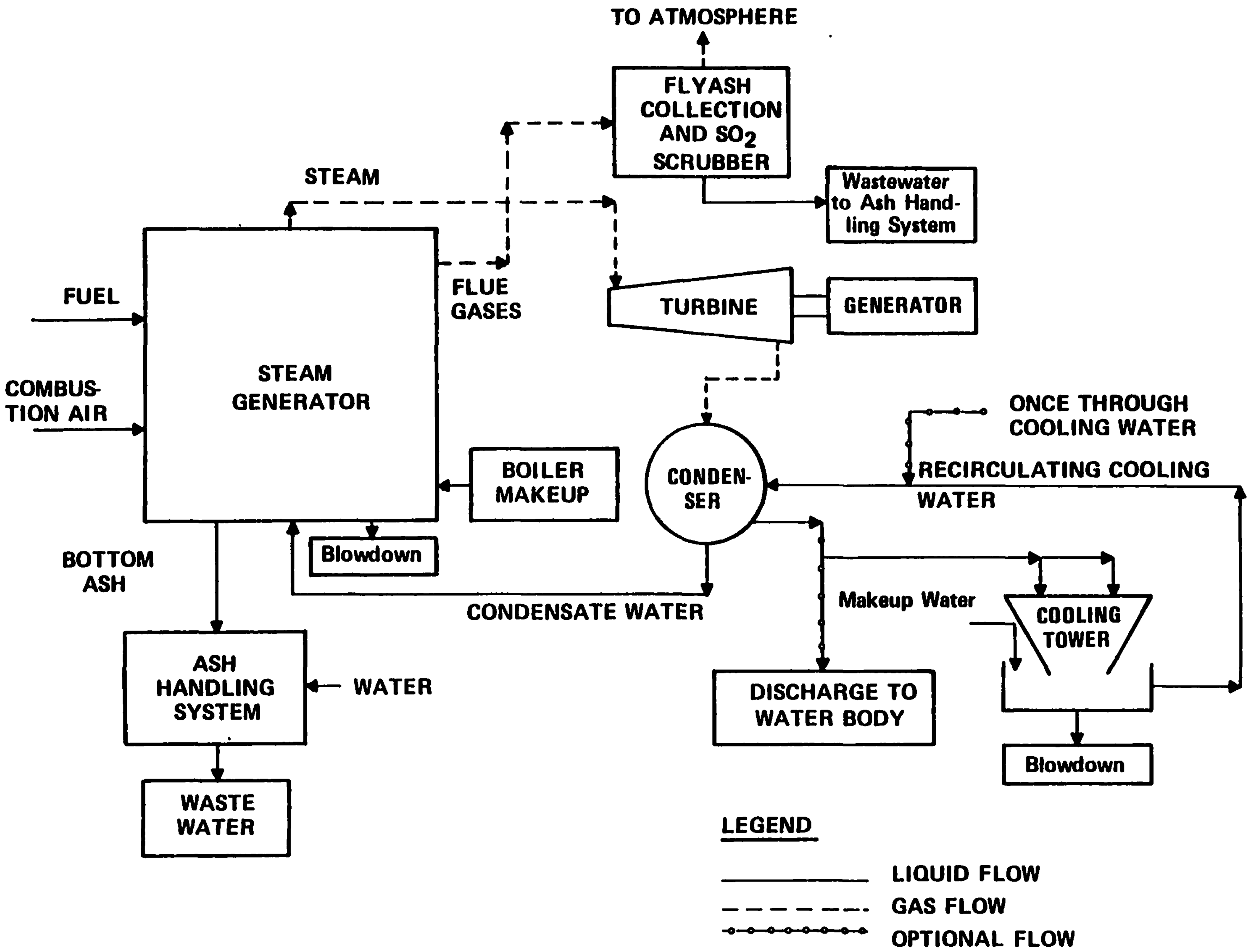

Figure 3-1. Coal-fired electric generating plant with scrubbing system. (Adapted from Sugarek and Sipes, 1978.)

Combustion of coal in the furnace produces both flyash (airborne) and bottom ash (settled). Both bottom ash and collected flyash along with sludge from a throwaway flue gas desulfurization system (where used) are the major sources of solid waste from coal-fired utilities. These solid wastes, which are in a slurry form, are usually sluiced to a solid-liquid separator; the solids settle out and clarified water is returned to the system or discharged. Ultimate disposal of the wastes may be either in an onsite settling pond, or, after further dewatering and treatment, in a landfill.

Water impurities build up in the boiler, cooling tower (if used), and scrubbing system. To prevent scale formation, blowdown operations are performed: a portion of the high impurity concentration water is removed and replaced by low concentration feedwater. Besides these blowdown operations, ash sluicing water and wastes from water conditioning operations are the other major sources of wastewater in power plants (Sugarek and Sipes, 1978).

3.2 COAL CHARACTERIZATION

Coal compositions vary greatly across the U. S. Generally speaking, Western coals have lower heating values, lower sulfur content, and higher moisture content than Eastern coals. Table 3-1 summarizes ultimate analyses of 21 different coals.

Of particular concern to the designer of a wet scrubber system is the chlorine content of the coal. The chlorine content of coal (in the form of sodium and potassium chlorides) may vary from a trace amount to as high as 0.5 percent, as shown in Table 3-2. During combustion, some of the chlorine is converted to hydrogen chloride or other volatile chlorides. Most of the hydrogen chloride will be absorbed in scrubbing liquor, thereby increasing the potential for chloride stress-corrosion.

3.3 CHARACTERIZATION OF FLUE GAS FROM COAL-FIRED UTILITY BOILERS

The successful design of a wet scrubber system on a particular coal-fired boiler requires careful consideration of the flue gas characteristics of that boiler. The following sections are an attempt

TABLE 3-1. EXAMPLE COAL ULTIMATE ANALYSES

No.	Type	C	H_2	N_2	S	O_2	Ash	H_2O	Btu/lb
1	PA	79.84	1.78	0.25	0.71	1.96	9.7	4.5	12,745
2	PA	79.45	2.21	0.77	0.60	1.95	11.9	2.5	12,925
3	VA	70.00	3.24	0.77	0.62	2.55	20.2	2.0	11,925
4	WV	84.21	4.47	1.21	0.74	2.51	5.1	1.0	14,715
5	PA	77.52	4.16	1.30	1.68	2.08	10.3	1.3	13,800
6	PA	76.74	4.15	1.38	1.68	2.68	10.2	1.5	13,720
7	PA	75.42	4.48	1.21	2.20	2.84	10.2	1.5	13,800
8	PA	72.66	4.62	1.45	1.82	4.96	11.2	1.5	13,325
9	KY	79.94	5.14	1.50	0.70	6.26	3.3	2.5	14,480
10	OH	67.39	4.75	1.17	4.00	6.16	9.1	3.6	12,850
11	IL	64.24	4.39	1.28	2.70	7.26	11.7	5.8	11,910
12	UT	69.83	4.90	1.49	0.90	10.33	6.4	5.2	12,600
13	IL	59.88	4.31	1.13	3.20	7.18	9.0	12.2	11,340
14	MT	63.48	4.00	1.02	0.43	9.57	7.0	14.1	11,140
15	WY	53.89	3.62	1.14	0.30	12.07	3.7	25.0	9,345
16	WY	47.10	3.56	0.57	0.55	11.83	4.8	31.0	8,320
17	ND	42.46	2.86	0.53	0.40	12.15	4.2	37.0	7,255
18		70.7	4.7	1.1	3.4	10.3	7.1	2.7	12,400
19		53.13	3.70	1.00	0.39	14.17	4.62	23.	
20	Western	72.7	5.3	1.1	1.0	9.0	8.9	2.0	13,135
21	Eastern	69.9	4.9	1.3	1.1	7.1	13.7	2.0	12,640

Source: Leivo (1978)

Note: Coal 1-17 are from "Steam" (1966).

TABLE 3-2. CHLORINE CONTENT OF SELECTED AMERICAN COALS

Source of Coal		
State	Bed	Chlorine Content, wt. pct.
Ohio	Sharon	0.01
Illinois	No. 6	0.39
Illinois	Central Illinois	0.35
West Virginia	Pittsburgh	0.07
West Virginia	Wyoming	0.11
West Virginia	Upper Freeport	0.17
West Virginia	Sewell	0.27
Pennsylvania	Lower Freeport	0.14
Pennsylvania	Upper Kittanning	0.13
Indiana	No. 4	0.06
Indiana	Lower Kittanning	0.16
Oklahoma	Henryetta	0.46

Source: Iapalucci, et al. (1969) and Smith and Gruber (1966).

to summarize the physical and chemical properties of flue gas as well as the characteristics of the dust burden that typically would be encountered in coal-fired utility boilers.

Physical and Chemical Properties of Flue Gas

In designing a wet scrubber system, the volume of gas handled, inlet and outlet temperatures, humidity, and SO_2 concentration are all important considerations. Typical power plant flue gas volumes range from 3000 to 4000 acfm/MW depending on coal composition, boiler heat rate, gas temperature, and amount of excess air. Because of economies of scale, the utility industry has tended toward larger and larger power stations implying that scrubber systems must be capable of handling volumes of gas as large as 4,000,000 acfm.

The temperature of the gas entering the scrubber is determined by the efficiency of the air heater. Most steam power plants operate in the range of 250-300°F downstream of the air heater. Exit temperatures from the scrubber vary with sulfur content and range from 150°F below 1 percent sulfur to 180°F above 3 percent sulfur (McIlvaine, 1974). Because exit temperatures are low, most scrubbing systems incorporate reheat systems which provide greater plume buoyancy and prevent corrosive condensation.

Flue gas contains from 5 to 15 percent moisture depending on the amount of volatile matter and on the moisture content of the coal. The concentration of sulfur dioxide in the flue gas depends on the sulfur content of the coal: for an average sulfur content of 2.5 percent, there will be approximately 1500 ppm of SO_2 in the flue gas (McIlvaine, 1974). On the average, 1-3 percent of the SO_2 will be converted to SO_3. Sulfur oxides in the flue gas make for a corrosive environment; special alloys, coatings, and linings must be used on scrubber internals.

Characterization of Flyash

Particulate matter in utility flue gas is composed of flyash. The characteristics of flyash (concentration, size distribution, and chemical composition) affect both the performance and maintenance of the scrubber.

Particulate Emission Quantity --

The concentration of flyash in utility flue gas depends primarily on the following variables: (1) amount of ash in the coal, (2) method of burning the coal, and (3) rate at which coal is burned (Sitig, 1977). Figure 3-2 is a nomograph for estimating particulate emissions from uncontrolled coal combustion, or equivalently, the inlet dust loading to the scrubber. As shown in Figure 3-2, for a given coal, pulverized coal units produce greater quantities of dust than stoker or cyclone units. Furthermore, for a given furnace type, the flyash emission quantity will be approximately proportional to the ash content of the coal. Inlet dust loadings in utility flue gas may vary from 2 to 12 gr/dscf, but 4 or 5 gr/dscf is fairly typical.

In general, the size distribution of the flyash and not the emission quantity determines the collection efficiency of a particular scrubber. However, the dust concentration does affect the abrasiveness of the flue gas, and hence, the potential for eroding a scrubber system. In cases where the inlet dust loading is very heavy, some scrubbing systems use mechanical collectors before the scrubber.

Flyash Size Distribution --

The particle collection efficiency of a scrubber is lowest for fine particles (<3.0 microns, aerodynamic). Hence, the collection efficiency of a particular scrubber will depend on the amount of fine particles in the inlet dust.

Figure 3-3 shows flyash size distributions from four utility boilers. The fine fraction varies widely, ranging from roughly 4 percent to 45 percent of the inlet dust loading, and representing about 0.05 gr/dscf to 0.5 gr/dscf. This variation is accounted for in part by the coal and furnace type. Lignite, for example, appears to produce a very fine distribution. Because of the limited amount of data, however, generalizations are difficult to make. Further, the effect of process variables on the size distribution is not known. Suffice it to say that if the design of the optimum wet scrubber system is to be based on impactor measurements of the inlet flyash size distribution, then careful measurements in sufficient number must be made to accurately determine the fine particle fraction.

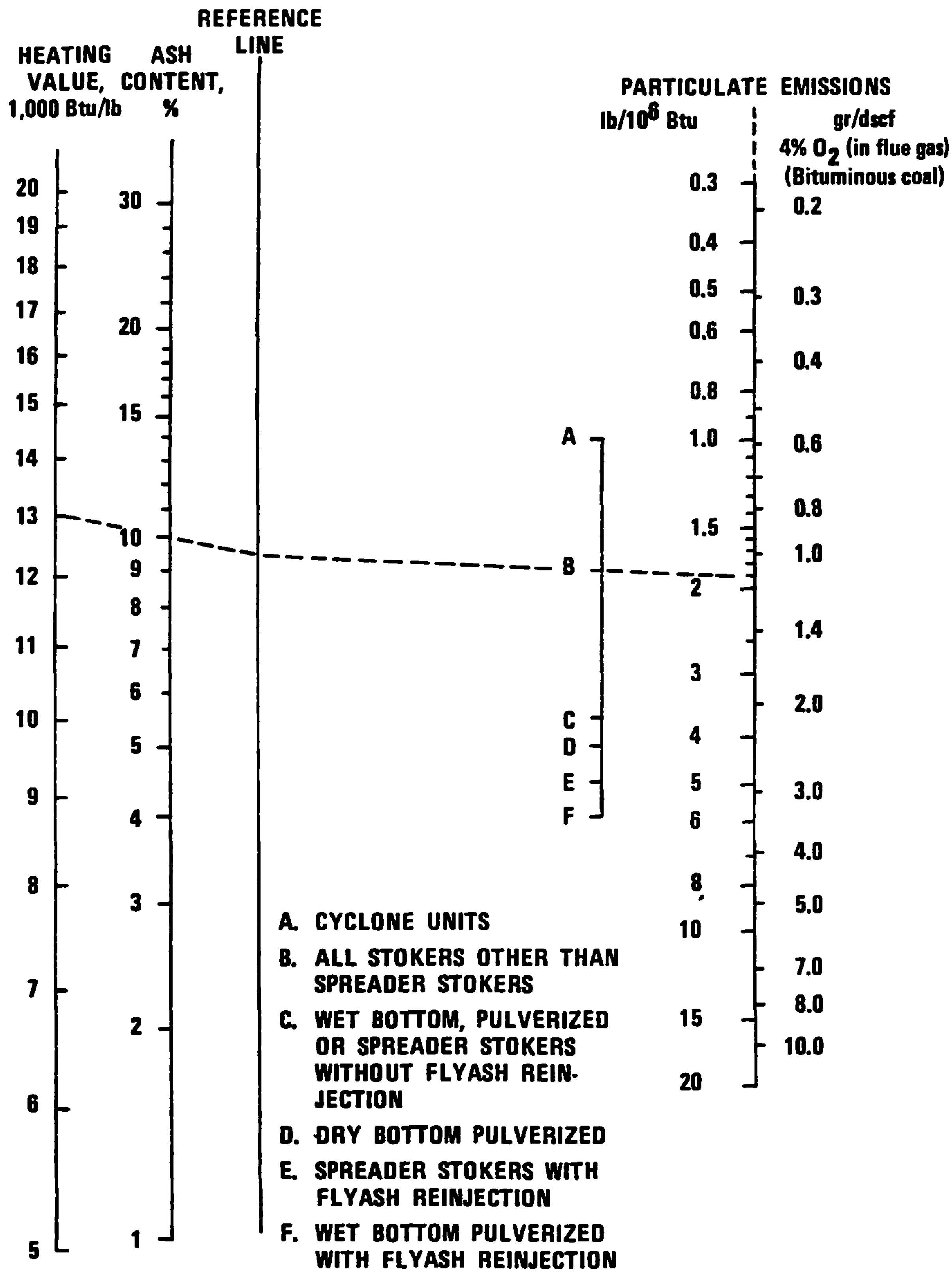

Figure 3-2. Nomograph for estimating uncontrolled emissions from coal combustion. (Adapted from Smith and Gruber, 1966.)

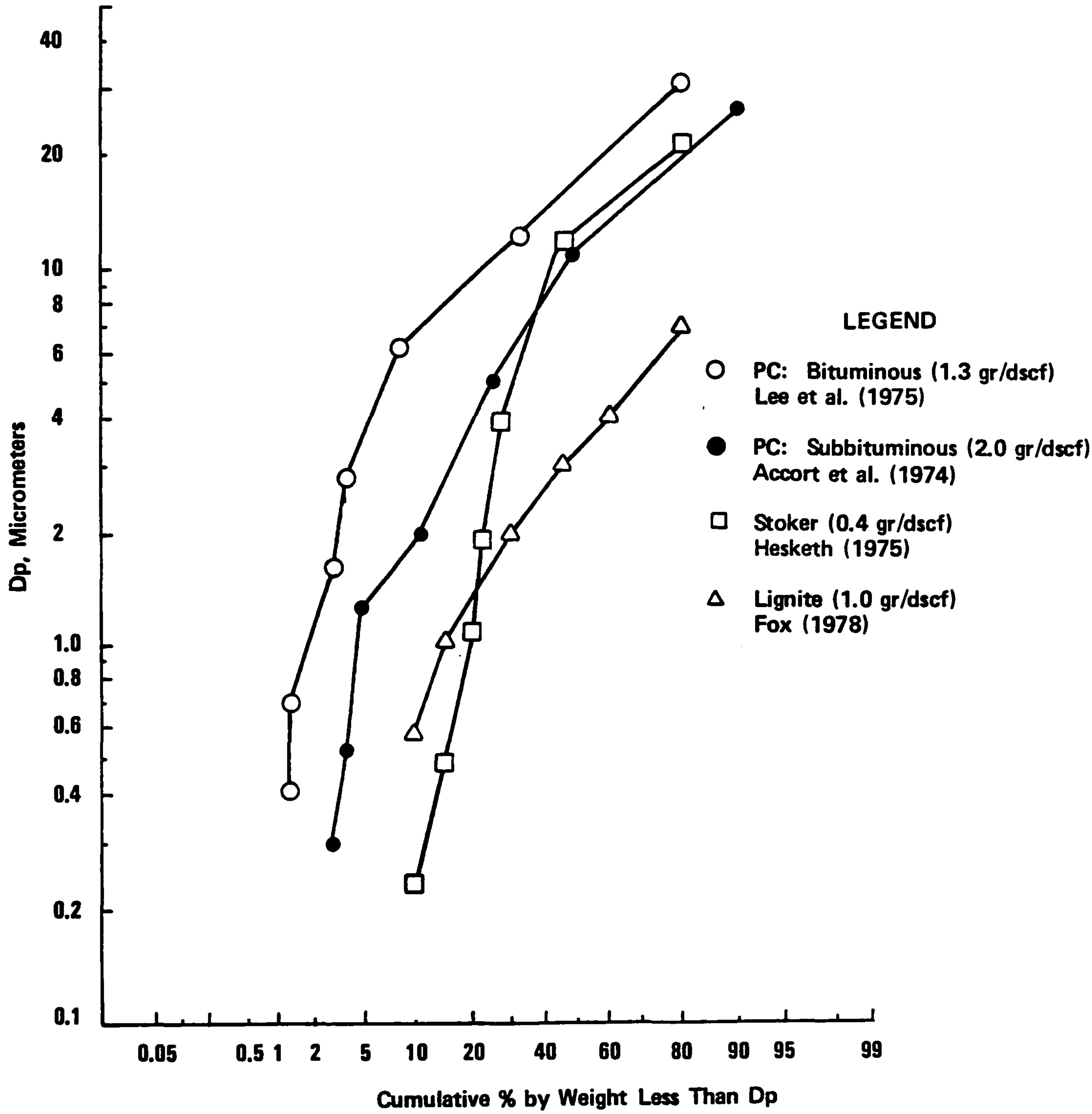

Figure 3-3. Flyash size distributions from several utility boilers.

(Figure 3-3 shows that the flyash size distribution from the stoker unit had a large fraction of fine particles, contrary to what one would expect from this method of firing. The distribution was indeed biased toward the smaller sizes by the scrubbing system sampling duct which acted like a mechanical collector (Hesketh, 1975). Nevertheless, the sampled flue gas did contain approximately 0.1 gr/dscf below 3.0 microns).

Chemical Composition of Flyash --

Flyash is composed primarily of silicates, oxides, sulfates, and unburned carbon. Flyash also contains a number of trace elements (less than 0.1 percent). Table 3-3 shows the chemical composition of flyash from six different utilities. Studies have shown that certain trace elements become concentrated in the submicron flyash particles. This concentration effect arises presumably because of volatilization and subsequent condensation of trace elements in the furnace. Those elements which readily condense will form fine particles or be deposited on the surfaces of small particles (Natusch, 1974).

For purposes of designing a particulate scrubber system, the calcium oxide content of the flyash is an important consideration: the calcium oxide will scrub a certain amount of SO_2 thereby forming calcium sulfate and increasing scaling potential. Cases where the flyash was extremely alkaline have been used to advantage in the design of a combined particulate-SO_2 scrubbing system which utilized the collected flyash as the scrubbing reagent (Grimm et al., 1978).

3.4 LEGAL ASPECTS: THE NEW SOURCE PERFORMANCE STANDARD FOR PARTICULATE MATTER FROM COAL-FIRED UTILITY BOILERS

At this writing, the standard for particulate matter from fossil-fuel fired steam generations (greater than 73 megawatts heat input rate) are for emissions not to exceed: (1) 0.10 lbs of particulate/million Btu, and (2) 20 percent opacity. (Code of Federal Regulations, Sec. 60.40). The proposed revised standards are for emissions not to exceed; (1) 0.03 lbs of particulate/million Btu, and (2) 10 percent opacity. (Draft copy, "Proposed Standards of Performance for Electric Utility Steam Generating Units," 1977). The mass emission rate, however, is the binding constraint; that is, if a utility meets the emission standard

TABLE 3-3. COMPARISON OF FLY ASH FROM VARIOUS UTILITY PLANTS

Compound or Element	Plant 1	Plant 2	Plant 3	Plant 4	Plant 5	Plant 6
SiO_2, %	59.	57.	43.	54.	NR	42.
Al_2O_3, %	27.	20.	21.	28.	NR	17.
Fe_2O_3, %	3.8	5.8	5.6	3.4	20.4	17.3
CaO, %	3.8	5.7	17.0	3.7	3.2	3.5
SO_3, %	0.4	0.8	1.7	0.4	NR	NR
MgO, %	0.96	1.15	2.23	1.29	NR	1.76
Na_2O, %	1.88	1.61	1.44	0.38	NR	1.36
K_2O, %	0.9	1.1	0.4	1.5	NR	2.4
P_2O_5, %	0.13	0.04	0.70	1.00	NR	NR
T_iO_2, %	0.43	1.17	1.17	0.83	NR	1.00
As, ppm	12.	8.	15.	6.	8.4	110.
Be, ppm	4.3	7.	3.	7.	8.0	NR
Cd, ppm	0.5	0.5	0.5	1.0	6.44	8.0
Cr, ppm	20.	50.	150.	30.	206.	300.
Cu, ppm	54.	128.	69.	75.	68.	140.
Hg, ppm	0.07	0.01	0.03	0.08	20.0	0.05
Mn, ppm	267.	150.	150.	100.	249.	298.
Ni, ppm	10.	50.	70.	20.	134.	207.
Pb, ppm	70.	30.	30.	70.	32.	80.
Se, ppm	6.9	7.9	18.0	12.0	26.5	25.
V, ppm	90.	150.	150.	100.	341.	440.
Zn, ppm	63.	50.	71.	103.	352.	740.
B, ppm	226.	200.	300.	700.	NR	NR
Co, ppm	7.	20.	15.	15.	6.0	39.
F, ppm	140.	100.	610.	250.	624.	NR

Source: Ray and Parker (1977)

but fails to meet the opacity standard it may apply for a variance (Personal communication with John Copeland, OAQPS, EPA, RTP, North Carolina).

It is useful to convert the emission standard to a measurable dust concentration. The relationship between the emission standard and a dust concentration depends on the type of coal that is burned and the oxygen content of the flue gas. Specifically, this relationship is given by the following equation (Code of Federal Regulations, Sec. 60.46):

$$C = \frac{E}{F} \frac{20.9 - \%O_2}{20.9}$$

C = dust concentration, gr/dscf

E = emission standard, lbs/million Btu

F = factor representing ratio of volume of dry flue gas to calorific value of the coal, dscf/million Btu

The value of F is taken as 10,140 dscf/million Btu for anthracite and 9820 dscf/million Btu for subbituminous and bituminous coals.

Most coal-fired, electric generating plants operate at about 3-4 percent O_2 (roughly 20-25 percent excess air) in the flue gas. From the equation, then, the proposed standard of 0.03 lbs of particulate/million Btu would be roughly equivalent to 0.017 gr/dscf. This figure should be kept in mind when comparing the performance of existing scrubbing systems.

For a typical dust loading of 4.0 gr/dscf, compliance with the proposed emission standard would require greater than 99.5 percent overall collection efficiency. Since a significant percent of flyash (4 to 45 percent, see Figure 3-3) is below 3.0 microns, only those collection devices with high collection efficiencies of fine particles will be able to meet this standard.

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4.0 WET SCRUBBER SYSTEMS

Wet scrubber systems can be classified according to their design function, either particulate removal, SO_2 removal, or combined particulate-SO_2 removal. For purposes of this study, only those systems designed for particulate removal or for combined particulate-SO_2 removal need be considered.

The first major application of scrubber systems to power plants occurred in the early 1970's in the West. Here, because of the use of low-sulfur coal, scrubber systems were designed primarily for particulate removal. At the time, scrubbers were considered an attractive alternative to electrostatic precipitators in light of the high resistivity coals found in the West. However, numerous operating problems such as scaling, plugging, and corrosion occurred because of the newness of the application. But experience gained at these installations did advance scrubber technology.

More recently, a number of utilities have chosen double-function scrubber systems for both particulate and SO_2 removal. The reason for this decision is clearly economic: where a scrubber system is needed to meet SO_2 emission standards, and a throwaway flue gas desulfurization system (such as lime, limestone, or alkaline flyash) is used, it is less costly to remove the dust with a particulate scrubber than with an electrostatic precipitator (McIlvaine and Ardell, 1978). One disadvantage of double-function scrubber systems is that it may not be possible to bypass one of the functions.

4.1 SCRUBBER SYSTEMS IN USE AT POWER PLANTS

Scrubber Classes

Three classes of particulate scrubbers have been used on coal-fired utility boilers: gas-atomized, preformed spray and mobile-bed scrubbers. Gas-atomized spray scrubbers are by far the most common. To achieve combined SO_2 and particulate removal, some systems use an SO_2 absorber following the particulate scrubber; other systems use a wash tray located inside the particulate scrubber.

A brief description of these classes of particulate scrubbers follows with examples from specific installations. Simplified flow diagrams from a number of power plants with particulate or combined particulate-SO_2 scrubber systems are included in Appendix A.

Gas-Atomized Spray

Gas-atomized spray scrubbers use a moving gas stream to atomize the liquid into droplets and then accelerate the droplets. Particle collection results primarily from inertial impaction as the gas flows around the droplets. High particle collection efficiency requires a substantial pressure drop with, consequently, large power consumption. Because gas velocities are high, gas residence times are short precluding particle collection by diffusion. As regards operational problems, plugging is not likely, but high throat velocities can cause excessive wear.

Various geometries have been used on coal-fired utility boilers including venturi, annular orifice, and rod bank design. Two installations have been chosen for illustration: the Four Corners Station (Arizona Public Service), where an adjustable venturi is used to remove particulates, and the Lawrence No. 4 Station (Kansas Power and Light), where a rod bank particulate scrubber followed by a spray tower absorber are used to remove both particulates and SO_2.

Figure 4-1 shows a simplified flow diagram of the particulate scrubbers at the Four Corners Station (575 MW; Arizona Public Service). Flue gas entering the module is scrubbed by slurry sprays in the venturi section. The gas then passes through a mist eliminator, a water-sprayed induced-draft fan, a second mist eliminator and reheater, and finally exits the stack. A portion of the scrubber liquor is recycled directly to the scrubber and (internal) mist eliminator. The other portion is bled off to the distribution tank and thickener where suspended solids settle out. Makeup water for the scrubber slurry comes from the liquid transfer tank which contains lime-treated thickener overflow. Solid wastes are pumped to an ash pond. The pond is periodically dredged and wastes ultimately disposed of in a mine. Although primarily designed for particulate removal, the scrubber does remove some SO_2 (35-40 percent with lime addition, LaMantia et al., 1977).

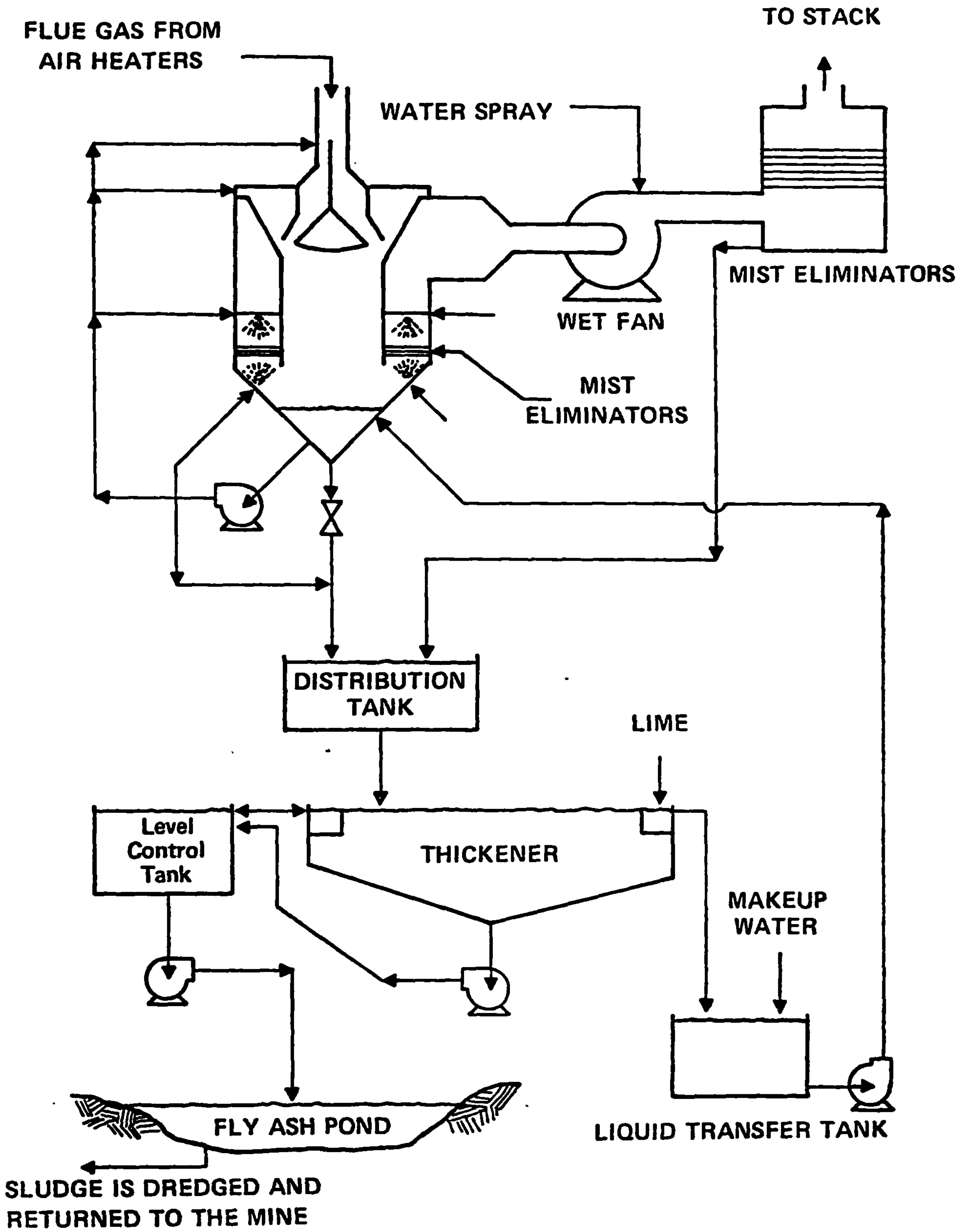

Figure 4-1. Simplified flow diagram of flyash scrubbers, Four Corners Plant (Arizona Public Service)

Source: LaMantia _et al_., 1977.

Figure 4-2 depicts a flow diagram of the combined particulate-SO_2 scrubbing system at Lawrence No. 4 Station (125 MW; Kansas Power and Light). Flyash is collected in the rod scrubber section; SO_2 is removed in the spray tower which uses limestone as a reagent. The gas then passes through mist eliminators and reheaters before exiting the stack. Slurry from the spray tower reaction tank is bled to the rod scrubber collection tank. Effluent from the collection tank is then pumped to a thickener and ultimately, a settling pond. Thickener overflow along with water from the pond provide makeup water for the scrubber system.

Preformed Spray

A preformed spray scrubber collects particles or gases on liquid droplets which have been atomized by spray nozzles. The atomized spray is directed into a chamber through which the inlet gas passes. Horizontal and vertical gas flowpaths have been used; spray entry can be cocurrent, countercurrent, or crossflow to the gas.

Inertial impaction is the principal collection mechanism. Residence times, especially with high-pressure sprays, are sufficiently short so as to preclude collection by diffusion. Efficiency is a function of droplet size, gas velocity, liquid-to-gas ratio, and droplet trajectories. The properties of the droplets are determined by the configuration of the nozzles, type of liquid, and pressure in the nozzle. Liquid-to-gas ratios for preformed spray scrubbers are generally higher than those for gas-atomized spray scrubbers causing heavy liquid entrainment. The pressure drop of the gas is low because atomization of the liquid is done by the nozzles and not by the gas. Plugging of the nozzles is the major operating problem with this type of scrubber.

The only applications of preformed spray scrubbers to power plants are at the Clay Boswell (360 MW) and Syl Laskin Stations (116 MW) (Minnesota Power and Light Co.) where they are used for particulate removal. Figure 4-3 shows a flow diagram of the Clay Boswell scrubber.

Flue gas passes cocurrently through a quench spray and high pressure spray. The high pressure spray is atomized when the liquid impinges on vertical rod baffles, the resulting turbulence causing the

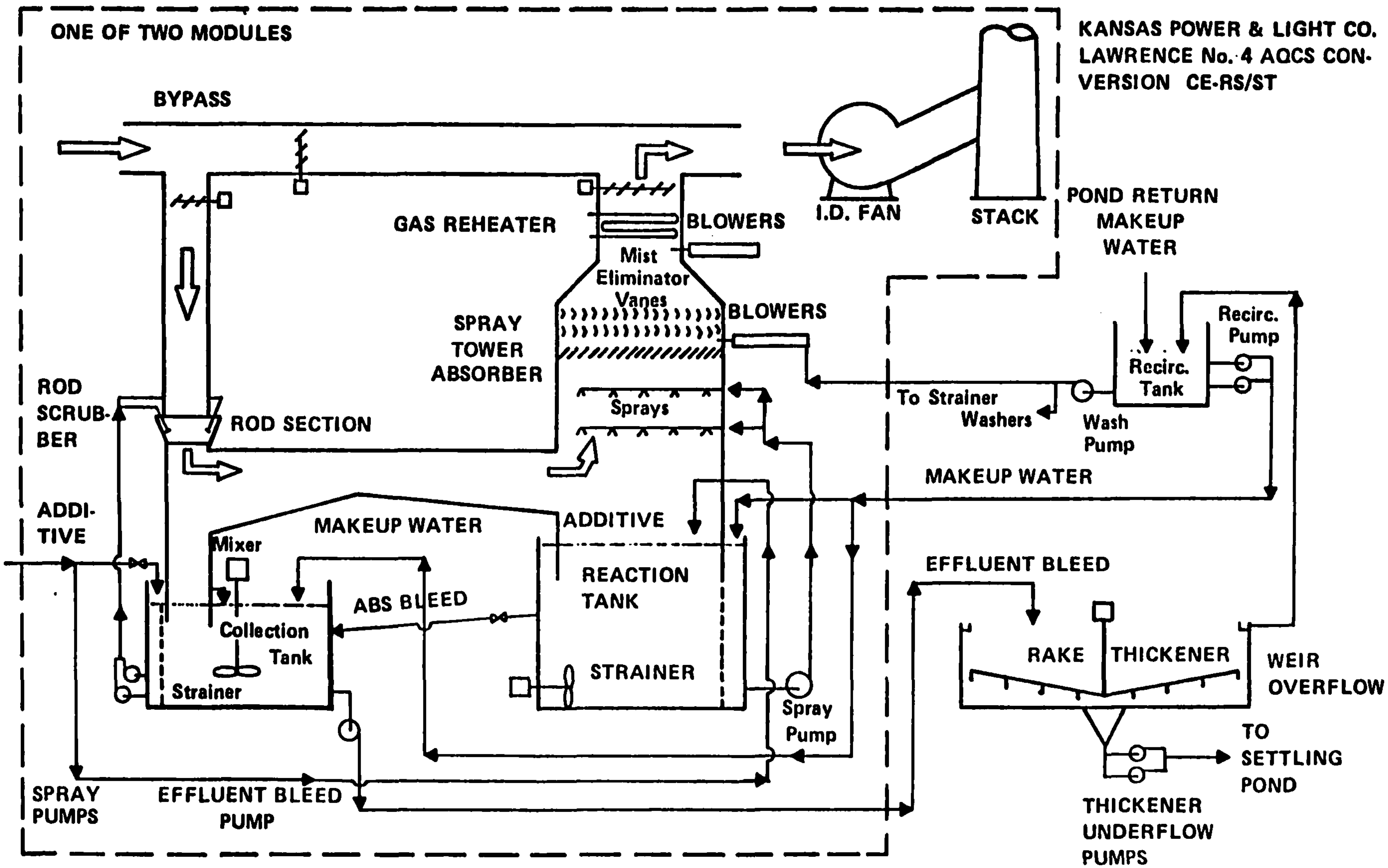

Figure 4-2. Flow diagram of combined particulate-SO_2 scrubber system at Lawrence No. 4 (Kansas Power and Light).

Source: Green and Martin, 1977.

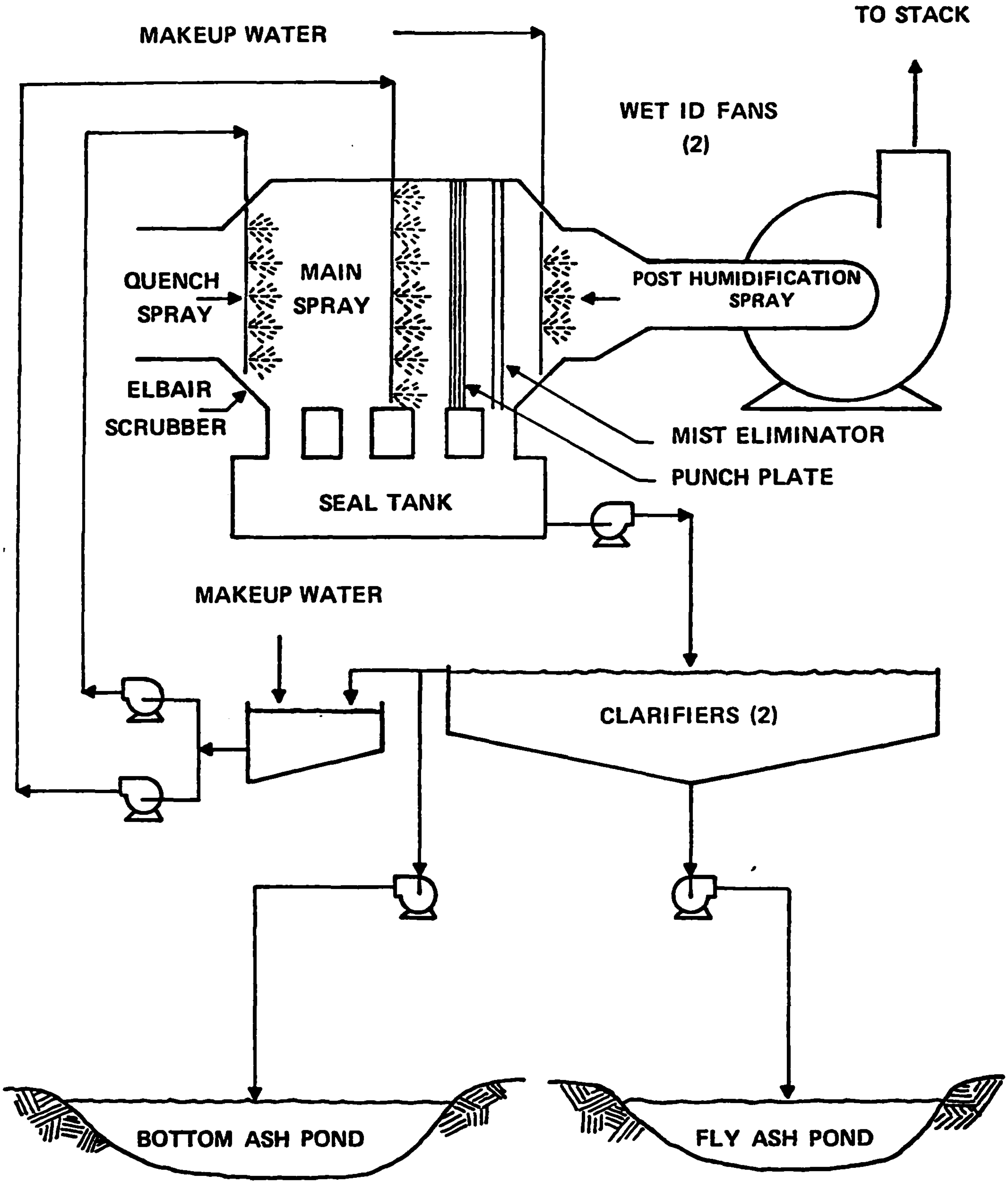

Figure 4-3. Simplified Flow Diagram for the Clay Boswell Station Particulate Scrubber (Minnesota Power and Light Company).

Source: LaMantia et al., 1977.

scrubbing. The gas then passes through a bank of vertical chevron demisters, a post humidification spray, and then exits the stack. Scrubbing slurry is supplied to the quench spray and high pressure spray nozzles. Fresh makeup water is used for the post humidification spray. Sprayed liquid drains to the seal tank at the base of the scrubber. Slurry from the seal tank is pumped to two clarifiers. Overflow from the clarifiers along with makeup water is recycled to the sprays. Clarifier underflow is pumped to a flyash pond.

Moving-Bed

Moving-bed scrubbers provide a region of mobile packing, such as plastic or marble spheres, where gas and liquid mix. Gas passes upward through the bed, while liquid is sprayed up from the bottom or passed down from the top. Particle collection is due to inertial impaction on atomized liquid and on mobile elements. Energy requirements are relatively low, typically a pressure drop of 4 in. W.G. per stage. Moving-bed scrubbers have excellent absorption capabilities and have been used as the SO_2 absorber following the venturi particulate scrubber at Cholla (Arizona Public Service) and Green River (Kentucky Utilities). Ball wear and wear of the supporting grids are the major operating problems with these scrubbers. At present, mobile-bed scrubbers are used for particulate removal at the Valmont, Arapahoe, and Cherokee Stations (Colorado Public Service) and at the EPA test facility at Shawnee (TVA).

Figure 4-4 shows a flow diagram of the scrubber at the Arapahoe Station which is typical of the scrubbers used by the Colorado Public Service. Flue gas entering at the base of the scrubber is presaturated before passing upward through the mobile-bed consisting of hollow plastic spheres. The gas is scrubbed by a countercurrent flow of liquor. Before exiting the stack, the gas passes through a chevron mist eliminator and steam coil reheater. Scrubber slurry supplied to the top of the tower and makeup water supplied to the demisters drain into the base of the tower. Most of the sump liquor is recycled to the mobile-bed; the rest is blown down to a slurry surge tank. Slurry from the tank is pumped to a clarifier. Clarifier overflow is discharged; underflow is pumped to sludge ponds. Ultimate disposal of sludge and ash is in a landfill.

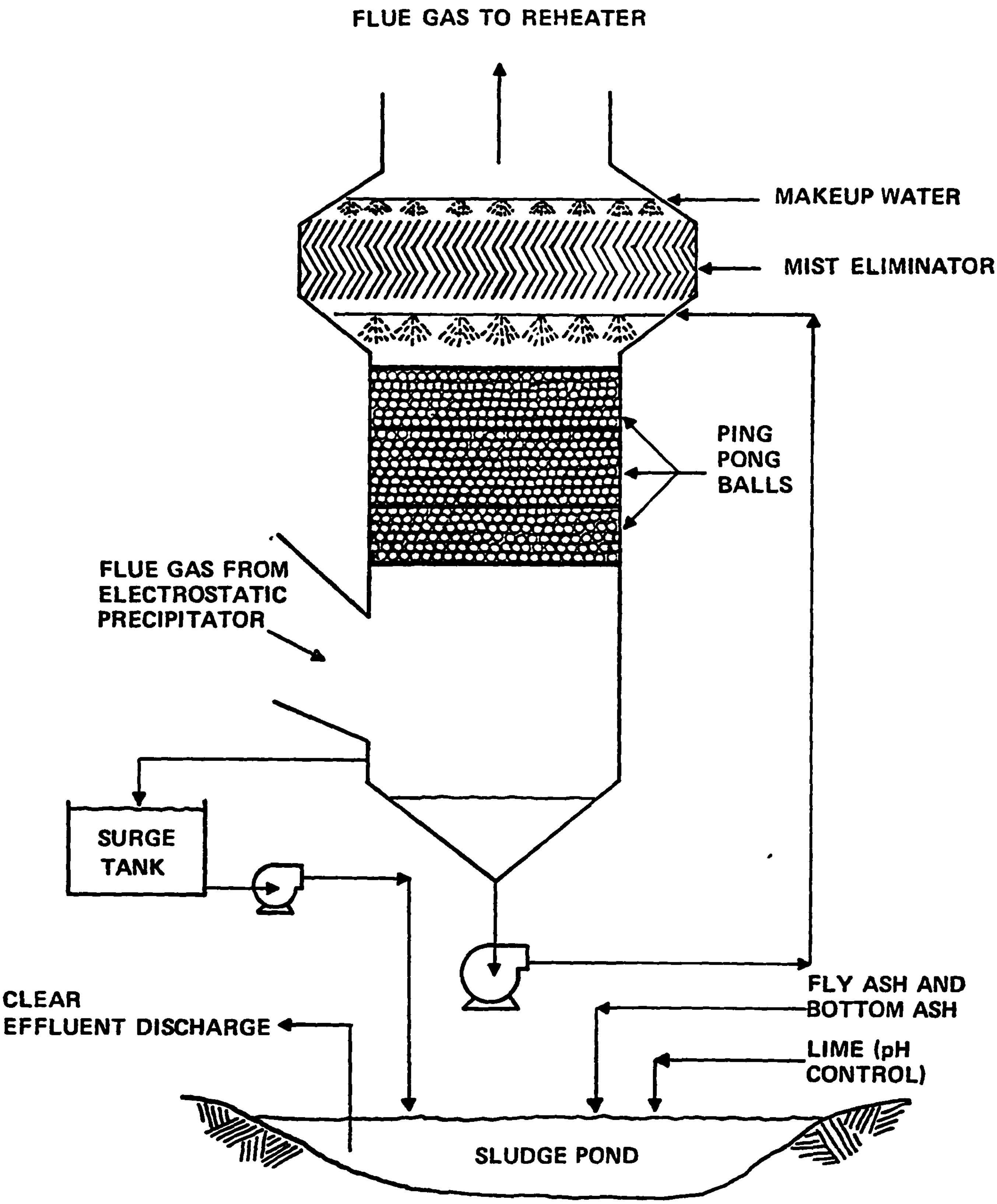

Figure 4-4. Simplified Arapahoe Station Scrubber Flow Diagram (Colorado Public Service).

Source: LaMantia et al., 1977.

Summary of Existing Scrubber Systems in the U.S.

Table 4-1 is a summary of the design and operating parameters of the various particulate and particulate-SO_2 scrubber systems in use at coal-fired power plants across the U. S. As indicated previously, gas-atomized scrubbers, and particularly, venturis, are the most widely used scrubber design for particulate removal.

The newer installations generally have better particulate removal capabilities, greater availabilities (defined as the fraction of a year that the scrubber appeared to be in operable condition), and treat larger volumes of flue gas. Landfill and ponding are the predominant methods of waste disposal. Few of the existing scrubber systems are now meeting the proposed New Source Performance Standard for particulates, 0.03 lb of particulate/million Btu, or about 0.017 gr/dscf. Only those systems operating with relatively large pressure drops, greater than 15.0 in. W.G., appear to be able to meet the Standard.

4.2 ESTIMATING POWER REQUIREMENTS

Estimating the power requirements of a particulate wet scrubber is a two-step process: first a determination of the size distribution of the dust is made; and second, an estimate is made of the power requirements for the scrubber which are necessary to meet emission standards. Two approaches, the contact-power rule and the cut-power rule, have been developed and are discussed below.

Contacting-Power Rule

The contacting-power rule, developed by Semrau (1977), represents a completely empirical approach to the design of particulate scrubbers. The fundamental assumption is that, for a given dust, scrubber performance depends only on the power consumed in gas-liquid contacting, regardless of scrubber size or geometry.

Power consumed in gas-liquid contacting depends on the manner in which the energy is introduced. For gas-atomized scrubbers, where the energy comes from the gas stream, theoretical power consumption is given by

$$P_G = 0.158 \, \Delta P, \text{ hp/1000 acfm} \qquad (1)$$

where ΔP = pressure loss across unit in inches W.G.

TABLE 4.1. CONDENSED SUMMARY OF PARTICULATE AND PARTICULATE-SO_2 SCRUBBERS IN THE U.S. PARTICULATE-SO_2 SCRUBBERS

Utility	Pennsylvania Power Co.	Kentucky Utilities	Montana Power Co.	Tennessee Valley Authority	Tennessee Valley Authority	Arizona Public Service Co.	Northern States Power	Kansas City Power & Light	Kansas Power & Light	Nevada Power Co.
Station	Bruce Mansfield No. 1, 2	Green River Station	Colstrip No 1, 2	Shawnee 10A	Shawnee 10B	Cholla Station	Sherburne No. 1, 2	La Cygne No. 1	Lawrence No. 4	Reid Gardner No. 1, 2, 3
Design and Operating Parameters:				(Test facility)	(Test facility)					
Start-up date	4/76	9/75	9/75	4/72	4/72	12/73	3/76	2/73	1/77	3/74
Reagent	lime	lime	flyash/lime	lime/limestone	lime/limestone	limestone	limestone	limestone	limestone	soda ash
Vendor	Chemico	AAF	CEA	UOP	Chemico	R C	CE	B&W	CE	CEA
Design	Venturi	Venturi/ Moving Bed	Venturi/ Wash Tray	Moving Bed	Venturi/ Spray Tower	Venturi/ Spray Tower	Venturi/ Moving Bed	Venturi/ Sieve Tray	Rod Scrubber/ Spray Tower	Venturi/ Wash Tray
Number of equipped boilers	2	3	2	1	1	1	2	1	1	2
Number of scrubber modules	12	1	6	1	1	2	24	8	2	2
Installed scrubber capacity, MW	1650	180	720	10	10	115	1400	870	125	330
Collector preceding scrubber		Mech	·	·						Mech
Reheat?	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Bypass?	No	Yes	No	No	No	Yes	No	No	Yes	Yes
Annual cost, mills/kWh	4.25	2.0	0.26	·		• 2.2	0.4	1.4	NA	NA
Coal heating value, Btu/lb	11,900	10,800	8,840	10,600(ave.)	10,600(ave.)	10,400	8,300	9,000 - 9,700	10,000	11,800
Sulfur in coal, pct.	4.7	3.7	0 8	coal type variable	coal type variable	0.5	0.8	5 - 6	0.5	0.6
Ash in coal, pct.	12.6	13.4	9			13.6	8	20 - 30	9.8	9.4
Calcium oxide in ash, pct.	NA	NA	22			3.5	NA	6.9	13.2	18
L/G, gal/1000 acf	20	39.5	15 for venturi 18 for spray	37	21 for venturi 9.4 for tower	10 for venturi 49 for tower	17 for venturi 10 for bed	12 for venturi 26.5 for tower	20 for scrubber 30 for tower	12.5
ΔP particulate scrubber, in. W.G.	20	7	17	8 - 16	3 - 16	15	11	7	9	15
ΔP system, in. W.G.	NA	NA	25.5			23.5	22	22	24	20
Inlet dust loading, gr/dscf	5 - 6.5	2.2	2.7	3.5 - 8.5	3.5 - 8.5	2.0	2.0 - 4.0	5.6	4 3	0.3 - 0.6
Inlet SO_2, ppm	2,200 - 2,600	2,200	800	2,500 - 4,000	2,500 - 4,000	420	400 - 800	4,500	425	300
Outlet dust loading, gr/dscf	0.007 - 0.017	99%(design)	0.018	0.036 - 0.090	0.003 - 0.050	0.016	0.035 - 0.044	0.074	0.04	0.02
SO_2 removal, pct.	92%(design)	90	80	60 - 99	60 - 99	59	50 - 55	80	90	85
Waste disposal	Landfill	Pond	Pond	Pond	Pond	Pond	Pond	Pond	Pond	Pond
Availability	97+	85.4	90+		·	95	90	NA	NA	90
Reference	1, 2, 3	3, 4	3, 5, 6	7, 8, 9	7, 8, 9	3, 10, 11	2, 3, 12	2, 3, 13	2, 3, 14	11

TABLE 4.1 (cont.) CONDENSED SUMMARY OF PARTICULATE AND PARTICULATE-SO_2 SCRUBBERS IN THE U.S. PARTICULATE SCRUBBERS

Utility	Arizona Public Service	Pacific Power & Light		Public Service Company of Colorado		Minnesota Power & Light		Montana-Dakota Utilities
Station	Four Corners	Dave Johnston	Valmont	Cherokee	Arapahoe	Clay Boswell	Syl Laskin	Lewis and Clark
Design and Operating Parameters:								
Start-up date	12/71	4/72	11/71	11/72-7/74	9/73	5/73	6/71	12/75
Vendor	Chemico	Chemico	UOP	UOP	UOP	Krebs	Krebs	R-C
Design	Venturi	Venturi	TCA	TCA	TCA	Preformed Spray	Preformed Spray	Venturi
Number of equipped boilers	3	1	1	3	1	1	2	1
Number of scrubber modules	6	3	2	9	1	1	2	1
Installed scrubber capacity, MW	575	330	118	660	112	350	116	55
Collector preceding scrubber	-	-	Mech	Mech/ESP	Mech/ESP	-	-	Mech
Reheat?	Yes	No	Yes	Yes	Yes	No	No	No
Bypass?	No	No	Yes	Yes	Yes	No	No	No
Annual cost, mills/kWh	NA	NA	NA	NA	NA	NA	NA	NA
Coal heating value, Btu/lb	9,200	7,430	10,800	10,100	10,100	8,400	8,400	6,450
Sulfur in coal, pct.	0.75	0.5	0.8	0.6	0.6	0.9	0.9	0.5
Ash in coal, pct.	22	12	9.0	12	12	9	9	8.5
Calcium oxide in ash, pct.	6.3	20	10	4	4	11	11	NA
L/G, gal/1,000 acf	8.5	13.3	50	50	50	8	8	11
Δ P particulate scrubber, in. W.G.	18	10	10 - 15	10 - 15	10 - 15	2.5	2.5	13
Δ P system, in. W.G.	28	15	NA	NA	NA	4	4	14.5
Inlet dust loading, gr/dscf	12	4	0.8	0.4 - 0.8	0.8	1.25	2	1
Inlet SO_2, ppm	650	500	500	500	500	1,125	1,125	520
Outlet dust loading, gr/dscf	0.01 - 0.02	0.04	0.02(min.)[a]	0.02(min.)[a]	0.02(min.)[a]	0.03	0.04 - 0.046	0.03
SO_2 removal, pct.	30 - 40	40	40	20	20	40	40	50
Waste disposal	Mine	Landfill	Landfill	Landfill	Landfill	Pond	Pond	Pond
Availability	100	NA	75	70 - 90	40 - 70	100	100	NA
Reference	1, 11	11	11, 15	11, 15	11, 15	11,16	11, 16	11, 17, 18

[a]Best performance of scrubber at highest pressure drop (15).

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14. K. Green and J. Martin, 1977.

15. Private communication, B. Pearson, Public Service Company of Colorado.

16. Private communication, D. VanTassel, Minnesota Power and Light.

17. Private communication, D. Sadowsky, Montana-Dakota Utilities.

18. Private communication, M. Richmond and H. Fox, Research-Cottrell, Inc.

For preformed spray scrubbers, where the energy comes from the liquid stream, theoretical power consumption is given by

$$P_L = 0.583\ \Delta P_L\ Q_L/Q_G,\ \text{hp/1000 acfm} \qquad (2)$$

where ΔP_L = pressure loss in liquid, lb/in^2
Q_L = liquid flow rate, gal/min
Q_G = gas flow rate, ft^3/min

When scrubber overall particle collection efficiency for a constant inlet dust is measured over a range of power consumptions, it is often found that the "scrubber performance curve" plots as a straight line on log-log paper, implying a power relationship given by

$$N_T = \alpha P_T^{\gamma}$$

where N_T is the dimensionless transfer unit, related to efficiency (η) by $N_T \equiv \ln(1/(1-\eta))$ and P_T is given by

$$P_T = P_G + P_L.$$

The empirical constants, α and γ, depend only on the characteristics of the particulate, but are little affected by scrubber size or geometry.

The contacting-power rule finds a useful application in the design of particulate scrubbers: since the performance curve is independent of scrubber size, mini-scrubbers are first used on a particular dust to determine the pressure drop necessary to meet emission standards. The full-scale scrubber is then designed by scaling up from the mini-scrubber results.

The contacting-power rule further implies that scrubbers operated at higher power consumptions will be more efficient particulate collectors--provided the increased energy results in better gas-liquid contact. Figure 4-5, derived from Table 4-1, is a log-log plot of operating points, outlet dust loading at a given power consumption, for various power plant scrubber systems. (Theoretical power consumption was determined by Equations 1 and 2. Plotting outlet dust loading against power consumption is essentially equivalent to the

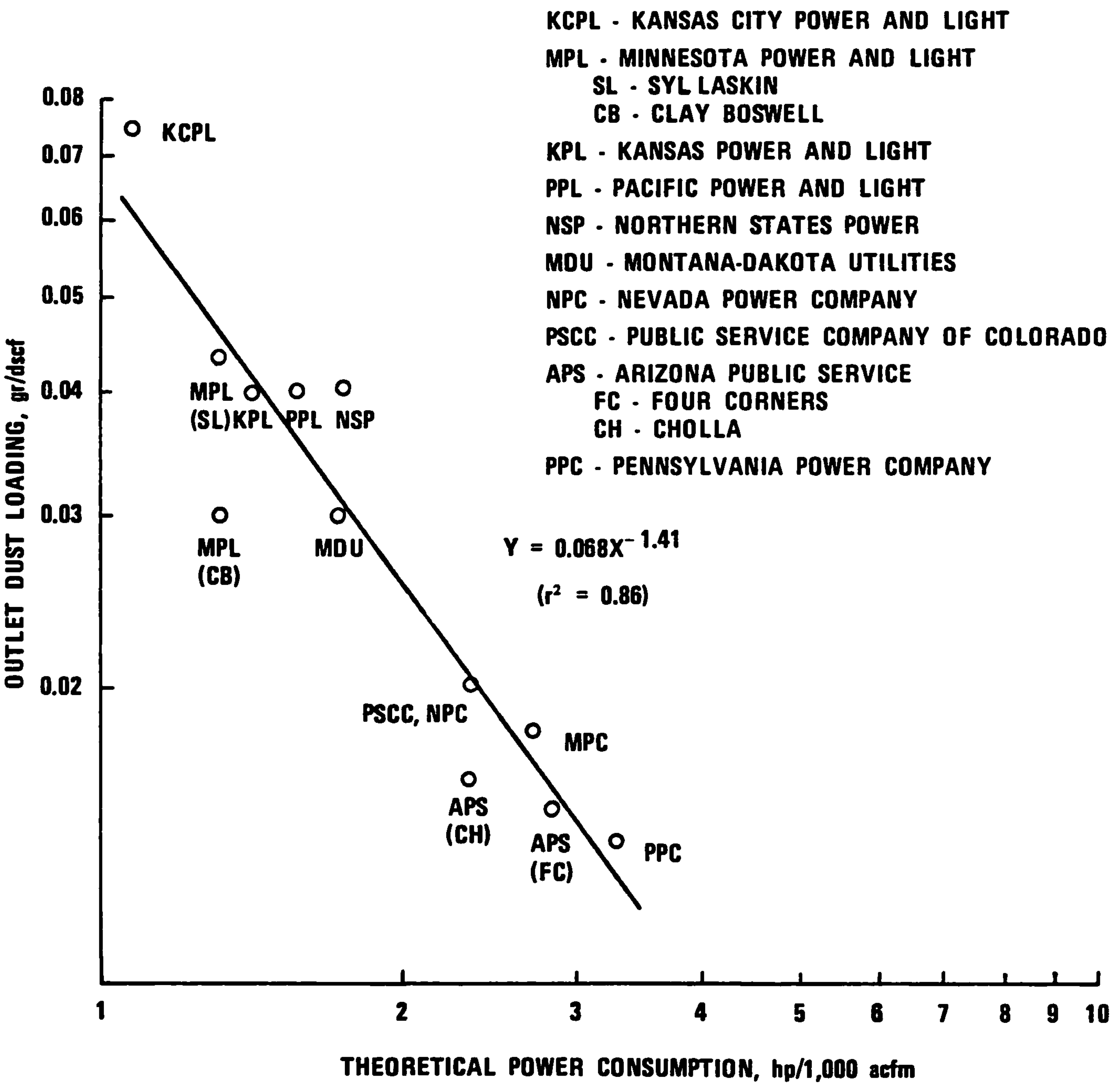

Figure 4-5. Correlation of scrubber outlet dust loading with theoretical power consumption.

procedure used in the contacting-power rule, assuming that flyash size distributions are the same for the various utility boilers.) As shown, the operating points can be readily fitted to a straight line, implying a power-function relationship between scrubber overall collection efficiency and power consumption. The least-squares correlation was $Y = 0.068\ X^{-1.41}$, $r^2 = 0.86$. The good fit is quite remarkable given the variety of coals, furnaces, process variables, and inlet particle size distributions among the plants. Based on this correlation, to achieve the proposed New Source Performance Standard for particulates of about 0.017 gr/dscf, approximately 2.7±0.3 hp/1000 acfm (95 percent confidence limits) theoretical power consumption, or equivalently, 17±2 in. W.G. pressure drop is required. Although this value is only approximate, it does underscore the fact that conventional scrubbers require a large power consumption to meet the proposed New Source Performance Standard. Further, this figure represents only the theoretical power consumption across the particulate scrubber. The actual system pressure drop will include fan losses, and losses across the absorber, mist eliminator, and ductwork.

Cut-Power Rule

Whereas the contacting power rule provides an empirical approach to the design of particulate scrubbers, it lacks generality in that it is specific to a particular dust. A more general and theoretical approach was taken by Calvert (1972, 1977) who related scrubber fractional efficiency to power consumption.

The cut-power rule uses the quantity called the "cut diameter," the diameter at which the collection efficiency of the scrubber is 50 percent. Most scrubbers that collect particles by inertial impaction perform in accordance with the following equation:

$$P = \exp(-A\ d_p^{\ B}) \qquad (3)$$

where P = particle penetration

A,B = dimensionless constants

d_p = aerodynamic particle diameter

Assuming a log-normal distribution, Equation 3 can be integrated, yielding a plot of overall penetration against the ratio of required cut diameter to mass median diameter. Hence, by knowing the inlet particle size distribution and the efficiency needed to meet emission standards, one can determine the required cut diameter. For example, for a "typical" flyash particle size distribution of d_g = 17 μm, σ_g = 4, to achieve 99% collection efficiency would require a cut diameter of approximately 0.6 μm. To determine which scrubber types can meet this cut diameter, Calvert developed theoretical impaction models of scrubber performance (cut diameter) versus power consumption for various scrubber types. To achieve a cut diameter of 0.6 μm, a venturi scrubber would require a theoretical pressure drop of 15 in. W.G., agreeing well with the figure of 17±2 in. W.G. determined from the empirical correlation above.

Figure 4-6 is a plot of theoretical venturi scrubber performance curves and actual performance points for scrubbers operating on coal-fired boilers (based on published data). The performance of the actual scrubbers suggests that, as expected, lower cut diameters (higher collection efficiencies) are achieved at the expense of greater power consumption. Further, the performance of the venturi scrubbers agrees well with the theoretically predicted performance for wettable particles. (The venturi scrubber performance model is evaluated for different values of the dimensionless factor f. The value f = 0.50 corresponds to wettable particles, whereas f = 0.25 corresponds to nonwettable particles (Calvert, 1977).)

The case of the moving-bed scrubber at Cherokee Station deserves special mention. As shown in Figure 4-6, independent measurements at similar pressure drops resulted in radically different values for the cut diameter. In this regard, Ensor et al., (1975) reported highly variable outlet particle concentrations which did not correlate with pressure drop, suggesting the presence of reentrained solids from the mist eliminator. The authors concluded that the "evidence... weighs against one considering the agreement between predicted and experimental cut diameters to be anything more than coincidence (Ensor et al., 1975)." It might also be noted that a valid model for the performance of moving-bed scrubbers has not yet been developed (Calvert, 1978).

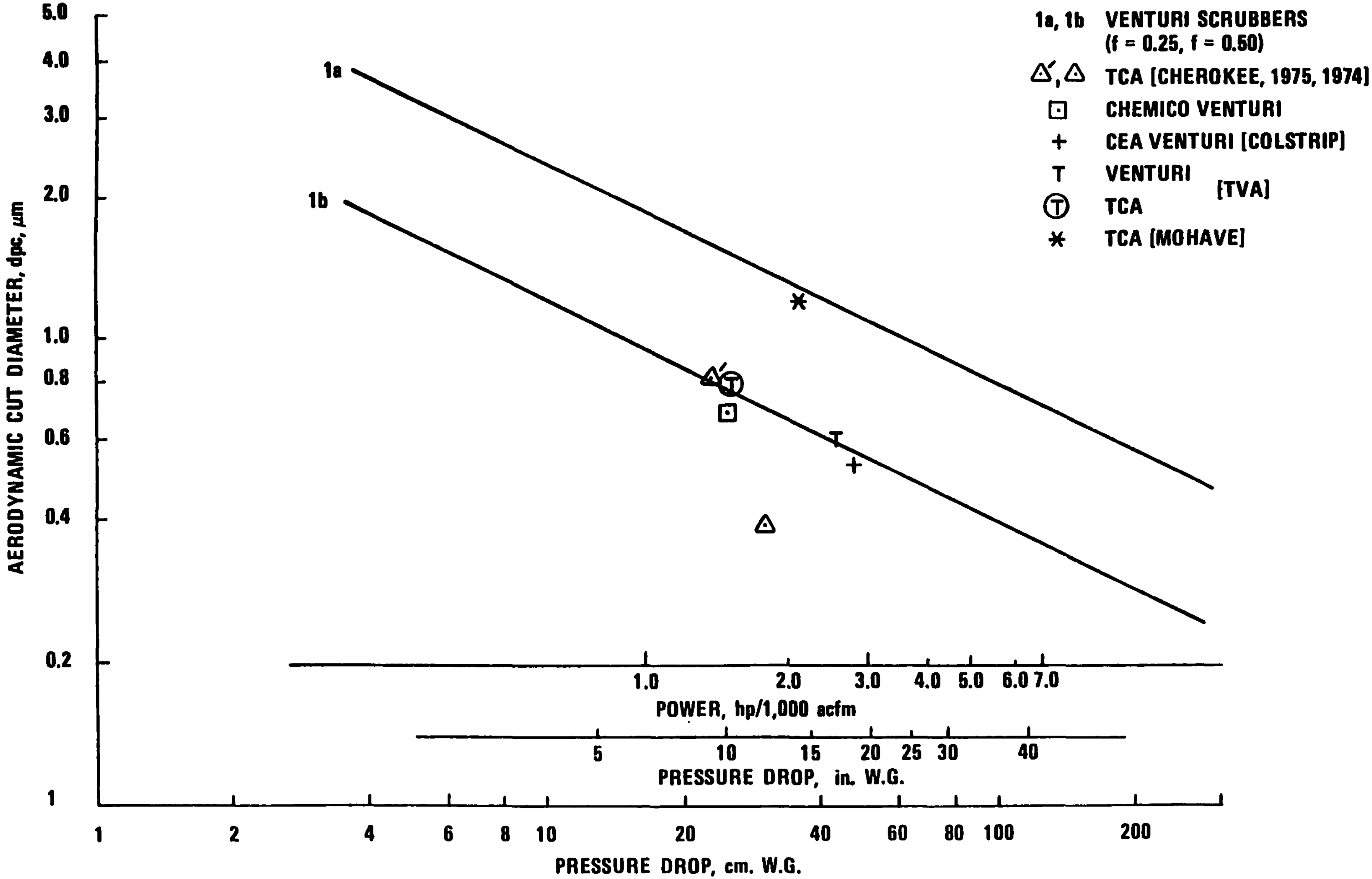

Figure 4-6. Theoretical and experimental cut diameters.

In general, the limitations of the techniques for measuring flyash size distributions (see Section 5.6) undermine the usefulness of the cut-power approach.

4.3 NOVEL SCRUBBERS

Conventional scrubbers collect particles primarily by inertial impaction. However, the collection efficiency of conventional scrubbers decreases significantly for fine particles, resulting in the need for relatively large power consumptions to remove the fine particles. As has been shown, flyash contains a substantial fraction of fine particles, with the result that scrubber systems operating on utility boilers may require pressure drops as high as 30 in. W.G. This pressure drop represents a large power loss to a utility.

In 1973, EPA initiated a novel device evaluation program. The purpose of the program was to identify, evaluate, and where necessary, develop devices which would have better collection efficiencies of fine particles. The results of this program indicate that the most efficient novel scrubbers are those that utilize additional collection mechanisms other than just inertial impaction.

The most promising of these novel devices are electrostatically augmented scrubbers and condensation scrubbers. The former increases particle collection by increasing the electrostatic attraction between particles and droplets. The latter increases particle collection by growing particles into a size range which is easier to collect and also, by increasing diffusiophoretic forces. Other novel scrubbers, which either consume large amounts of power or require the use of waste heat, are deemed inappropriate for use on utility boilers and are not discussed below.

Condensation Scrubbers

The use of condensing water to improve scrubber particle collection efficiency is not a new idea, but until EPA sponsored research on the subject, only small-scale laboratory studies had been done. Calvert 1973, 1974, 1975 and 1977) developed models for particle collection in condensation scrubbers and attempted to verify those models in bench- and pilot-scale studies.

Calvert's studies indicate that collection of fine particles in a condensation scrubber depends strongly on the inlet dust concentration and the flue gas enthalpy. In assessing the possible uses of condensation scrubbing, Calvert (1975) gives an approximate minimum enthalpy of 100 kcal/kg (about 180 Btu/lb) which would be necessary for high efficiency particle removal in a condensation scrubber. Flue gas from utility boilers typically contain 5 to 15 percent moisture (see Section 3.3). Even at 15 percent moisture, the enthalpy would only be about 180 Btu/lb, indicating that condensation scrubbers would have only marginal application to power plants (see Appendix B for a more detailed evaluation). Furthermore, the collection efficiency of condensation scrubbers decreases with increasing dust concentration because there is less water available to condense on each particle. Theoretical calculations by Calvert (APT, 1974) have shown, for example, that for a three-plate condensation scrubber operating at a condensation ratio of 0.1 g vapor condensed/g dry air, particle collection efficiency for 0.75 μm (aerodynamic) particles decreased from 100 percent at a concentration of 2×10^5 particles/cm^3 (about 0.01 gr/scf, assuming a density of 2.0 gm/cm^3) to about 60 percent at a concentration of 10^7 particles/cm^3 (about 0.6 gr/scf). Insofar as utility flue gas may contain dust loadings as high as 8 gr/scf, condensation scrubbing does not seem very feasible.

In short, whereas it may be possible to incorporate some condensation effects in scrubbers operating on utility flue gas, a condensation scrubber per se would not be recommended.

Electrostatically Augmented Scrubbers

A number of novel devices have been developed recently which use electrostatic forces to enhance particle collection. The scrubber types using electrostatic augmentation vary considerably in design, but can be classified according to whether the particles and/or the water is charged, and whether an external electric field is applied.

Two of the most tested electrostatically augmented scrubbers are the TRW Charged Droplet Scrubber and the UW Electrostatic Scrubber. The TRW scrubber uses charged droplets and an externally applied electric field to collect particles. It has been used successfully on emissions from a coke oven battery. The UW scrubber charges both the water droplets and the particles (charged to opposite polarity); a pilot scale unit has been successfully used on emissions from a power plant. Both of these devices have shown high efficiencies (over 90 percent) for submicron particles at substantially less power consumption than would be required for a conventional venturi.

Whereas the performance of these small scale units has been encouraging, several points must be borne in mind before a full-scale unit is planned for use on a power plant. First, utility flue gas contains a heavy dust loading, as large as 8 gr/dscf, and even greater. (The UW scrubber, although showing good collection efficiency of flyash from a power plant, because of the sampling arrangement, had extremely low inlet dust loadings of 0.5 gr/dscf or less (Pilat and Raemhild, 1978).) Heavy dust loading, for example, would probably necessitate greater charging in a UW-type scrubber. Secondly, most utilities handle large volumes of gas compared to the volumes handled by these small units. The same cost savings may not be realized in a scaled-up version of these smaller units; the economics would have to be worked out on an individual basis. Finally, any novel scrubber may suffer the same corrosion problems that conventional scrubbers have experienced at power plants. Section 5 of this report provides a summary of operating experience of conventional scrubbers at power plants, and hence, will be useful in the design of any novel scrubber.

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5.0 DESIGN CONSIDERATIONS FOR WET SCRUBBER SYSTEMS

Although scrubber technology has advanced considerably since the first applications of scrubbers to coal-fired boilers, much of this advancement has taken the form of ad hoc solutions to operating problems at various installations. Nevertheless, operating experience is not without interest since it seems to militate against certain bad designs or materials and to favor the use of particular operating or maintenance procedures.

In the following section, various scrubber topics, such as mist elimination or reheat, are discussed. The approach is to first summarize the state-of-the-art, including both utility experience and any theoretical treatments, and then to list sources of information on the topic. It is hoped that this approach will provide a useful base from which to design various components of the optimum wet scrubber system.

5.1 MIST ELIMINATORS

General Considerations

Mist elimination is a requisite for every scrubber system. Mist eliminators remove scrubber-liquid droplets that are entrained in the flue gas and return the liquid to the scrubber. Poor mist elimination, an all too common problem, can have serious consequences, including corrosion downstream, an increase in particle outlet loading, an increase in power requirements for reheat, and an increase in water consumption. The state-of-the-art of mist elimination is discussed below.

Design Considerations

In a system study for EPA, Calvert, Yung, and Leung (1975) evaluated the performance of various mist eliminators. The results of this study that are relevant to a utility scrubber system are as follows:

- Overall droplet collecton efficiency of a mist eliminator depends on primary collection and reentrainment. Both overall and primary collection increase with increasing gas velocity. At high gas velocities (nominally, 5 m/sec and over), reentrainment occurs, decreasing the overall collection even though primary collection remains high.
- Higher reentrainment velocities (greater mist eliminator capacity) are obtained with mist eliminators which have good drainage. Thus, horizontal gas flow mist eliminators have greater capacities than vertical gas flow types. Similarly, vertical gas flow mist eliminators with 45° baffles had larger capacities than those with baffles inclined at 30° or 0°.
- Pressure drop across a baffle mist eliminator is reasonably well predicted by a model based on the drag coefficient for a single plate held at an angle to the gas flow.
- Solids deposition is greater on inclined baffles than on vertical ones because of the increase in settling rate of suspended solids. Deposition rate decreases as the slurry flux on the surface increases.

Designs Used in Utility Scrubber Systems

A review of commercial mist eliminator designs in use in the utility industry revealed the following practices (Ellison, 1978):

- Vertical gas flow mist eliminators are used almost exclusively. The chevron multipass (continuous vane) construction and the baffle construction (noncontinuous slats) are common.
- Vane spacing is generally 1.5 to 3.0 inches except in the second stage of two-stage designs which generally use 7/8 to 1 inch spacing.
- Plastic is the most common material of construction due to reduced weight, cost, and corrosion potential.
- Precollection and prewashing stages are commonly used to improve demister operation.
- Demister wash systems typically operate intermittently using a mixture of clear scrubber liquid and fresh makeup water.

Horizontal gas flow mist eliminators have only recently been used in this country, although they are common in Japan and Germany. This type of mist eliminator has better drainage than vertical flow types, but space requirements are greater.

Sources of Information

See Calvert, Yung, and Leung (1975), Calvert (1978), Conkle *et al.*, (1976), and Ellison (1978). See McIlvaine (1974) for a review of proprietary designs.

5.2 CORROSION AND MATERIALS OF CONSTRUCTION

General Considerations

Wet scrubber systems operating on coal-fired boilers encounter an extremely corrosive and erosive environment. Materials of construction are subject not only to attack from absorbed SO_2 and SO_3 but also attack from chlorides. The chlorides enter the system from the coal, and the makeup water. Closed-loop operation of the scrubber system tends to build up the chloride concentration. Erosion from collected flyash aggravates the corrosion problem by destroying the protective layer of the material.

The general trend in selection of materials has been an increase in the use of higher grade alloys which are resistant to corrosion and erosion. The expense of these alloys, however, prevents extensive use of them in scrubber systems. Instead, various linings are often used to protect less corrosion-resistant metals. But linings are temperature sensitive: temperature excursions can be disastrous.

Plant Experience and Recommended Practices

Table 5-1 summarizes the materials of construction at a number of utility scrubber systems as well as some of the solutions to corrosion problems. Table 5-2 is a list of suggested materials of construction for an SO_2 absorber based on sulfuric acid and chloride concentrations (Gleason, 1975). A more detailed discussion of the materials of construction for components of a scrubber system follows.

Scrubber. Materials of construction include flake-lined steel, rubber-lined steel, or 316L stainless steel. In venturi scrubbers, abrasion-resistant materials such as brick-lined steel or high nickel alloys are recommended for the venturi throat. For SO_2 absorption, simple designs, such as spray towers, are recommended; moving-bed scrubbers suffer excessive wear.

TABLE 5.1. MATERIALS OF CONSTRUCTION FOR FULL-SCALE SYSTEMS

System	Scrubber	Outlet Duct	Mist Eliminator	Reheater	Fan	Pipes	Pumps	Valves	Tanks	Comments
Colstrip Station (MPC)	V-FL, A-FL V-Throat-Brick W.T.-316SS	FL	PP	Plate-1625, H-316LSS, Other-HG	H-RL	Slurry-RL Other-SS	RL	RL	FL	
Sherburne County Generating Plant (NSP)	V. Rod, M.B. and Drain Pots-316L, H-CL	CS	FRP	CS	DF-CS	RL, Hetron and CS	Ni-Hard	N.A.	N.A.	Main spray pipe is RL. Venturi rod section piping is Hetron. Some scrubber parts are FL.
Reid Gardner Station (NPC)	V-Throat-1825 V-RL W.T.-316LSS	P4L	316LSS	CS	DF-CS	RL	RL	N.A.	RL	Some rubber linings became loose during startup, original rigid flake in scrubber failed.
Cholla Station (APS)	V-316LSS, A-316SS A was FL	FL	PP	316L	DF-CS	P	RL	RL	FL	Future reheaters will be of Inconel. Absorbers were FL SS. Problems in second absorber.
Four Corners Plant (APS)	V-Throat-SCBL Other-PLL or SSL	PLL	N.A.	316SS	1625	Slurry-RL	RL	RL or SS	N.A.	Reheaters have been removed. Original 316SS fan was replaced due to stress fatigue. Original alloy 20 pumps have been replaced.
Dave Johnston Plant (PP&L)	V-PL	PL (Cracking)	PVC	None	I-1625 H-RL	RL	I-HM H-RL (Cracking)	RL	N.A.	Need to replace RL valves at high abrasion points. Changed to straight through plug. New plumbob SS due to PL failure.
Arapahoe Station (PSCC)	G-SS Other-RL	MS	SS	CS	DF-CS	RL	RL	316SS or RL	N.A.	
Cherokee Station (PSCC)	G-SS Other-RL	MS EJ-SS & F	SS(1&3) 316SS(4)	CS(1&4) SS(3)	N.A.	RL	RL	316SS (1&3) RL(4)	RL	1, 3 and 4 refer to Units 1, 3 and 4.
Valmont Station (PSCC)	G-SS Other-RL	MS EJ-SS & F	SS	CS	DF-CS	RL	RL	SS	RL	
Aurora Station (MP&L)	316ELC	FL	316L	None	316L	Slurry-316LSS Other-FRP or RL	316SS	Slurry-316SS	N.A.	Scrubber liquid discharge pipe changed from RL to 316LSS, FRP joints failed at 200 psi. *RL on pumps failed due to high pressure.*
Clay Boswell (MP&L)	316SS	FL	316L	None	316L	RL	RL	N.A.	N.A.	FRP piping replaced with RL.

See next page for explanation of symbols.

Source: LaMantia (1977).

Key to TABLE 5-1

Component		Materials		Other	
A	– Absorber	CL	– Ceilcote lining	N.A.	– Not available
DF	– Dry fan	CS	– Carbon steel		
EJ	– Expansion joints	F	– Fabric		
G	– Grid plate	FL	– Flake-lined		
H	– Housing	FRP	– Fiberglass		
I	– Impeller	HG	– Hastelloy G		
MB	– Marble bed	I625	– Inconel 625		
V	– Venturi	I825	– Inconel 825		
W.T.	– Wash tray	MS	– Mild steel		
		P	– Plastic		
		P4L	– Plasite 4004-S epoxy-lined		
		PL	– Polyester-lined		
		PLL	– Plastic-lined		
		PP	– Polypropylene		
		PVC	– Polyvinyl chloride		
		RL	– Rubber-lined		
		SCBL	– Silicon carbide brick lining		
		SS	– Stainless steel		
		SSL	– Stainless steel-lined		

TABLE 5-2. RECOMMENDED MATERIALS FOR FGD SCRUBBERS

Design	Chloride Concentration (p.p.m.)	H_2SO_4 Concentration (Percent)	Scrubber Region - Material	
			Lower Tower (Humidifier Section)	Upper Tower (Tray Section)
Once-Through	< 150	0.25	Mild steel, lead, brick	316 ELC stainless steel
Once-Through	150 - 3,000	0.25	Mild steel, lead, brick	Alloy - 20
Once-Through	>3,000	0.25	Mild steel, rubber lining, brick	Mild steel, rubber lining with titanium or Hastelloy C
Recycle	<150	2	Mild steel, lead, brick	316 ELC stainless steel
Recycle	<150	2 - 20	Mild steel, lead, brick	Alloy - 20 or Hastelloy C (+70° C)
Recycle	<150	20 - 30	Mild steel, lead, brick	Mild steel, lead or rubber, Hastelloy C trays
Recycle	19,000	0.25	Mild steel, rubber, brick	Mild steel, rubber, Hastelloy C
Recycle	150 - 1,000	2 - 5	Mild steel, rubber, brick	Alloy - 20
Recycle	1,000 - 5,000	2 - 5	Mild steel, rubber, brick	Mild steel, rubber lining, Hastelloy C

Source: Gleason (1975).

At Sherburne Station (Northern States Power) erosion has been minimized by the use of wear plates. At Cholla Station (Arizona Public Service) corrosion and erosion have been minimized by the use of Carpenter 20 (for stress corrosion) and Inconel alloy 625 and silicon carbide refractory (for corrosion and erosion).

Scrubber lining failures have been observed at many systems. The reasons for failure are not known for sure, but poor application, thermal shock, and deterioration are possible causes. Thermal shocks could be minimized by the use of emergency sprays regulated by temperature gauges.

Ducts. Lined steel or carbon steel have been used for ducts, the former being used for wet gas downstream of the scrubber, the latter for reheated gas. Here, too, linings and other materials of construction have failed due to acid condensate with subsequent corrosion. Expansion joints should probably be made of nonmetallic materials.

Mist Eliminators. Mist eliminators are typically made from 316L stainless or fiber reinforced plastic. Plastic types are recommended because of reduced weight, less solids buildup, and less corrosion potential.

Reheaters. Reheaters have been made from carbon steel, 316 stainless, or high grade alloys such as Inconel and Hastelloy. The reheater is a bad problem area since it is subject to both sulfur acids and chloride attack. The higher grade materials are recommended.

Fans. Materials of construction for fans include carbon steel, 316 stainless steel, rubber-lined steel, or Inconel. Carbon steel is used for dry gas after reheat. Abrasion, fatigue cracking, and solids buildup causing imbalance are the most common problems with fans.

Piping, Pumps and Valves. Rubber-lined steel is the most commonly used material for construction of pumps. However, high pressure rubber-lined pumps (200 psi) have failed at the Syl Laskin Station (Minnesota Power and Light) and were replaced by pumps made of 316 stainless. By contrast, pumps made of alloy 20 failed at Four Corners (Arizona Public Service) and were replaced by rubber-lined pumps.

Rubber-lined steel valves and stainless steel valves are used in scrubber systems. At the Dave Johnston Plant (Pacific Power and Light) rubber-lined valves have failed at high abrasion points.

Rubber-lined pipes are used most often, but stainless steel and plastic pipes are also used. Failure of high pressure fiber-reinforced plastic pipes occurred at the Syl Laskin Station and were changed to rubber-lined pipes.

Stacks. Stacks are subject to mortar joint damage when operated under wet gas conditions. Fiber-reinforced plastic has been successfully used as a stack liner.

Design Considerations and Maintenance Procedures

Some corrosion problems can be minimized by prudent design and careful construction. Since corrosion attack is known to be more severe underneath deposits, good scrubber designs incorporate provisions for effective drainage. Crevices are the single greatest source of localized corrosion. Hence, the actual construction must be scrutinized and any discovered crevices either filled with a plastic or welded shut. Welding procedures, too, must be carefully chosen since poor welds are often the target of corrosion attack. Welding can also damage coatings.

Finally, operating and maintenance procedures can prevent serious corrosion problems. The LaCygne Station (Kansas City Power and Light), where both particulates and SO_2 are scrubbed, is exemplary. Here maintenance procedures include a weekly cleaning of each scrubber module to remove scale. Operating procedures include regulation of the pH (in the range of 5.5 to 5.7) to minimize scale and measurement of the slurry chloride level to insure a low level.

Source of Information

Power plant experience is summarized by LaMantia *et al.*, (1977). The state-of-the-art in corrosion and materials of construction for wet scrubber systems was greatly advanced by a recent joint NACE, APCA, and IGCI conference held in Atlanta, Georgia, January 1978. The proceedings from this conference were reviewed by Javetski (1978) and McIlvaine (1978).

5.3 REHEATERS

General Considerations

Although reheating of scrubbed flue gas is not required by law, reheaters are often incorporated into flue gas wet scrubber systems. Usually, little attention is given to the design of reheaters, yet failure of the reheater can cause severe operational problem.

There are four major reasons for providing reheat in flue gas wet scrubber systems:

- avoid downstream condensation
- avoid a visible plume
- enhance plume rise and pollutant dispersion
- protection of the induced-draft fan.

Reheat may also prevent acid rain and stack icing, as well as reduce plume opacity.

There are three types of reheaters commonly used at utilities. These are in-line reheaters, direct combustion reheaters, and indirect hot air reheaters. In-line reheaters are heat exchangers placed within the gas stream. Steam or water are used as the source of heat. Direct combustion reheaters burn either oil or gas, mixing the combustion gas with the flue gas. Combustion chambers can be located either in-line or external to the duct. Indirect hot air reheaters inject heated ambient air into the flue gas stream. The air is heated either in an external heat exchanger or in the boiler preheater. Alternatively, some utilities have chosen not to use any reheat system, operating the stack under wet conditions.

Operational Experience and Design Considerations

Operational experiences with these types of reheaters and the option of no reheat are summarized in Tables 5-3 through 5-7. In general, the choice of reheater type depends on space limitations and on the amount of power that can be expended. For the same degree of reheat, indirect hot air reheat has the highest energy requirements, but does provide the beneficial effect of dilution (Leivo, 1978). The characteristics of the particular installation must be considered in the design of any reheat system.

TABLE 5-3. SURVEY OF IN-LINE REHEAT SYSTEMS USING STEAM

Power Plant	Kansas City Power & Light	Arizona Public Service		Montana Power	Public Service Company of Colorado		Commonwealth Edison
	LaCygne	Cholla No. 1	Four Corners No. 1,2	Colstrip No. 1,2	Cherokee No. 1	Cherokee No. 2	Will County
Scrubbing System	Limestone	Limestone (R-C)	Venturi (Chemico)	Alkaline Flyash (CEA)	TCA (UOP)	TCA (UOP)	Limestone (B&W)
Heating Medium (Steam)							
Pressure, psig	115	250	260		300	300	350
Temperature, °F	650	Saturated	600		420	720	485
Consumption, lb/hr	50,000	20,000	7,800		33,000	19,300	50,000
Heat Exchanger							
Tube size	5/8" O.D., bare tube	1" O.D., bare tube	Finned tubes	Plate type	5/8" O.D., bare tubes	5/8" O.D., bare & finned tubes	5/8" O.D., bare tube
Number of tube banks	4 banks, 4 rows/bank	2 banks	2 banks		2 banks, 3 rows/bank	3 banks, 3 rows/bank	3 banks, 8 rows/bank
Materials of construction	SS 316 L	SS 316 L	SS 316 L	Inconel 625, Hastelloy G	Carbon steel	Carbon steel	SS 316 L & carbon steel
Soot blowing	250 psi steam blower	Steam, 2 blowers/bank, once/4hrs	Steam blower, once/day		Steam blower, once/8hrs	Steam blower, once/8hrs	Every 4 hours
Reheat Temperature, °F	150	160	143	170	185	160	160
Reheater Problems	The 304 SS reheater failed because of chloride and acid corrosion. Reheater plugged with scrubber slurry.	Module A reheater (with scrubbing) Harmonic vibrations. Module B reheater (without scrubbing) Harmonic vibrations. Chloride and sulfurous acid attack.	Corrosion caused reheater to be removed after one year. Pitting corrosion thought to be caused by sulfate.	Loose scale formed on reheater but caused no operating problems.	Reheater originally had 3 banks. Upper bank was removed due to pluggage and corrosion.	After 6 months in service, a major jet washing cleaning job was done. After 2-1/2 years of operation, major acid attack was found throughout finned and bare tube sections.	Module A reheater: reheater tubes failed because of chloride corrosion. Reheater also plugged with solids. Module B reheater: reheater failed because of vibration and chloride corrosion.
Solution/Operation	Replaced 304 SS tubes with 316 L SS tubes. Increased reheater flue gas temperature from 147° F to 175° F Tubes preheated before flue gas enters.	Baffles installed Ducts above reheater insulated. Trough built around duct to catch run off before it reached reheater.	After removal of reheater, brick deterioration in the stack rain fallout, and low plume rise were noticed. No follow-up solution attempted.			Replacement reheater tubes of SS 316 L will be used.	Initially Module A was put back into service by cannabalizing Module B. Mist elimination improved by constant underspray and intermittent overspray of mist eliminator. Second stage demister installed above original demister. Module B rebuilt with 316 SS and carbon steel.

Source: Choi, et al. (1977) and Leivo (1978).

TABLE 5-4. SURVEY OF IN-LINE STACK GAS REHEAT SYSTEMS USING HOT WATER

Power Plant	Kansas Power and Light Lawrence No. 4	Kansas City Power and Light Hawthorn No. 4	Northern States Power Sherco
Scrubbing System	Limestone (CE)	Limestone (CE)	Limestone (CE)
Heating Medium (Hot Water)			
Inlet temperature, °F	250	325	350
Outlet temperature, °F	180	250	230
Flow rate, gpm	200	600	2,300
Heat Exchanger			
Tube size	1" O.D. finned tubes	NA	1/2" O.D. finned tubes
Number of tube banks	2 banks	NA	3 banks
Materials of construction	Carbon steel	Carbon steel	Carbon steel
Soot blowing	Compressed air blower, once/4hrs	Steam soot blower	Steam soot blowers
Reheat Temperature, °F	150	175	170
Reheater Problems	Frequent plugging of the reheater during early life of system. Tube failure due to acid corrosion after 6 years of operation.	Corrosion problems have been mild compared to pluggage problems.	Reheater is not yet in service. Results of pilot plant indicate system is satisfactory.
Solution/Operation	Plugging was alleviated by installing soot blowers, redesigning of mist eliminator, and installing vanes under marble bed to improve gas distribution. Entire scrubber system was replaced in 1977.	Reheater is normally cleaned every three days when scrubber is cleaned. The reheat pump is started prior to placing scrubber in service.	

Source: Choi, et al. (1977) and Leivo (1978).

TABLE 5-5. SURVEY OF INDIRECT HOT AIR STACK GAS REHEAT SYSTEMS

Power Plant	Nevada Power Company Reid Gardner No. 1,2	Public Service Company of Colorado Cherokee No. 4
Scrubbing System	Soda Ash (CEA)	TCA (UOP)
Heating Medium (Steam)		
Pressure, psig	460	575
Temperature, °F	760	483
Consumption rate, lb/hr	20,000 - 25,000	135,000
Heat Exchanger		
Tube size	5/8" O.D. finned tubes	5/8" O.D. finned tubes
Number of tube banks	3 banks, 8 rows/bank	2 banks
Materials of construction	Carbon steel	Carbon steel
Mixing of Gas	4 nozzles	-
Reheat Temperature, °F	169	175
Reheater Problems	Leak from weak spot of heater tube. No corrosion or mixing problems.	Difficulties with steam pressure reducing valve. Mixing problems due to poor design of reheater fan.
Solution/Operation	Reheater is placed in service after scrubber is in full operation and shutdown prior to scrubber shutdown to protect lined ducts.	Reheater fan interlocked with scrubber booster fan to prevent reverse flow of flue gas to reheater.

Source: Choi, et al. (1977) and Leivo (1978).

TABLE 5-6. SURVEY OF DIRECT COMBUSTION STACK GAS REHEAT SYSTEMS

Power Plant	Detroit Edison Company St. Clair	TVA Shawnee	Duquesne Light Phillips	Louisville Gas & Light Paddy's Run 6
Scrubbing System	Limestone (Peabody)	Lime/Limestone	Lime (Chemico)	Carbidge Sludge (CE)
Fuel and Combustion				
Combustion Chamber	External	External	In-line	In-line
Fuel Type	No. 6 fuel oil	No. 2 fuel oil	No. 2 fuel oil	Natural gas
Combustion rate	600 gph	37 gph	440 gph	20000 scfh
Gas temperature, °F	1,200 - 1,400	1,500 - 1,800	3,000	NA
Mixing of Gas	T connection	L-tube	-	
Reheat Temperature, °F	250 - 300	250	150	165 - 170
Reheater Problems	Failure of a thermal controller causing liner damage. Firebricks in mixing chamber fell off due to vibration. Poor mixing results in nonuniform temperature distribution.	No corrosion problems. Occasional carbon buildups.	Blower failed due to mechanical problems. Mixing was not effective causing nonuniform temperature distribution downstream.	No corrosion or other problems encountered.
Solution/Operation	Combustion chamber heated slowly to protect refractory material from abrupt temperature changes.	Original design had in-line burner. This was modified to an external chamber because of flame instability problems.	New acid proof stack liner installed. Reheater is little used due to oil shortage. Stack operated wet.	

Source: Choi, et al. (1977) and Leivo (1978).

TABLE 5-7. SURVEY OF SCRUBBING SYSTEMS WITH NO STACK GAS REHEAT

Power Plant	Pacific Power and Light Dave Johnston	The City of Key West Stock Island[a]	Boston Edison Mystic Station[a]
Scrubbing System	Venturi (Chemico)	Limestone (Zurn)	MgO scrubbing (Chemico)
I.D. Fan Maintenance	To prevent solid deposits on the fan blades, wash water is sprayed periodically.	Little solid deposits on fan blades. Clean up once a year. Wash with fresh water.	No I.D. fan.
Stack Maintenance	An acid-resistant lining was installed to protect the stack. Condensate pH = 3.5.	Concrete gunite-type liner might be attacked by acid. The stack is checked periodically.	No acid attack was found in the brick liner and the base of the stack.
Acid Rain or Fallout Problems	None	NA	No problems.
Plume Visibility Problems	No effect to visibility.	No effect to visibility.	Dense plume that dissipated rapidly.
Comments	Experience with wet stack has been satisfactory.	Scrubber went into service in 1972. Due to problems with the scrubber, operation has been limited. Based on this limited experience, no reheat has been satisfactory.	During the 2-year intermittent operation, MgO agglomeration in the stack was more serious than acid attack to the brick structure.

[a]Both power plants burn No. 6 Fuel Oil.

Source: Choi, et al. (1977).

Experience gained with reheaters has produced some useful caveats. In-line reheaters are subject to plugging, corrosion, and vibration. Plugging can be minimized by good mist elimination and the use of soot blowing, done at frequent intervals. Corrosion is a difficult problem since neither carbon steel, 304SS, 316SS, nor Corten appear to be able to withstand combined acid and chloride-stress corrosion. More exotic and expensive materials, such as Inconel 625 and Hastelloy G, have been used successfully at Colstrip. Design against vibration can readily be done by using frequency analysis. Direct combustion reheaters are best designed with an external combustion chamber, preventing the problems encountered with in-line reheaters. Both direct combustion reheaters and indirect hot air reheaters require interlocks to prevent the heated gas from damaging ductwork when the cold flue gas is not present. At the Dave Johnston Plant, where reheat is not used, the induced draft fan is periodically washed with water to prevent solid deposits and an acid-resistant lining is used on the stack.

In summary, reheaters are used in wet scrubber systems to provide greater plume buoyancy and prevent downstream condensation. Utility experience militates against the use of in-line reheaters because of many operational problems. Where reheaters are not used, prophylactic measures must be taken to prevent stack deterioration and (induced draft) fan imbalance.

Sources of Information

See Leivo (1978) and Choi et al., (1977).

5.4 WASTE DISPOSAL

Disposal of utility ash, either in ponds or landfills, has been practiced for many years. Indeed, if a wet scrubbing system is used for particulate removal only, disposal of the collected flyash poses no difficulties. But if the scrubber system also consists of a throwaway flue gas desulfurization system, disposal of wastes is problematic because sludge is exceedingly difficult to manage.

Disposal of sludge is complicated by several undesirable properties of the material: (1) a large percentage of occluded water which makes the sludge physically unstable and expensive to transport, (2) a large number of small calcium sulfite crystals which limit the amount of dewatering that can be done by settling only and (3) the presence of soluble and slightly soluble materials which are potential sources of water pollution.

A typical ponding operation consists of dewatering the raw sludge in a thickener and then pumping it in a pipeline to an ultimate disposal site. The disposal site may be either a man-made pond or a naturally occurring dry lake (in arid regions). A second pipeline recirculates clear supernatant back to the scrubbing facility. Although easier and cheaper than using a landfill, ponding has several drawbacks: first, it requires a large land area, which will not be reclaimable (unless measures are taken to stabilize the sludge); and second, there is potential water pollution from runoff and leaching. Leaching can be minimized in man-made ponds by using an impervious liner.

Disposal of sludge in a landfill requires greater dewatering than ponding, and also, further processing to increase the compressive and shear strength of the sludge. Besides thickeners, other methods of dewatering include filtration, centrifuging, and mixing with dry-collected flyash and lime. The physical stability of the sludge can be increased by addition of certain chemical additives; commercially, both the Dravo Corporation and IUCS offer additives that have been used at utilities. Runoff from landfills can be minimized by covering the site with earth and revegetating (local regulations permitting).

Table 5-8 summarizes the waste disposal practices of several utilities. No clear trends emerge, but the choice of waste disposal methods is site-specific, depending on economics, location, and local regulations.

TABLE 5-8. SLUDGE DISPOSAL PRACTICES

Station	Size, MW	Total Dry[a] Weight, tons/hr	Method of Disposal	Liner	Additives or Supplemental Alkali
Particulate-SO_2 systems:					
Bruce Mansfield	1650	NA	Landfill	No	Dravo
Colstrip	720	31.5	Pond	NA	Lime (0.3 tons/hr)
Cholla	115	1.9	Pond	No	Limestone (0.6 tons/hr)
Sherburne	1400	30.4	Pond	Yes	Limestone (3.5 tons/hr)
LaCygne	870	NA	Pond	No	Wet flyash
Reid Gardner	250	3.9	Pond	No	None
Particulate systems:					
Four Corners	575	69.2	Mine	No	Lime (0.6 tons/hr)
Dave Johnston	330	19.9	Landfill	NA	Lime (0.5 tons/hr)
Arapahoe[b]	100	0.95	Pond	NA	NA
Cherokee[b]	600	6.35	Landfill	NA	NA
Valmont[b]	166	2.76	Landfill	NA	NA
Syl Laskin[b]	116	3.0	Pond	NA	NA
Clay Boswell	350	32.7	Pond	NA	NA

[a] Estimated by adding flyash and SO_2 removal from the system and supplemental alkali added in the system. (CO_2 is excluded from supplementary alkali if limestone is added.)

[b] Supplemental alkali added to neutralize effluent only. Quantity of alkali used is not available.

Source: LaMantia (1977) and Federal Power Commission (1977).

Sources of Information

Flue gas desulfurization waste disposal has been the subject of investigation both by EPA and EPRI. For more extensive treatments, see, for example, Leo and Rossoff (1978), Fling et al., (1978), Corbett et al., (1977) and also McIlvaine (1974).

5.5 SCALING AND OTHER OPERATING PROBLEMS

Scaling is the single greatest operational problem in wet scrubbers and one that is most difficult to control. In scrubbers used for particulate removal only, the calcium and other alkalis present in the flyash react with SO_2 causing scale deposits (calcium sulfate). In lime and limestone systems, calcium sulfite (from the reaction of absorbed SO_2 and slurry alkali) and calcium sulfate (from the reaction of dissolved sulfite and oxygen) tend to precipitate out and form scale. In lime systems, calcium carbonate may also be precipitated when CO_2 from the flue gas reacts with the lime (pH is high).

Various techniques for controlling scale include:

- Control of pH -- If a limestone system is operated at pH's above 5.8 to 6.0 or if a lime system is operated above 8.0 to 9.0, there is a danger of sulfite scaling (Leivo, 1978). The pH is controlled by adjusting the feed stoichiometry. On-line pH sensors have been successful in controlling the feed in lime systems but not in limestone systems because the pH is fairly insensitive to the limestone feed rate in the normal pH range. However in the limestone system, the feed can be controlled by varying the flue gas flow rate. In particulate control systems, the pH is generally low, hold time in the retention tank is short, and suspended solids concentration is low. All these contribute to the formation of calcium sulfate scale. Hence, it is desirable to increase the scrubber liquor pH by addition of supplementary alkali.
- Hold Tank Residence Time -- By providing greater residence times in the scrubber hold tank, the supersaturation of the liquor can be decreased before recycle to the scrubber. Typical retention times of 5 to 15 minutes are used.
- Control of Suspended Solids Concentration -- Supersaturation can be minimized by maintaining a supply of seed crystals in the scrubber slurry. Typical concentrations range from 5 to 15 percent suspended solids. Solids are generally controlled by regulating slurry bleed rate.

- Regulating Oxygen Concentration -- Since calcium sulfate scaling depends on the presence of dissolved oxygen, control techniques center on regulating the oxygen concentration. In the forced oxidation method, air is bubbled into the reaction tanks to encourage sulfate crystal formation. These crystals have better settling characteristics than sulfite crystals. In the co-precipitation method, magnesium sulfite is used to depress the sulfate saturation level. Precipitation of sulfate in the holding tank is achieved by co-precipitation of sulfate with sulfite in a mixed crystal.
- Liquid-to-Gas Ratio -- High liquid-to-gas ratios reduce scaling potential since the scrubber outlet is more dilute with respect to absorbed SO_2. Unfortunately, increasing the liquid-to-gas ratio also increases operating costs and sludge disposal.
- Additives -- Two additives, Calnox 214DN and Calgon CL-14, when used together, have been found to effectively reduce sulfate scaling in limestone systems (Federal Power Commission, 1977).
- Alkali Utilization -- Experience at the TVA test facility at Shawnee indicated that certain mud-type solid deposits, which tended to form particularly in the mist eliminators, could be reduced by improving alkali utilization. Above about 85 percent alkali utilization, these solids could be removed easily with infrequent (once per 8 hours) washings. Control of calcium sulfate scaling at TVA was effected by varying the operating parameters listed above (Williams, 1977).

A summary of scaling and other operating problems at various utilities is provided in Table 5-9. As with other aspects of wet scrubber systems, the solutions to these problems tend to be site-specific, making generalizing difficult.

Sources of Information

See Leivo (1978), LaMantia et al. (1977), and Slack and Hollinden (1975).

5.6 SAMPLING CONSIDERATIONS

Sampling and measurement of various constituents of the flue gas stream before and after the scrubber system are needed to evaluate its performance. It is desirable that adequate sampling ports be incorporated during the engineering design of the scrubber system to facilitate several sampling procedures which require a variety of probes and collection equipment.

TABLE 5-9. OPERATING CHARACTERISTICS AND PROBLEMS IN SCRUBBER SYSTEMS

System	Chemical Scale	Mist Eliminator Washing	Fan Washing	Wet/Dry Interface	Comments
Colstrip Station (MPC)	--	Wash tray & 0.8 on demister (F&R)	Dry I.D. fan	Venturi	Close loop operation.
Sherburne County Generating Plant (NSP)	Reheater	Washing afrer 3-4 days (R)	Dry I.D. fan	Venturi rod	Effluent discharged from the system, sluice water, etc. (2-3 gpm/Mw) is combined with scrubber system (forced oxidation).
Reid Gardner Station (NPC)	--	Wash tray	Dry F.D. fan	--	Close loop maintained by evaporation from pond.
Cholla Station (APS)	Pond outlet pipe, venturi, cyclone separator, reheater	Intermittent (R)	Dry F.D. fan	Venturi	Close loop maintained by evaporation from pond.
Four Corners Plant (APS)	Venturi, reheater and pipes	N.A. (R)	Wet fan (R)	--	Scale and buildup is controlled by flushing from the system.
Dave Johnston Plant (PP&L)	Gypsum scale in scrubber and pipes	R	1.3 (C&F)	Scrubber, lignosulfate is used to avoid buildup	L/G = 7.6 is intermittently used to avoid buildup in scrubber and results in discharge of effluent.
Arapahoe Station (PSCC)	--	Intermittent washing (C)	Dry F.D. fan	Presaturation Section	
Cherokee Station (PSCC)	--	Intermittent washing (C&F)	Dry F.D. fan	Presaturation Section	Scale and buildup is controlled by maintaining effluent from the system.
Valmont Station (PSCC)	--	Intermittent washing (F)	Dry F.D. fan	Presaturation Section	
Aurora Station (MP&L)	Scrubber and liquid lines-gypsum scale	N.A. (R)	Wet fan (F)	--	Scaling and plugging is controlled by effluent discharge.
Clay Boswell Station (MP&L)		1.2 (R)	0.2 (F)	Scrubber, spray piping	Scaling and plugging is controlled by effluent discharge.

Note: All the numbers represent liquid to gas ratio, gpm/1,000 acfm.
C - Cooling tower blowdown
F - Fresh plant supply water
R - Recycle stream in scrubber system
F.D. - Forced draft
I.D. - Induced draft

Source: LaMantia, et al.(1977).

Sampling operations for the evaluation of the scrubber system will be aimed primarily at characterizing the gas flow, particle size distribution, mass loading, and gas composition. Secondary sampling may also be required to determine emission characteristics for the assessment of environmental effects of the installation.

To obtain a representative sample of the particulate matter, and information regarding gas flow rate, the gas flow at the sampling points must be stable. Bends, expansion and contraction zones, and the presence of an obstacle in the flow path can induce secondary flows such as vortices, rotation, and large eddies. Sufficiently long runs of a straight uniform duct are usually recommended at the sampling location before and after the sampling point. As a rule, the sampling location should be separated by 8 to 10 diameters downstream and by more than two duct diameters upstream from any disturbances in the flow.

Another factor in designing sampling locations in a scrubber system is the ease in the operation of the sampling equipment. Proper orientation of the sampling port and availability of a clear platform area near the port are desirable.

In the scrubber system it is also desirable to be able to evaluate the scrubber section as well as the demister section separately, as shown in Figure 5-1. Three sampling locations are required for evaluating the system performance.

Most interfaces for sampling from ducts are designed to be compatible with 3 inch (nominal) Schedule 40 pipe nipples used as sampling ports. Occasionally an experimental system has required a 4 or 6 inch opening. The size of the port opening necessary to insert a probe (with the usual bend to allow sampling parallel to the flow) also depends on the length of the port opening. In an experimental scrubber system where a variety of sampling procedures may be used, it is recommended that 6 inch ports be made available. Other considerations include availability of diametrically opposite ports so that opacity monitors may be installed if necessary.

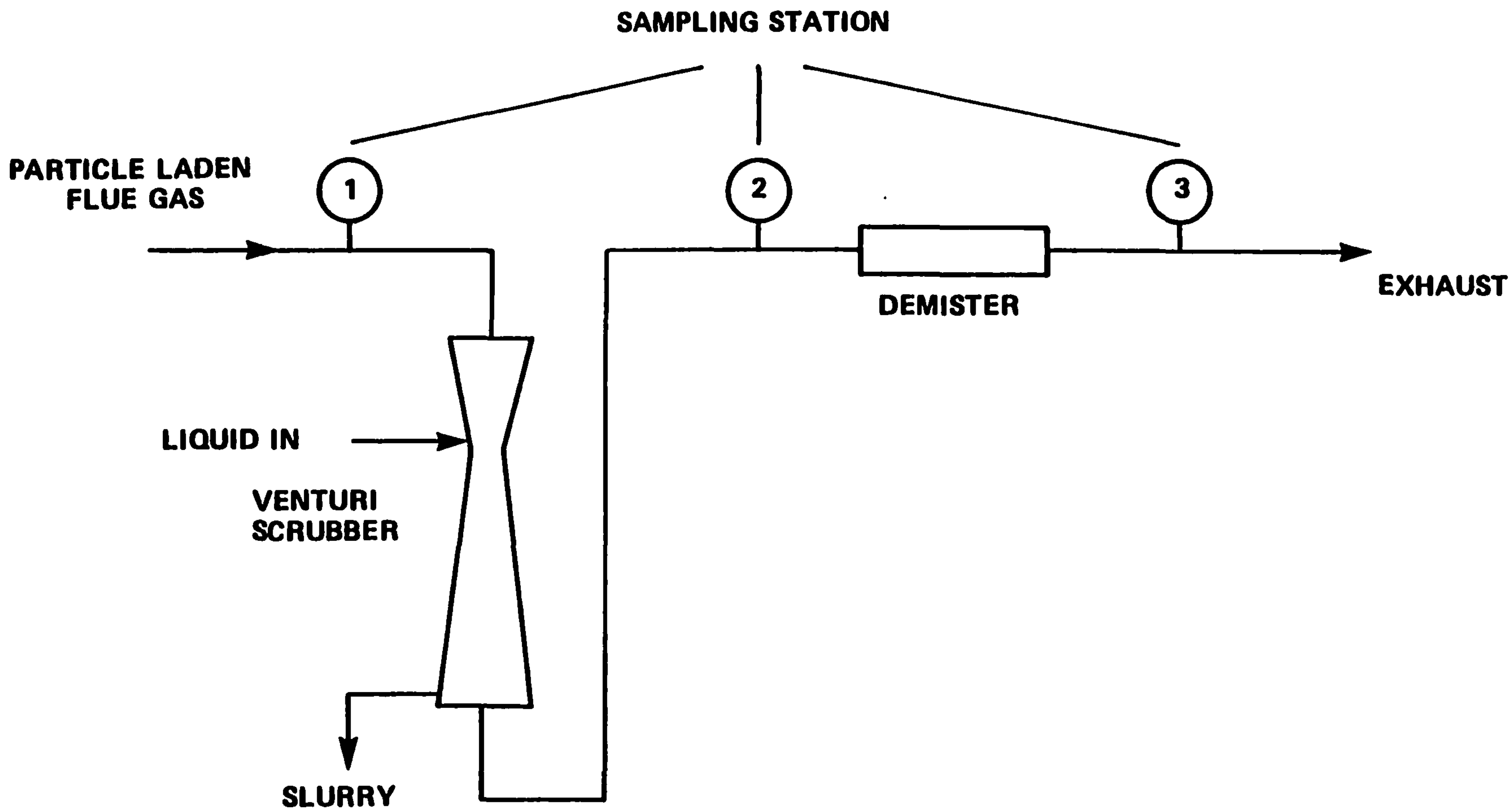

Figure 6-1. Sampling Stations for Scrubber Installation

Sampling Operations

A list of gas stream characteristics and measurement methods of particular interest for a particulate scrubber on a coal-fired boiler is given in Table 5-10. Information on the gas stream flow field, and flow rate is necessary so that correct sampling conditions may be chosen to obtain a representative sample. Standardized methods for determining gas composition and particulate mass loadings have been developed and are available in the Code of Federal Regulations under Title 40--Protection of Environment, Chapter 1--Environmental Protection Agency, Subchapter C--Air Programs, Part 60--Standards of Performance for New Stationary Sources, and Appendix A--Reference Methods.

Experiences in determining particle size distributions from coal-fired boilers have shown a number of potential sources of error. Hesketh (1975), in studying the performance of a pilot venturi scrubber, found as much as 70 percent weight gain on glass fiber filters due to reaction products; other surfaces such as silver foil, fluoropore, and polyvinyl chloride also showed some weight gain. McCain (Southern Research Institute, 1976), similarly reported weight gains on a number of glass fiber filters; the reaction products were identified as sulfate. Preconditioned materials showed significantly less weight gain. Hesketh (1975) reported that the use of Dow silicone lubricant as a greased substrate on impactor surfaces during blank runs resulted in loss of weight; presumably, the weight loss was due to the low pH environment and not the temperature (only 135°F). Wesa (1977), in summarizing Detroit Edison's experience with sampling trains, pointed out that metal probes produce corrosion products, even if heated above 250°F; an inert probe was recommended. Ensor et al., (1975), in fractional efficiency testing of the mobile-bed scrubber at the Cherokee station, found high and variable outlet particle concentrations presumably due to reentrainment of solids from the entrainment separator. Recently, Smith, Cushing, and McCain (1977) have developed a manual for the evaluation of electrostatic precipitators. Most of the information on sampling in this manual is also applicable in scrubber evaluation.

TABLE 5-10. A SUMMARY OF EMISSION CHARACTERISTICS MEASUREMENT METHODS

QUANTITY MEASURED	SAMPLING METHOD	APPARATUS	REFERENCE
Traversing points	Method 1	–	Federal Register *41*, 111, 23061 (1976)
Velocity + volumetric flow rate	Method 2	Type S pilot tube	Federal Register *41*, 111, 23063 (1976)
CO_2, excess air, dry molecular weight	Method 3	Orsat Analyzer, glass or stainless steel (S.S.) probe, particulate filter	Federal Register *41*, 111, 23069 (1976)
Moisture (in absence of droplets)	Method 4	Orsat Analyzer, glass or S.S. probe, particulate filter, ice bath, impingers	Federal Register *41*, 111, 23072 (1976)
Particulate emissions mass loading	Method 5	Sampling Train Cyclone/ filter holders (>225°F)	Federal Register *41*, 111, 23076 (1976)
Particulate emissions mass loading	Method 17	In-stack filter thimble	Federal Register *41*, 111, 42020 (1976)
Particulate emission mass loading	ASTM	In-stack filter thimble	–
SO_2	Method 6	Pyrex Probe, impingers	Federal Register *41*, 111, 23083
NO_x	Method 7	Pyrex Probe, collection flask	Federal Register *41*, 111, 23085
SO_2, SO_3, and H_2SO_4	Method 8	Pyrex Probe, impingers	Federal Register *41*, 111, 23087
Opacity	Method 9	Visual, qualified observer	Federal Register *41*, 111, 230
Opacity	Extractive	Extractive sample	Ensor and Hooper (1977)
Aerodynamic diameter >0.5μm-10μm	Extractive or In-stack	Heated impactor, in-stack impactor	Calvert, Lake, and Parker (1976) Harris (1977) Smith, Cushing, and McCain (1977) Ensor and Hooper (1977) Calvert, Barbarika, Monehan (1977)
Aerodynamic diameter >0.3μm-10μm	Extractive or In-stack	Cyclones (4 in diameter port)	Smith and Wilson (1978)
Particle size distribution <0.5μm	Extraction	Probe, Diluter Electrical Aerosol Analyzer, diffusion battery, condensation nuclei counter	Smith, Cushing, and McCain (1977) Ensor and Hooper (1977) Calvert, Barbarika, Monahan (1977)
Drop size distribution	In situ probe	Hot wire droplet detector	
Environmental assessment Level 1	Effluent collection + analysis + bioassays	Source Assessment Sampling System (SASS Train)	Hamersma, Reynolds, and Maddalone (1976)

The Environmental Protection Agency has developed a procedure for environmental assessment (Hamersma, Reynolds, and Maddalone, 1976). The Basic Level 1 Sampling and Analytical Scheme for particulates and gases is shown in Figure 5-2. In a scrubber system, sampling of solid, liquid, and slurry discharges is also required for a complete environmental assessment of the installation. A scheme for the sampling and analysis of solids, slurries, and liquids is given in Figure 5-3.

Information on quantities of particulate and other matters needed for the environmental assessment is available in the procedure document referred to above.

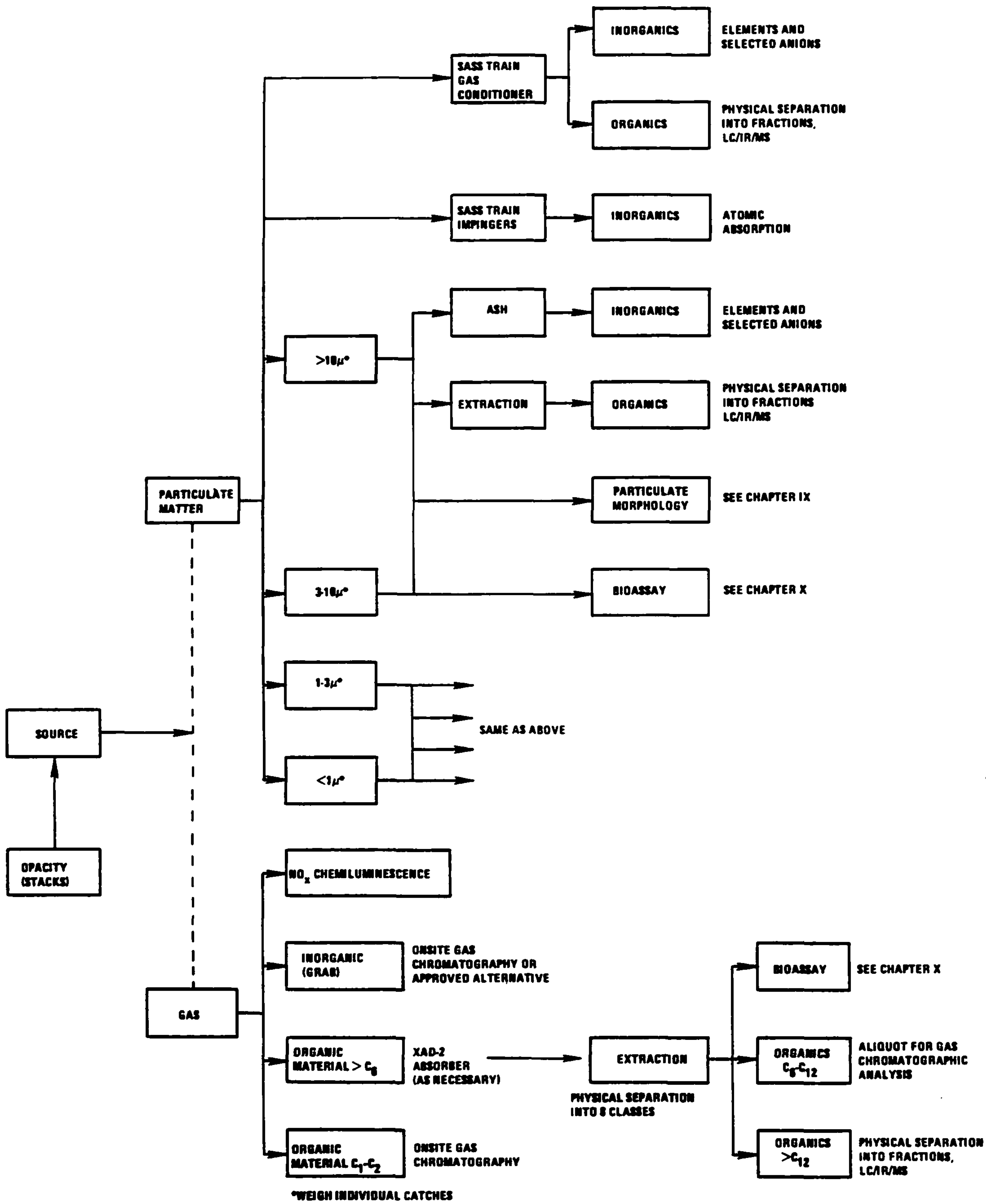

Figure 5-2. Basic Level 1 Sampling and Analytical Scheme for Particulates and Gases

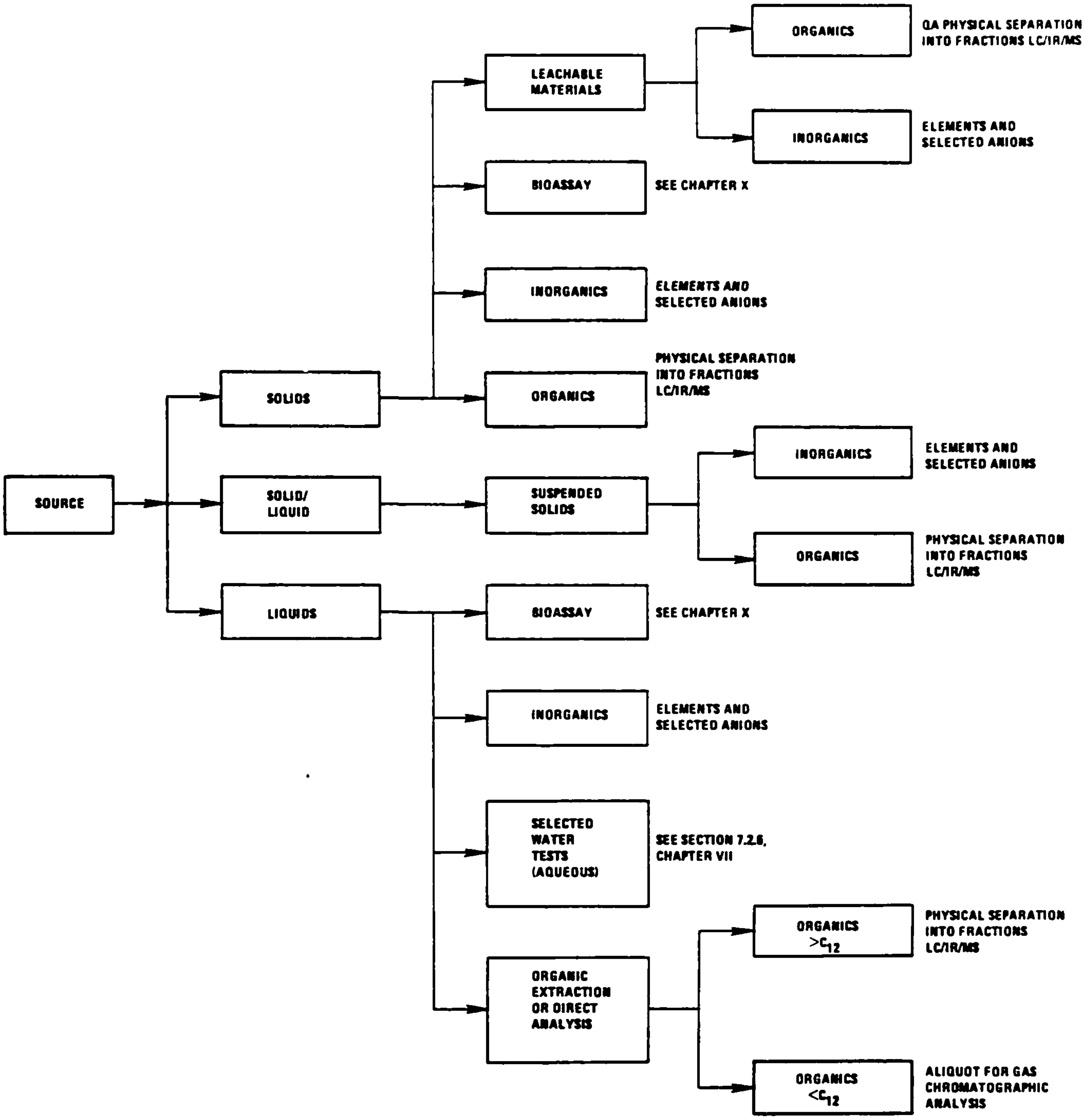

Figure 5-3. Basic Level 1 Sampling and Analytical Scheme for Solids, Slurries and Liquids

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APPENDIX A

FLOW DIAGRAMS OF EXISTING UTILITY PARTICULATE AND PARTICULATE-SO_2 SCRUBBER SYSTEMS

(References for this section are included in the references for Section 4.0)

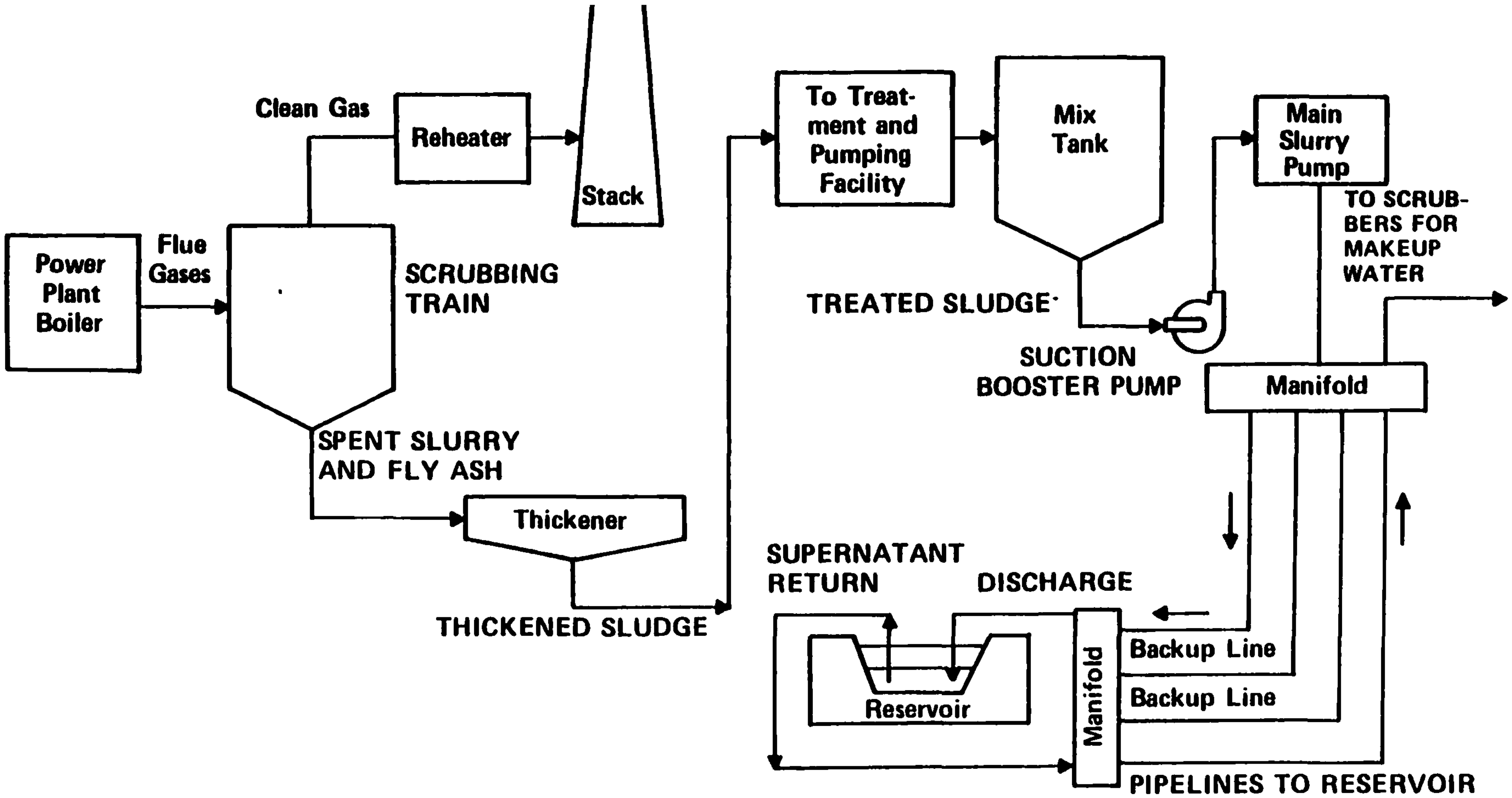

Figure A-1. Simplified process diagram - Bruce Mansfield No. 1 (Pennsylvania Power Co.).

Source: Devitt et al., 1978.

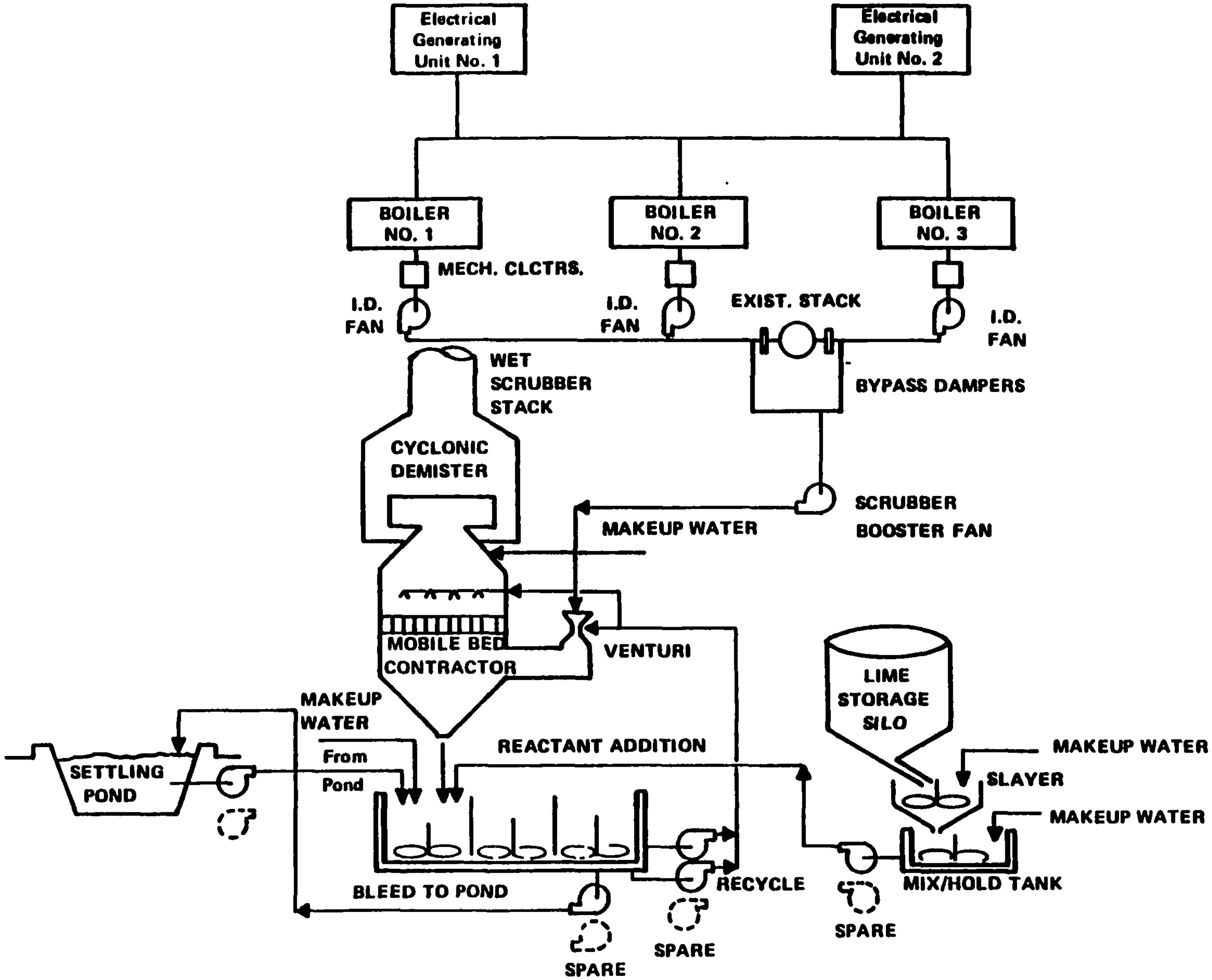

Figure A-2. Process flow diagram - Green River No. 1, 2, and 3 (Kentucky Utilities).

Source: Devitt et al., 1978.

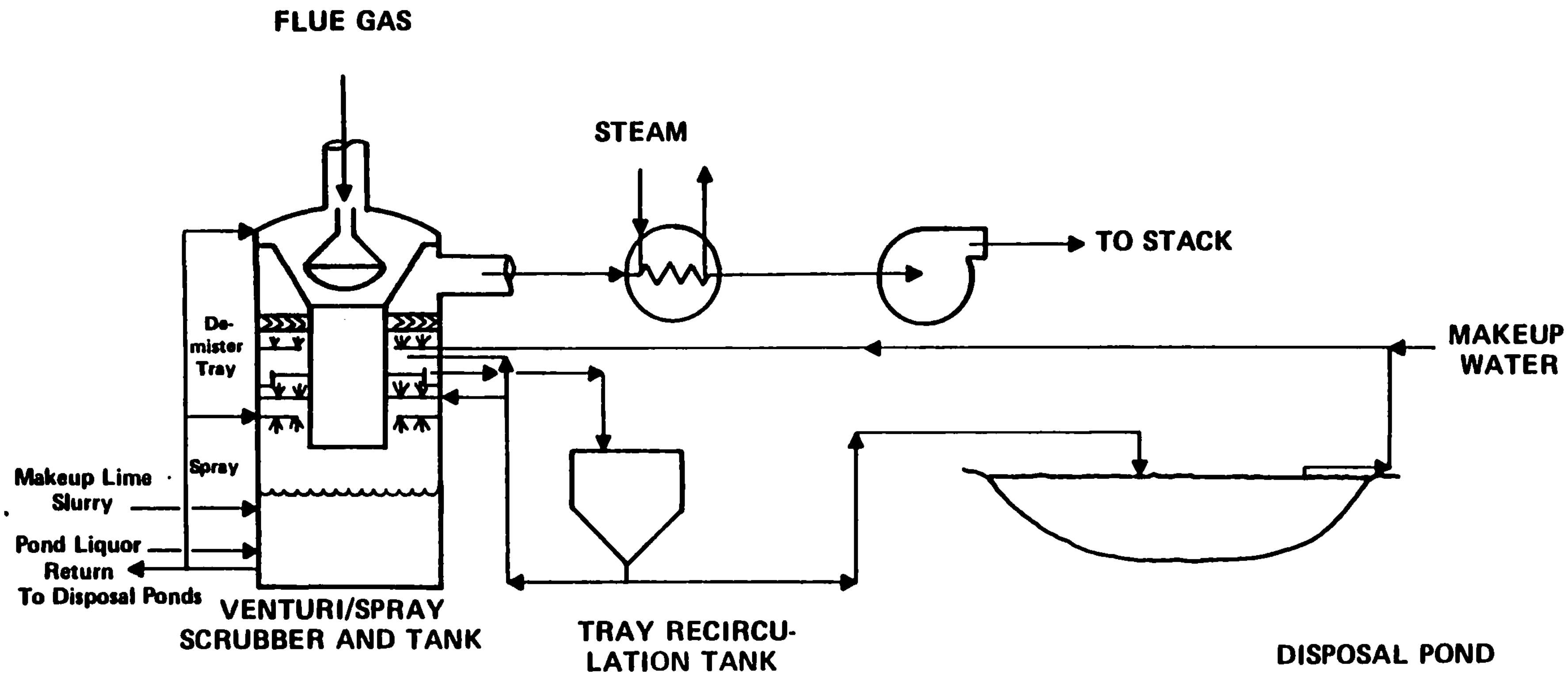

Figure A-3. Flow diagram of combined particulate - SO_2 scrubber system at Colstrip (Montana Power Co.).

Source: LaMantia et al., 1977.

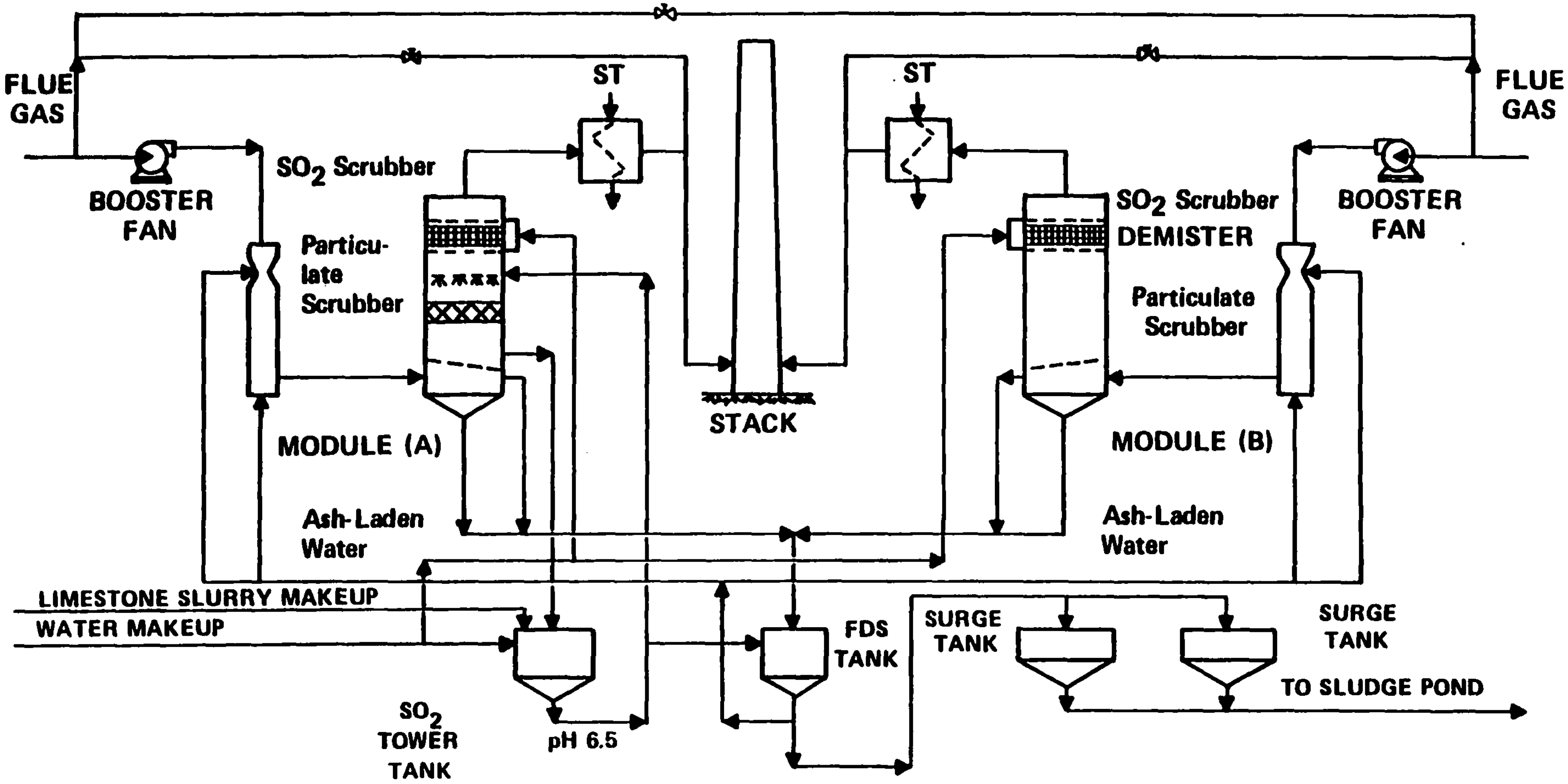

Figure A-4. Process Flow Diagram of the FGD System at the Cholla Power Plant (Arizona Public Service).

Source: LaMantia <u>et al</u>., 1977.

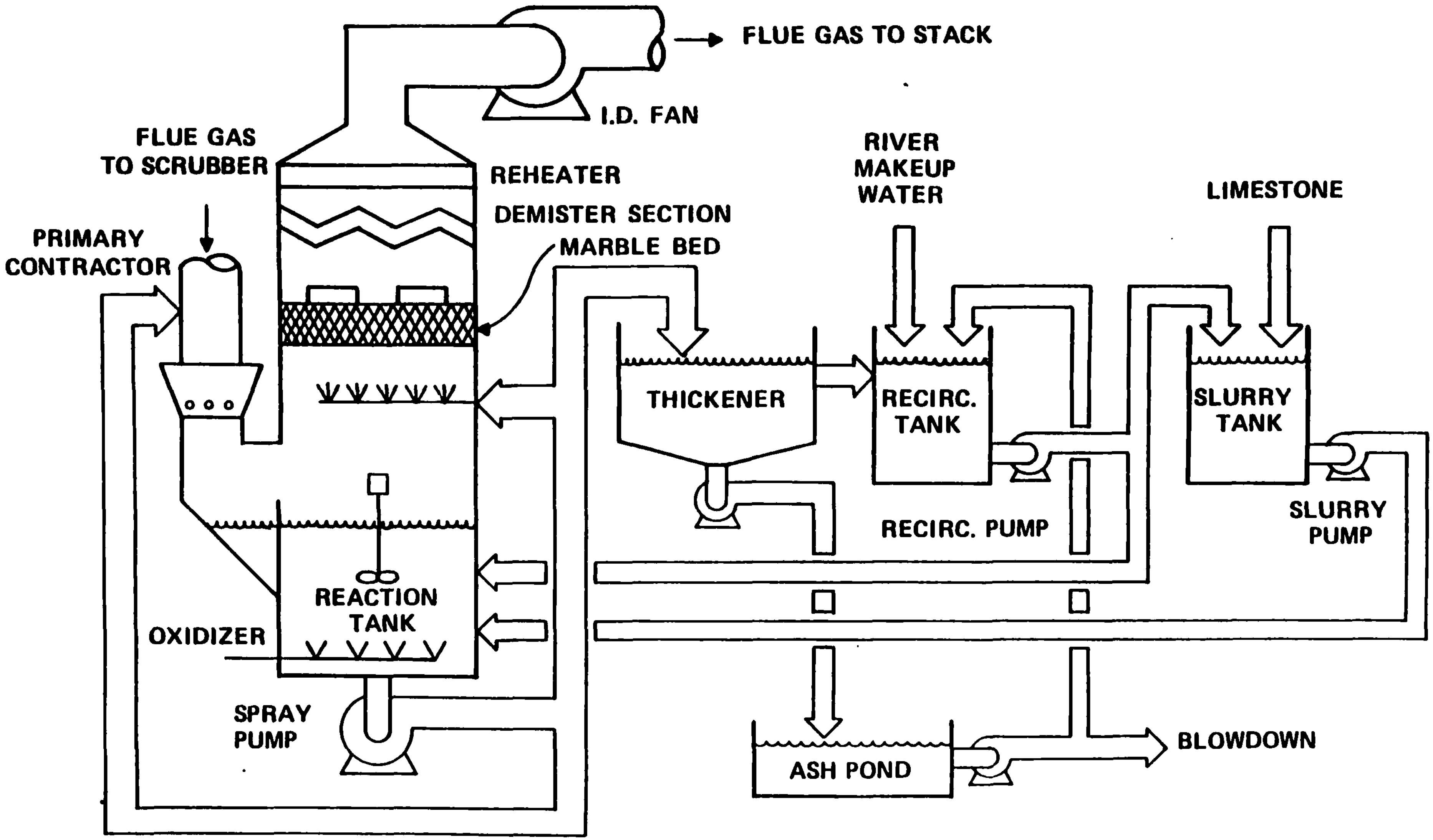

Figure A-5. Simplified Flow Diagram of Sherburne County Generating Station (Northern States Power Company).

Source: LaMantia *et al.*, 1977.

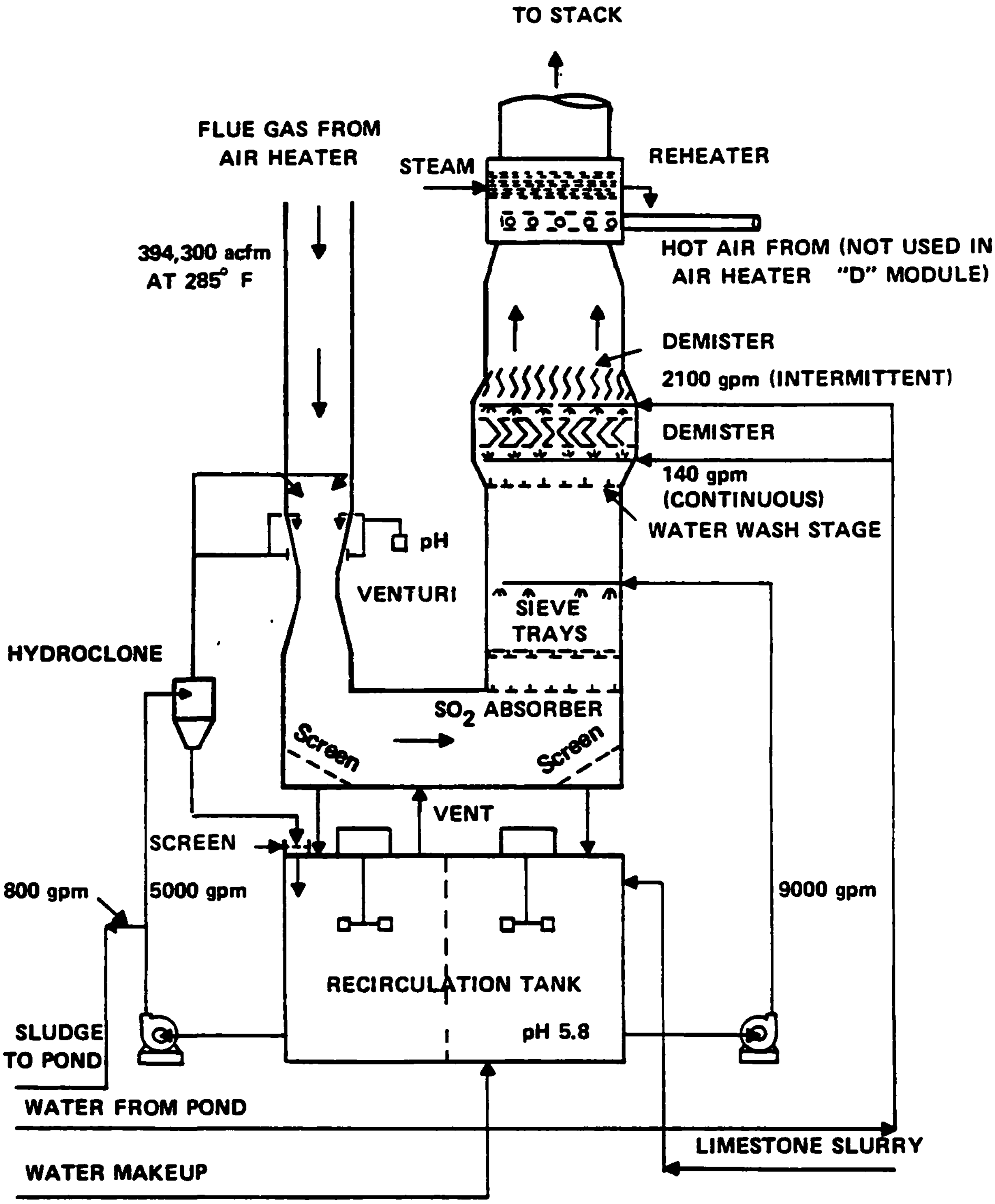

Figure A-6. Flow diagram of one of the eight FGD modules - La Cygne No. 1 (Kansas City Power and Light).

Source: Devitt et al., 1978.

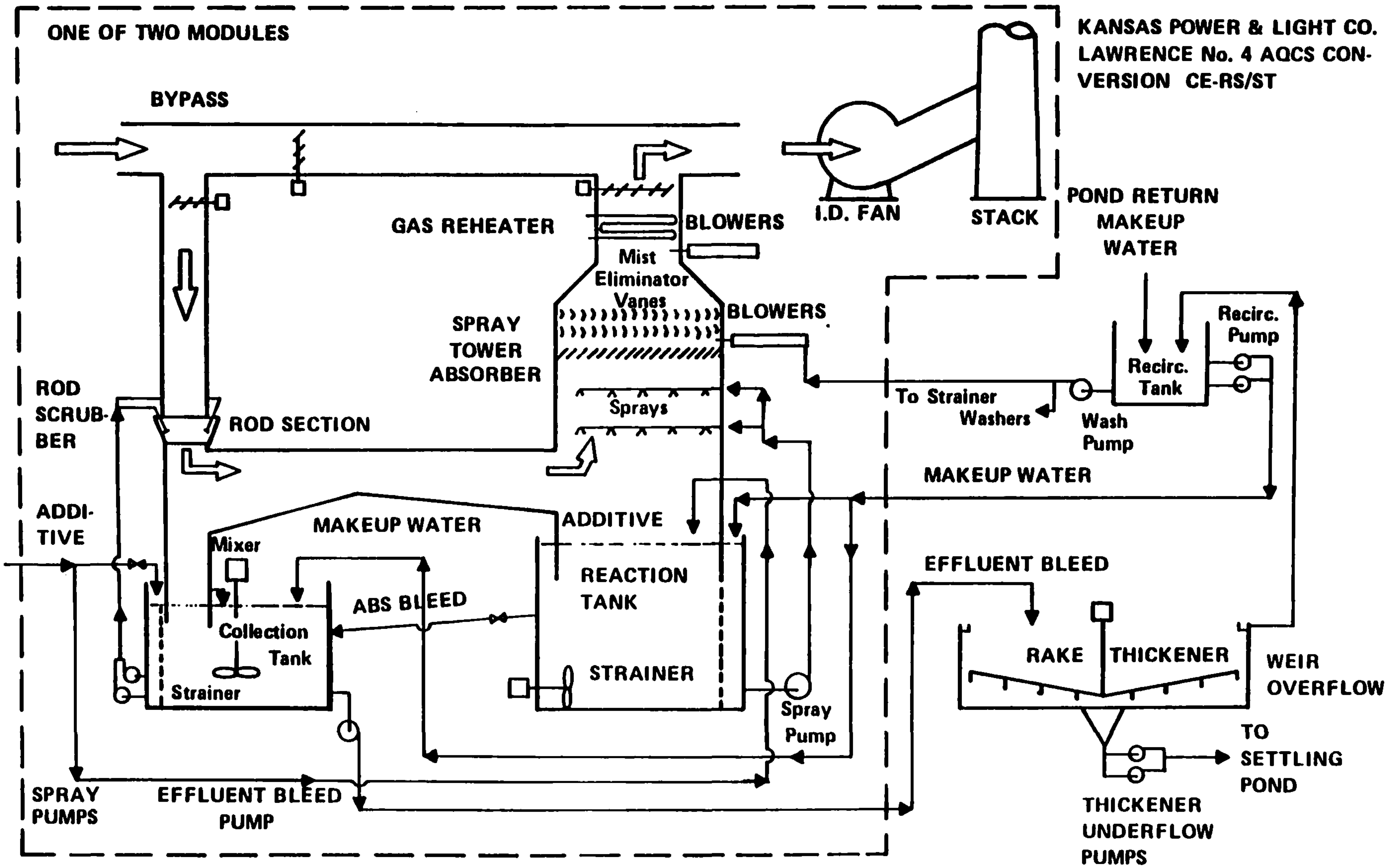

Figure A-7. Flow diagram of combined particulate-SO_2 scrubber system at Lawrence No. 4 (Kansas Power and Light).

Source: Green and Martin, 1977.

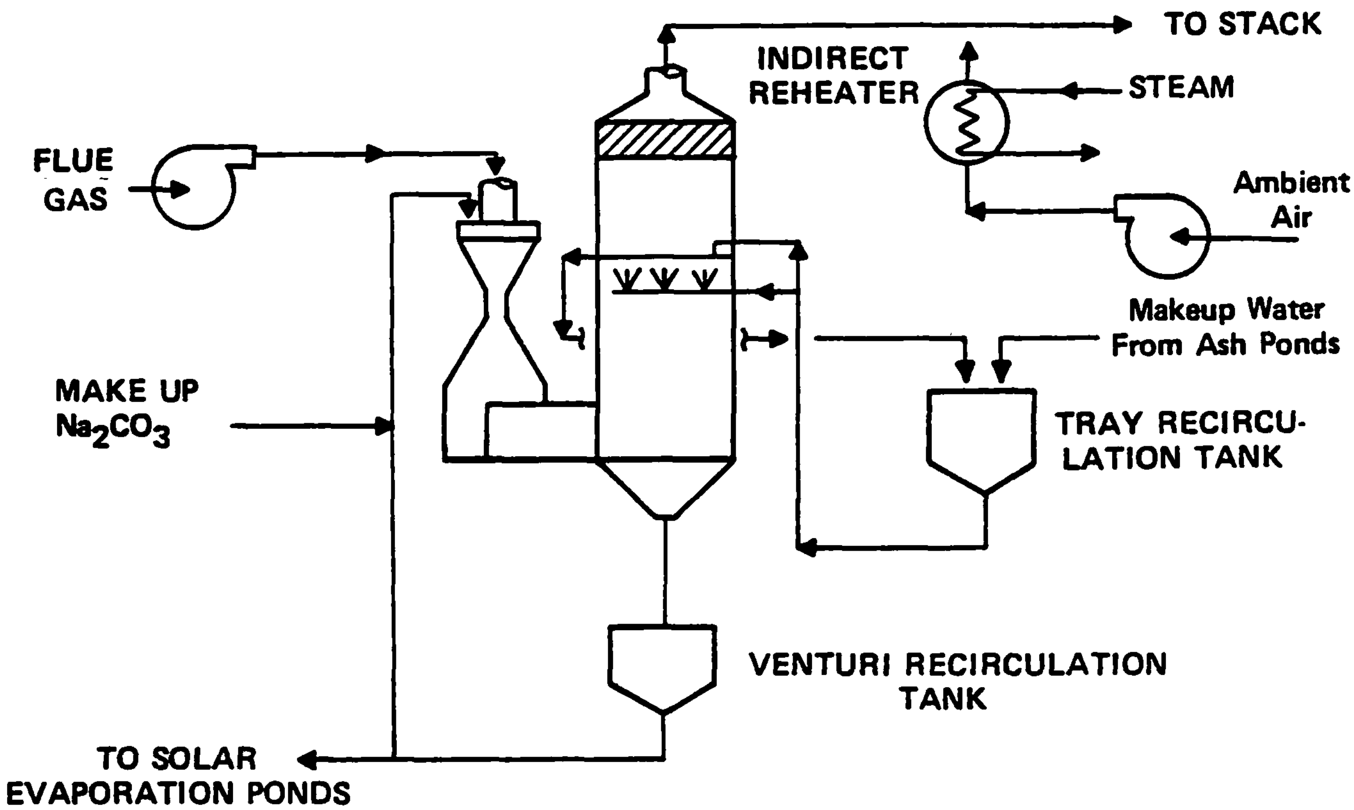

Figure A-8. Flow diagram of SO_2-particulate scrubber system at Reid Gardner Nevada Power Co.).

Source: LaMantia et al., 1977.

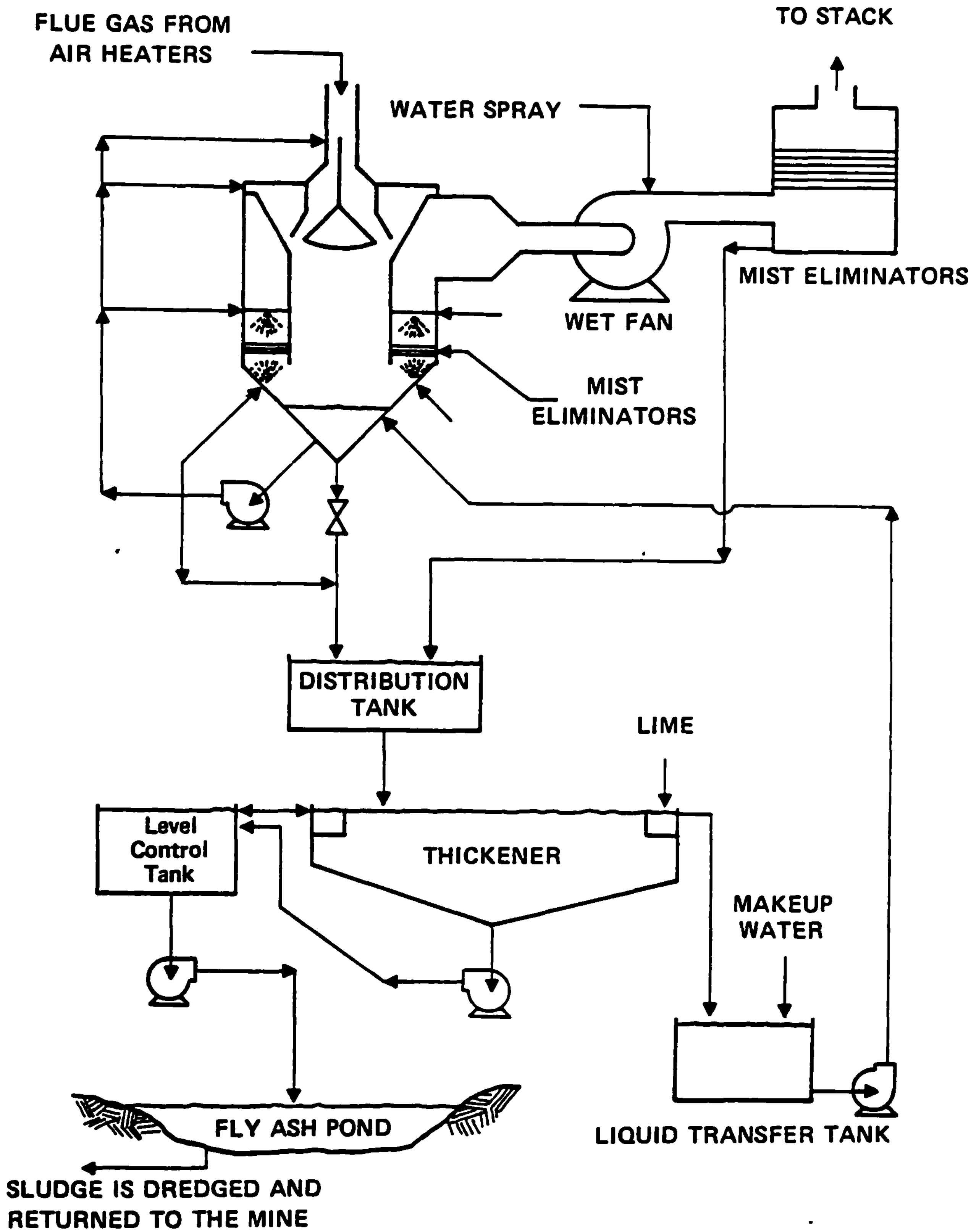

Figure A-9. Simplified flow diagram of flyash scrubbers, Four Corners Plant (Arizona Public Service).

Source: LaMantia et al., 1977.

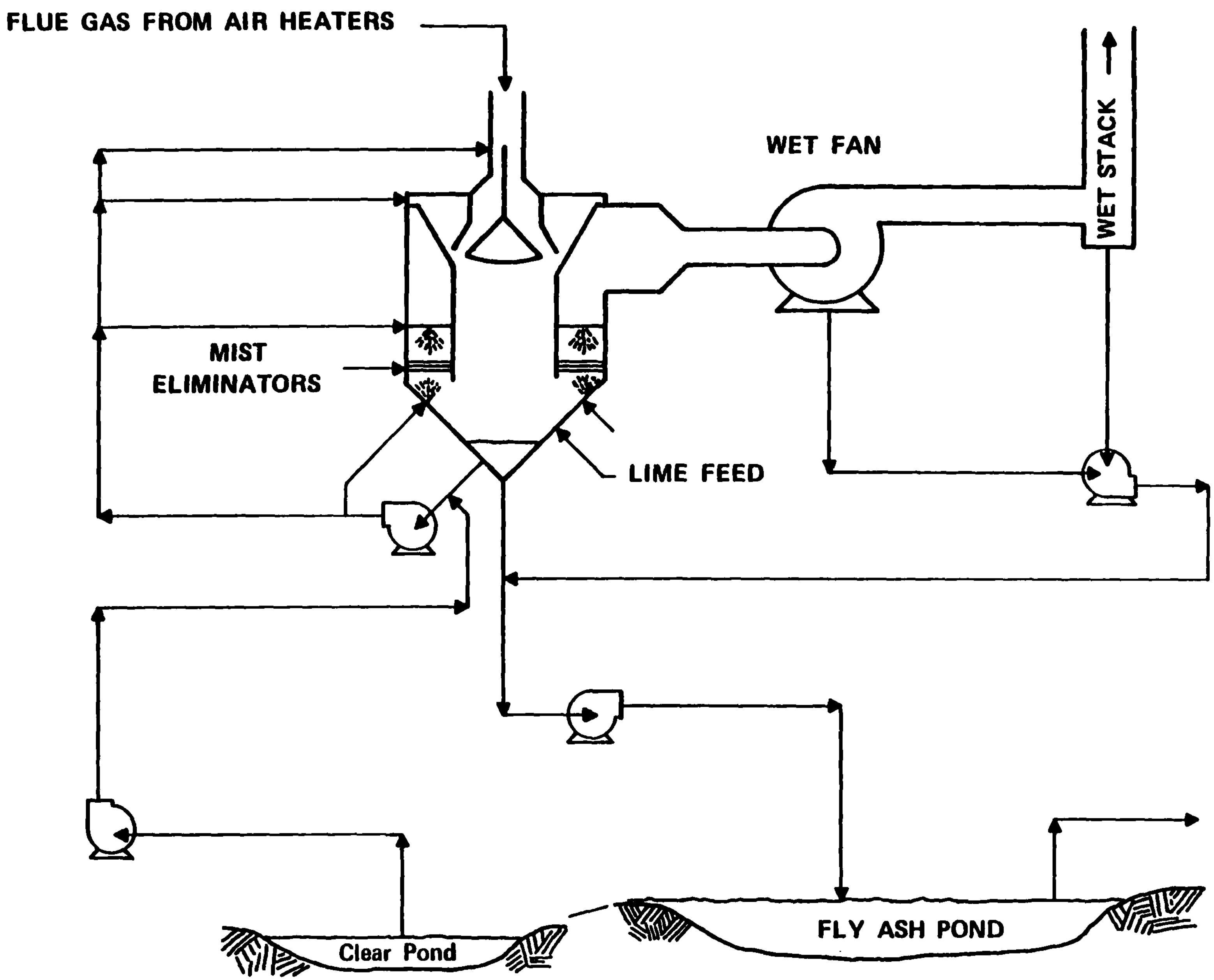

Figure A-10. Simplified Flow Diagram for the Dave Johnston Flyash Scrubbers (Pacific Power and Light).
Source: LaMantia et al., 1977.

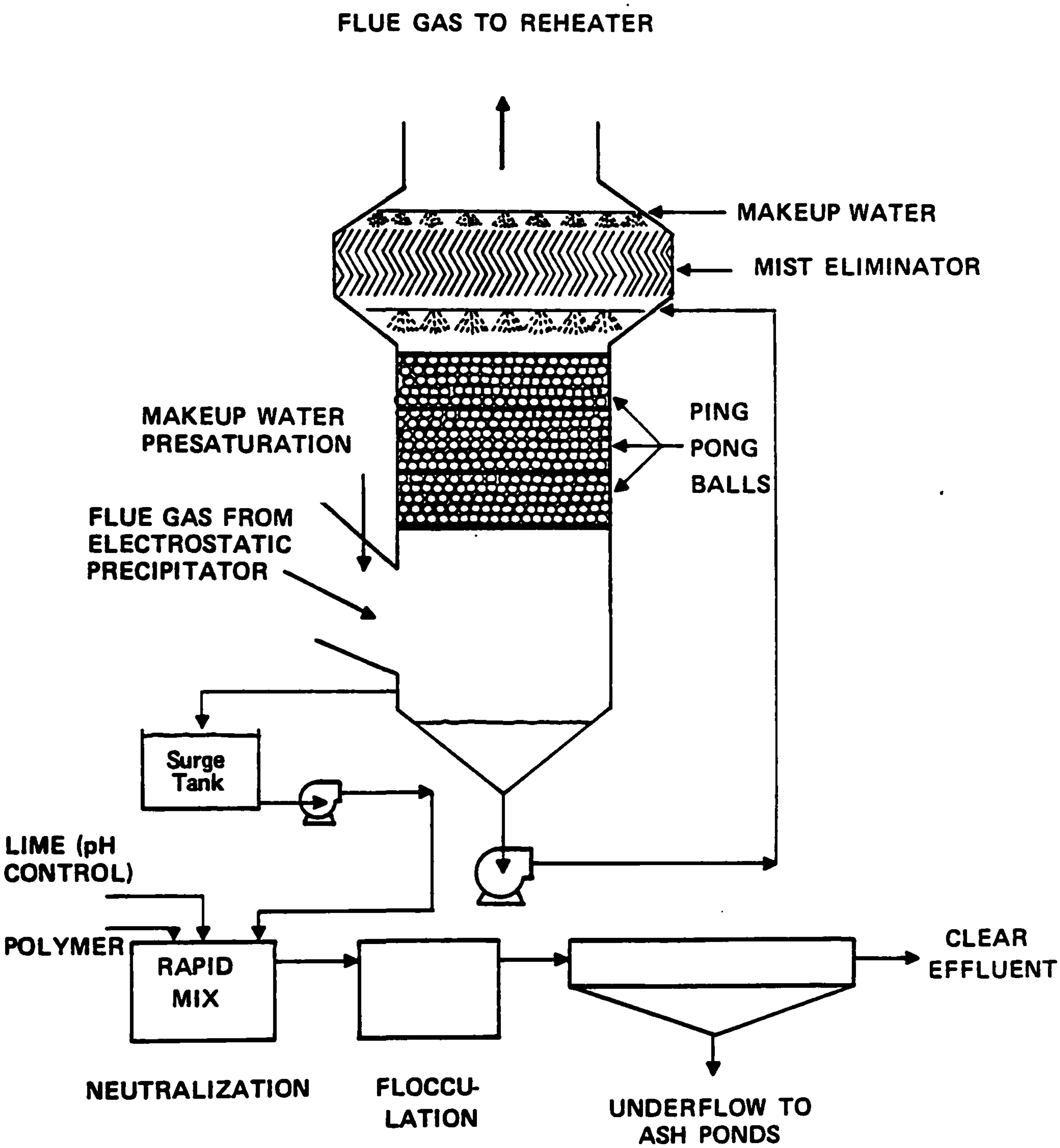

Figure A-11. Simplified Cherokee Station Scrubber Flow Diagram (Public Service of Colorado Company).

Source: LaMantia et al., 1977.

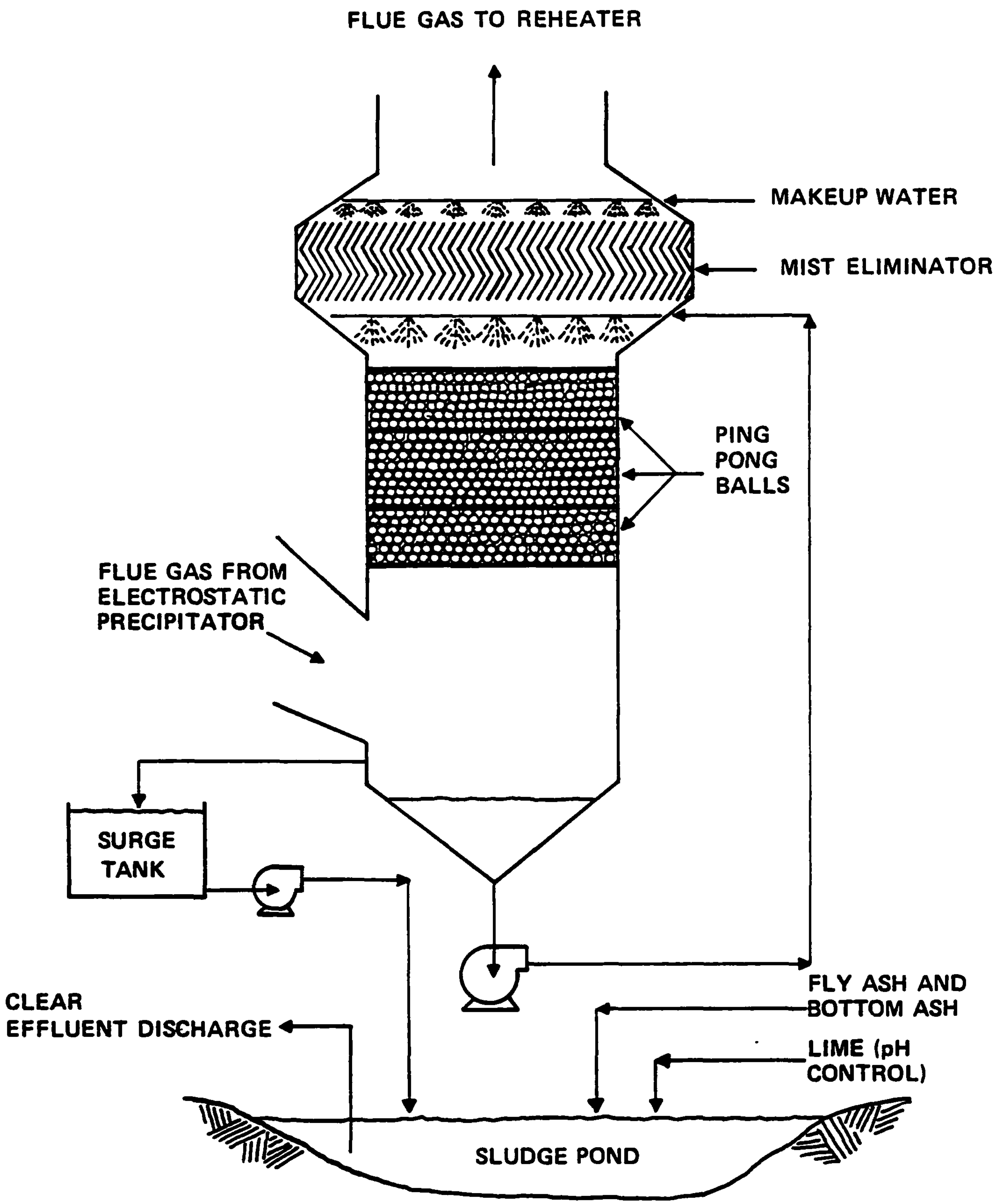

Figure A-12. Simplified Arapahoe Station Scrubber Flow Diagram (Colorado Public Service).
Source: LaMantia et al., 1977.

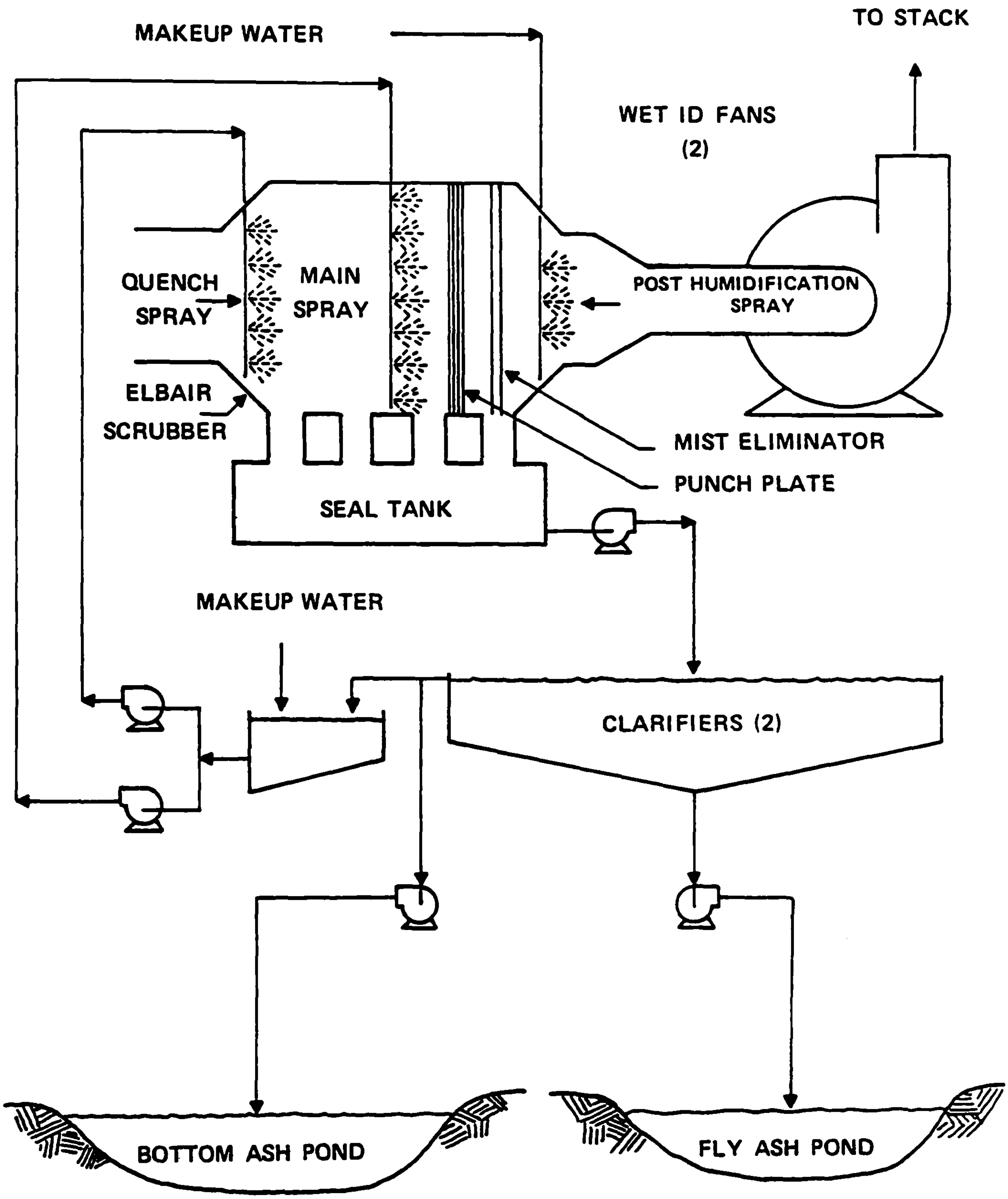

Figure A-13. Simplified Flow Diagram for the Clay Boswell Station Particulate Scrubber (Minnesota Power and Light Company).

Source: LaMantia et al., 1977.

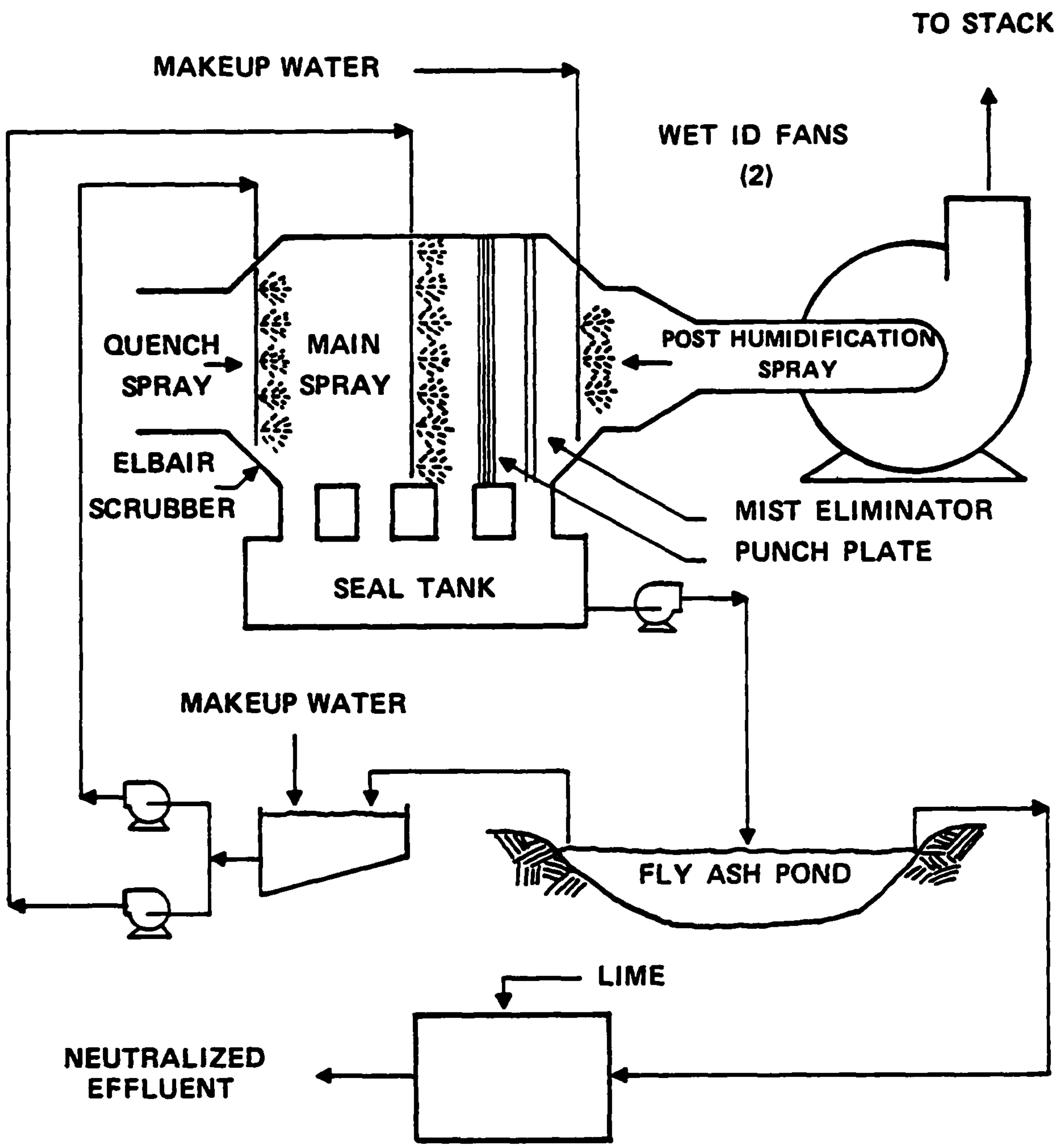

Figure A-14. Simplified Flow Diagram for the Syl Laskin Station Particulate Scrubber (Minnesota Power and Light Company).

Source: LaMantia et al., 1977.

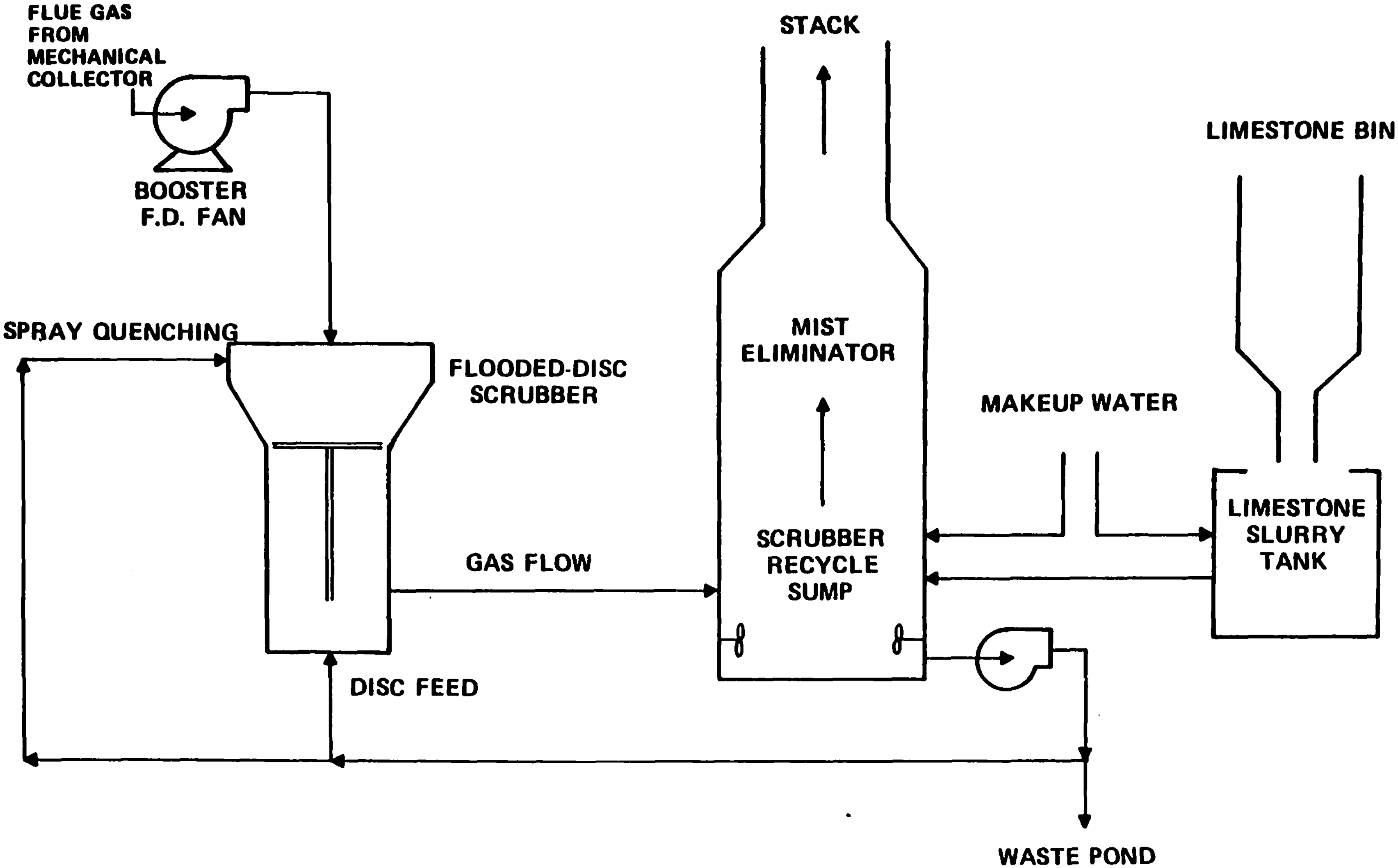

Figure A-15. Simplified flow diagram of flyash scrubber, Lewis and Clark Plant (Montana-Dakota Utilities).

Source: Szabo and Gerstle, 1977.

APPENDIX B

POSSIBLE USE OF CONDENSATION SCRUBBERS ON COAL-FIRED UTILITY BOILERS

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As indicated in the text (Section 4.3), condensation scrubbers would not be recommended for use on coal-fired boilers. Because the enthalpy of the flue gas entering the scrubber is low (about 110-190 Btu/lb, assuming 5 to 15 percent moisture at 300°F) and because the particle concentration is high, a condenser section placed before a conventional scrubber (the design for an optimum flux-force condensation scrubber given in Calvert (1977)) would probably give only a marginal increase in collection efficiency. (Calvert's studies indicate that collection efficiency for 0.75 μm particles would decrease from 100% at a dust concentration of 0.01 gr/scf to 60% at a dust concentration of 0.6 gr/scf. But utility flue gas may have dust concentrations as high as 8.0 gr/scf.)

It may be possible, however, to incorporate condensation effects into a scrubber system for use on coal-fired utility boilers. One conceivable design would involve a two-stage particulate scrubber. The first stage would be a moderate energy scrubber for removing large particles, thereby significantly reducing the mass loading, followed by a condenser section to enhance fine particle collection, and finally, a second stage scrubber to remove these particles. It might even be possible to use an SO_2 absorber as the second stage of the scrubber. But detailed calculations would be necessary to insure that there would be a significant effect at reasonable cost.

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16. ABSTRACT The report gives results of a review of the performance and operating experience of existing utility scrubber systems and the state-of-the-art in design of scrubber components. It also gives guidelines for the design of the optimum wet scrubber system, based on this review. The U.S. EPA's Industrial Environmental Research Laboratory, Research Triangle Park, North Carolina, is considering a demonstration of an optimum wet scrubber system for use on a coal-fired utility boiler. The optimum wet scrubber system has such design goals as maximum particulate collection, low power consumption, and low maintenance.

17. KEY WORDS AND DOCUMENT ANALYSIS

a. DESCRIPTORS		b. IDENTIFIERS/OPEN ENDED TERMS	c. COSATI Field/Group	
Air Pollution	Utilities	Air Pollution Control	13B	
Flue Gases	Boilers	Stationary Sources	21B	13A
Coal	Design	Particulate	21D	14A
Combustion	Dust			11G
Scrubbers			07A,13I	
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