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Survey of Flue Gas Desulfurization Systems: Bruce Mansfield Station, Pennsylvania Power Co.

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Survey of Flue Gas Desulfurization Systems: Bruce Mansfield Station, Pennsylvania Power Co.

by

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ACKNOWLEDGMENT

This report was prepared under the direction of Mr. Timothy Devitt. The principal author was Mr. Bernard Laseke.

Mr. Norman Kaplan, EPA Project Officer, had primary responsibility within EPA for this project report. Information on plant design and operation was provided by the following members of the Pennsylvania Power Company: Mr. Russell Forsythe, Engineer; Mr. C. E. Brown, General Coordinator of Operations; Mr. Dale Billheimer, Production Engineer; Mr. T. O. Flora, Associate Engineer A; and Mr. W. F. Reeher, Vice-president of Power Production.

SUMMARY

The Bruce Mansfield plant is a three-unit, 2751-MW (gross), coal-fired power generating station, located on the Ohio River in the Borough of Shippingport, Pennsylvania. The plant is owned by the Central Area Power Coordination Group (CAPCO), made up of the Ohio Edison Company, Pennsylvania Power Company, Cleveland Electric Illuminating Company, Duquesne Light Company, and Toledo Edison Company. The plant is being constructed and operated by the Pennsylvania Power Company, a subsidiary of the Ohio Edison Company. Bruce Mansfield 1 and 2 are currently operational. Bruce Mansfield 1 was placed in service on December 11, 1975, and was placed in full commercial operation on June 1, 1976. Bruce Mansfield 2 was placed in commercial service on October 1, 1977. Bruce Mansfield 3, currently under construction, is expected to begin commercial operation in April 1980.

Bruce Mansfield 1 and 2, each rated 917 MW (gross), fire a high-sulfur, eastern, bituminous coal having a maximum sulfur content of 4.75 percent and an ash content of 19.7 percent. To meet emission regulations promulgated by the Commonwealth of Pennsylvania, each unit is fitted with a wet lime scrubbing system for the control of particulate and sulfur dioxide.

The wet lime scrubbing systems for Bruce Mansfield 1 and 2 were designed and supplied by Chemico. Each system consists of six parallel, two-stage, scrubbing trains. Each train includes a variable-throat venturi scrubber, a wet induced-draft fan, and a fixed-throat venturi absorber. The scrubbing trains are arranged in two groups of three. Flue gas from the three trains in each group flows together into an oil-fired reheat chamber and then is discharged to the atmosphere through a 950-ft chimney. The chimney, which serves both operating units, contains four carbon steel flues

with polyester flaked glass coating for receipt of the discharge gases from the four oil-fired reheat chambers. The chimney was not within Chemico's scope of supply.

The lime used in the scrubbing operations is a proprietary reagent, known as Thiosorbic lime, supplied by the Dravo Corporation. This lime, which contains 2 to 6 percent magnesium oxide, offers the advantage of increased sulfur dioxide removal efficiency and allows a subsaturated mode of operation.

The flue gas cleaning wastes produced by the scrubbing systems are treated and disposed of in an environmentally acceptable manner in a waste disposal system designed and built by the Dravo Corporation. The waste disposal system is a three-part process consisting of a pumping and treatment facility, a transportation facility, and a containment area. In the pumping and treatment facility a cementitious stabilizing agent, Calcilox,[R] is added to the scrubber thickener underflow. This mixture is then pumped via pipeline to a disposal area approximately 7 miles west of the power plant. The disposal area is a ravine with an earthen dam at one end, creating a reservoir into which the waste slurry is pumped and deposited on the valley floor under a covering of water.

Bruce Mansfield 1 commenced commercial operation on June 1, 1976. Although the performance of the scrubbing system was characterized by an adequate degree of availability* during the balance of 1976 and the first quarter of 1977 (approximately 80 percent[+]), several major problems were encountered that have since limited the availability and operation of the entire scrubbing system. Specifically, the major areas of concern have been the performance of the scrubber mist eliminators, excessive water entrainment and carryover out of the chimney, pH measurement and control, water balance, reheat burner performance, excessive maintenance associated with the wet induced-draft fan housings, and chimney flue

*Availability: the number of hours the FGD system is available for operation (whether operated or not), divided by the number of hours in the period, expressed as a percentage.

[+]Includes downtime due to chimney coating failures.

liner failures. The last three problems have been the primary causes of the reduced system availability and unit operation.

Bruce Mansfield 2 commenced commercial operation on October 1, 1977. This unit is identical to Bruce Mansfield 1 in design, and the performance of its scrubbing system has been nearly identical. As in the case of Bruce Mansfield 1, scrubbing system availability and unit operation have been limited primarily by problems with the reheaters, induced-draft fan housings, and chimney flue liners.

Pennsylvania Power Company has reported the total capital cost of the emission control systems for Bruce Mansfield 1 and 2, including the air quality control and waste disposal systems, to be $221,278,000. Of this total, $137,607,000 covers direct and indirect capital costs of the air quality control system, and $83,671,000 covers direct and indirect capital costs of the waste disposal system. Based on a gross generating capacity of 1834 MW, this amounts to approximately $120.65/kW. The total annual cost of the scrubbing system, including the air quality control system and waste disposal system, was reported to be $54,560,047. This includes $21,589,625 in variable charges and $32,970,422 in fixed charges. Based on a station capacity factor of 40.09 percent for 1977, giving a total net power production of approximately 3.621×10^9 kWh, this amounts to approximately 15.07 mills/kWh in total annual costs.

Bruce Mansfield 3, which is currently being erected alongside Bruce Mansfield 1 and 2, will have an air quality control system supplied by Pullman Kellogg. The emission control strategy for Bruce Mansfield 3 will be somewhat different from Bruce Mansfield 1 and 2, in that primary particulate control will be by electrostatic precipitators (ESP's) installed upstream of the sulfur dioxide control system. Sulfur dioxide will be removed in a wet lime horizontal spray chamber system, and the resulting wastes will be stabilized and disposed of in the existing waste disposal system. The cost of the entire air quality control system, including the ESP's, fans, ash handling, absorbers and related equipment, thickener, and chimney, is reported to be $232/net kW.

Table 1 summarizes data on the facility and FGD system.

TABLE 1. DATA SUMMARY: BRUCE MANSFIELD 1 and 2

Units	1 and 2
Gross rating, MW	1834
Net rating, MW	1650
Fuel	Coal
Average fuel characteristics:	
Heating value, kJ/kg (Btu/lb)	27,593 (11,863)
Ash, percent	15.11
Moisture, percent	5.53
Sulfur, percent	2.44
FGD process	Lime
FGD system supplier	Chemico
Application	New
Status	Operational
Startup dates:	
Initial	Dec. 1975 (Unit 1)
Commercial	June 1976 (Unit 1); Oct. 1977 (Unit 2)
Design removal efficiency:	
Particulate, percent	99.8
Sulfur dioxide, percent	92.1
Water loop	Open[a]
Sludge disposal	Stabilized sludge disposed in an offsite dammed reservior
Economics (reported):	
Capital, $/kW (gross)	120.65
Annual, mills/kWh (net)	15.07

[a]The system is designed for closed loop operation; however, it operates in an open loop because of excess water inputs from improper set points of seal water flow rate to recycle pumps, failure of fly ash slurry pumps necessitating the use of river water to remove fly ash from boiler hoppers to the thickeners, leakage of river water past emergency water values, and other sources.

SECTION 1

INTRODUCTION

The Industrial Environmental Research Laboratory (IERL) of the U.S. Environmental Protection Agency (EPA) has initiated a study to evaluate the performance characteristics and reliability of flue gas desulfurization (FGD) systems operating on coal-fired utility boilers in the United States.

This report, one of a series on such systems, covers the Bruce Mansfield plant of the Pennsylvania Power Company. It includes pertinent process design and operating data, a description of major startup and operational problems and solutions, atmospheric emission data, and capital and annual cost information.

This report is based on information obtained during and after plant inspections conducted for PEDCo Environmental personnel on July 7, 1976, and March 22, 1978, by the Pennsylvania Power Company. The information presented in this report is current as of August 1978.

Section 2 provides information and data on facility design and operation; Section 3 provides background information and a detailed description of the air quality and waste disposal systems; Section 4 describes and analyzes the operation and performance of the air quality and waste disposal systems; and Section 5 provides a detailed review of capital and annual costs, including utility-reported and PEDCo-adjusted values. Appendices A, B, and C contain details of plant and system operation, reported and adjusted capital and annual cost data, and photos of the installation.

SECTION 2

FACILITY DESCRIPTION

The Bruce Mansfield plant is a new 1650-MW (net), coal-fired, power generating station located in the Borough of Shippingport, Beaver County, Pennsylvania. It is situated in the southwest corner of the State, approximately 56 km (35 miles) downstream of Pittsburgh and 13 km (8 miles) east of the West Virginia-Pennsylvania State line. The area is highly industrialized and includes a number of chemical manufacturing plants and smelters. Another major power station, Beaver Valley, occupies a site approximately 1.6 km (1 mile) downstream of Bruce Mansfield. A general geographical map of the area, including the power stations, related facilities, and various population centers, is provided in Figure 1.

The Bruce Mansfield plant site runs more than 2.4 km (1.5 miles) along the Ohio River shore line. It occupies approximately 2 km^2 (500 acres), which is considered sufficient for ultimate expansion to include four coal-fired, power generating units. Plant grade is at an elevation of 222 m (730 ft), which is 20 m (65.5 ft) above normal pool elevation of the Ohio River and 10 m (33 ft) above the 100-yr design flood level. The boilerhouses and turbine rooms, one set for Bruce Mansfield 1 and 2 and one set for Bruce Mansfield 3 (now being erected), occupy an area approximately 89 m (292 ft) above grade.

Each unit is equipped with its own steam generator and turbine. The supercritical, pulverized-coal-fired steam generator is a once-through, balanced-draft, single reheat unit supplied by Foster Wheeler. Each unit produces 2910 Mg (6,415,000 lb) per hour of superheat steam at 540°C (1005°F) and 26.2 MPa (3785 psig) and 2360 Mg (5,200,000 lb) per hour of reheat steam

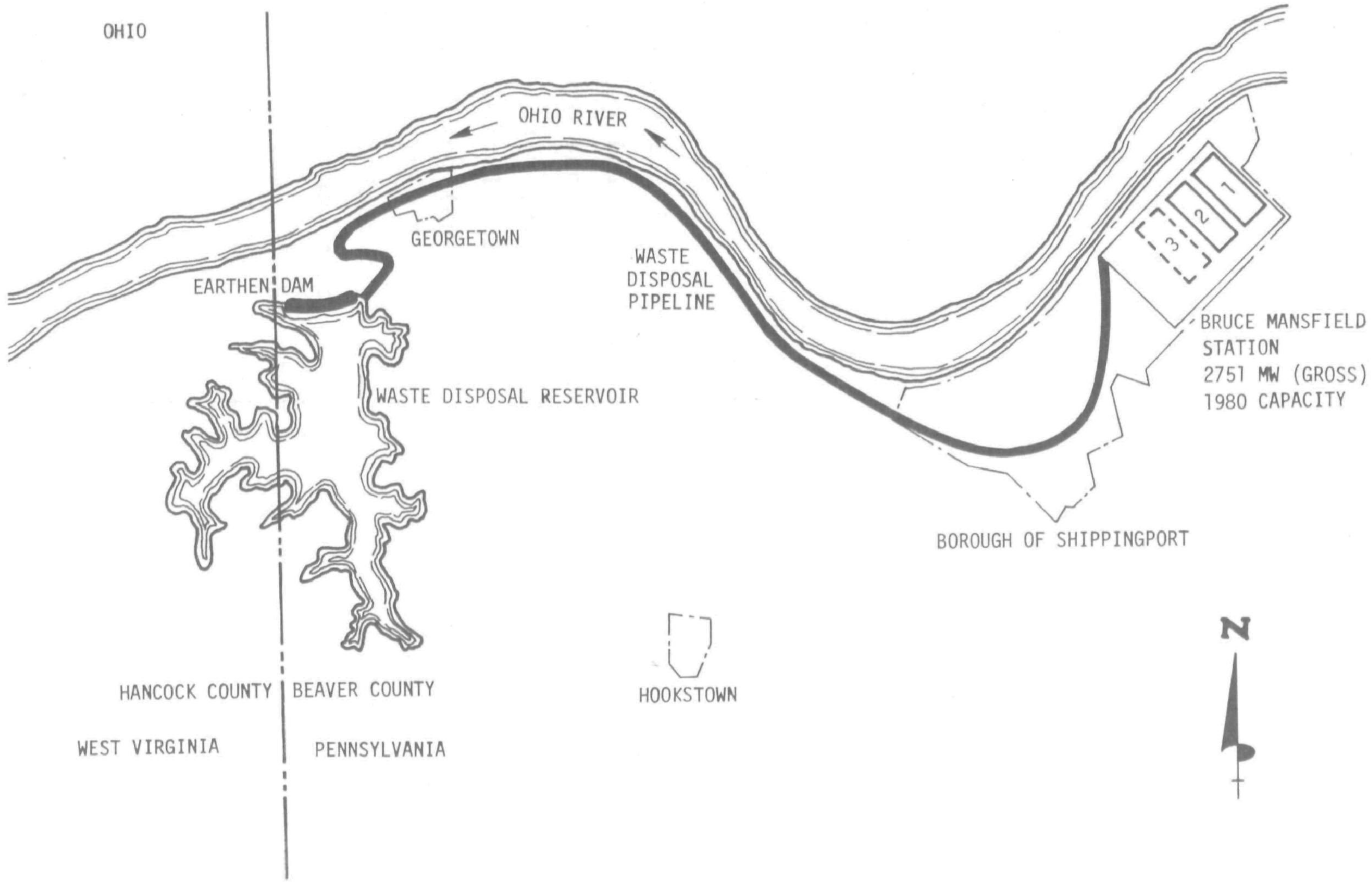

Figure 1. General geographical map showing power plants and related facilities and population centers in the vicinity of Shippingport, Pennsylvania.

at 540°C (1005°F) and 4.0 MPa (570 psig). The turbine generator is a 917-MW (gross), 26.1-MPa (3675-psig), 538°C/538°C (1000°F/1000°F), 5.1-kPa (1.5-in.-Hg), 3600-rpm unit supplied by General Electric. The station also contains three auxiliary oil-fired boilers, which are used for plant startups. These auxiliary boilers are all shop-assembled units that fire No. 2 fuel oil. Each produces 79.4 Mg (175,00 lb) of steam per hour at 299°C (570°F) and 2.3 MPa (325 psig).

The units burn an eastern, high-sulfur bituminous coal supplied primarily by several mines in Belmont and Monroe Counties in Ohio. In addition to obtaining coal from these contracted sources, the utility spot-purchases coal from mines in Maryland, Pennsylvania, and West Virginia. Table 2 presents the average characteristics of the coal burned at the plant.

Because of the large quantities of coal required at Mansfield--301 Mg (332 tons) per hour per unit, or 21.7 Gg (24,000 tons) per day, for all three units at full load--a highly flexible coal handling system was developed to accommodate coal deliveries by barge or truck; but virtually all of the coal delivered to Mansfield arrives by barge. Half of the plant harbor, one of the largest inland docking facilities in the United States, can accommodate up to 21 full jumbo barges. Coal can be unloaded from the barges at a maximum rate of 4.5 Gg (5000 tons) per hour and transferred via conveyor at a maximum rate of 2.7 Gg (3000 tons) per hour to the crusher house. The delivered coal is crushed to a maximum size of 3.2 cm (1.25 in.), then conveyed either to the plant for firing or to yard coal storage piles. Figure 2 illustrates the major components of the coal-handling system.

To meet air emission regulations promulgated by the Commonwealth of Pennsylvania for the Beaver Valley air basin, each unit includes a wet lime scrubbing system. These systems were supplied by Chemico for Bruce Mansfield 1 and 2 and by Pullman Kellogg for Bruce Mansfield 3 as an integral part of the power generating facilities, and duct work is arranged so that flue gas cannot

TABLE 2. CHARACTERISTICS OF COAL FIRED AT BRUCE MANSFIELD

Characteristic	Range	Average
Heating value, kJ/kg (Btu/lb)	25,600-27,800 (11,000-11,950)	26,700 (11,500)
Ash, percent	11.5 - 13.5	12.5
Moisture, percent	5.5 - 8.5	7.0
Sulfur, percent	1.75 - 3.75	3.0

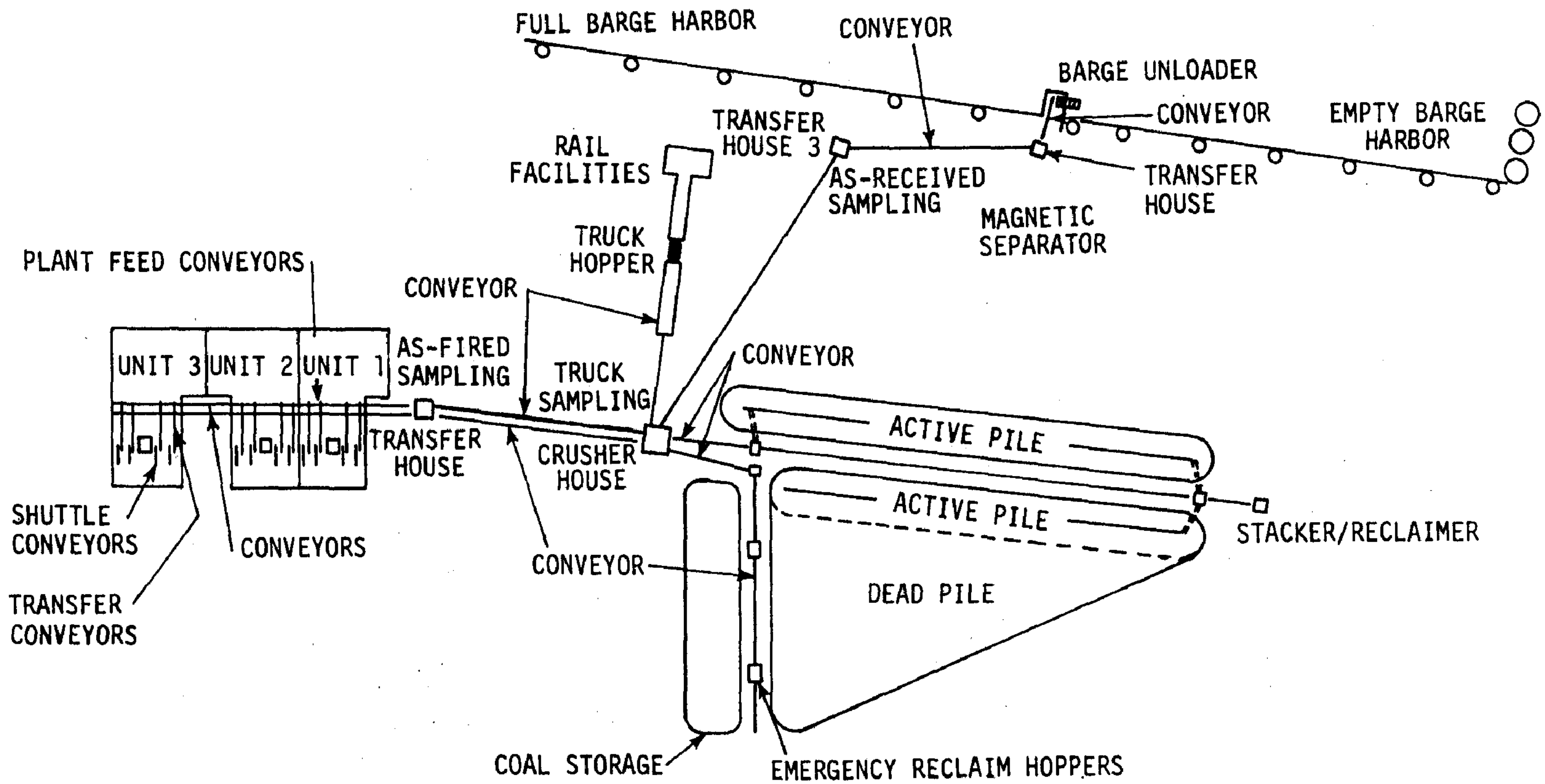

Figure 2. Major components of the Mansfield plant coal-handling system.

bypass the scrubbing modules. The concrete chimney with four coated carbon steel flues is not within Chemico's scope of supply.

A waste disposal system is provided along with the air quality control systems for disposal of flue gas cleaning (FGC) wastes in an environmentally acceptable manner. The wastes disposal system consists of a stabilization plant, which stabilizes the FGC wastes, and a dammed ravine, which provides a final disposal site for the treated wastes.

Chapter 123.11 of the Pennsylvania regulations governing the Bruce Mansfield units limits particulate emissions to 43 ng/J (0.1 lb/10^6 Btu) of heat input to the boiler and sulfur dioxide emissions to 258 ng/J (0.6 lb/10^6 Btu) of heat input to the boiler. Actual particulate emissions, as measured by the utility during performance tests, are 13 ng/J (0.03 lb/10^6 Btu) below the standard. Actual measured sulfur dioxide emissions showed that the sulfur dioxide removal efficiencies of the control equipment varied widely during initial operating stages. Specifically, the removal efficiency on Bruce Mansfield 1 varied from 60 to 94 percent over the course of several performance tests. This was attributed primarily to pH control problems.

Figure 3 provides a simplified process flow diagram of the Bruce Mansfield units, including the air quality and waste disposal systems. Table 3 presents data on plant design, operation, and atmospheric emissions.

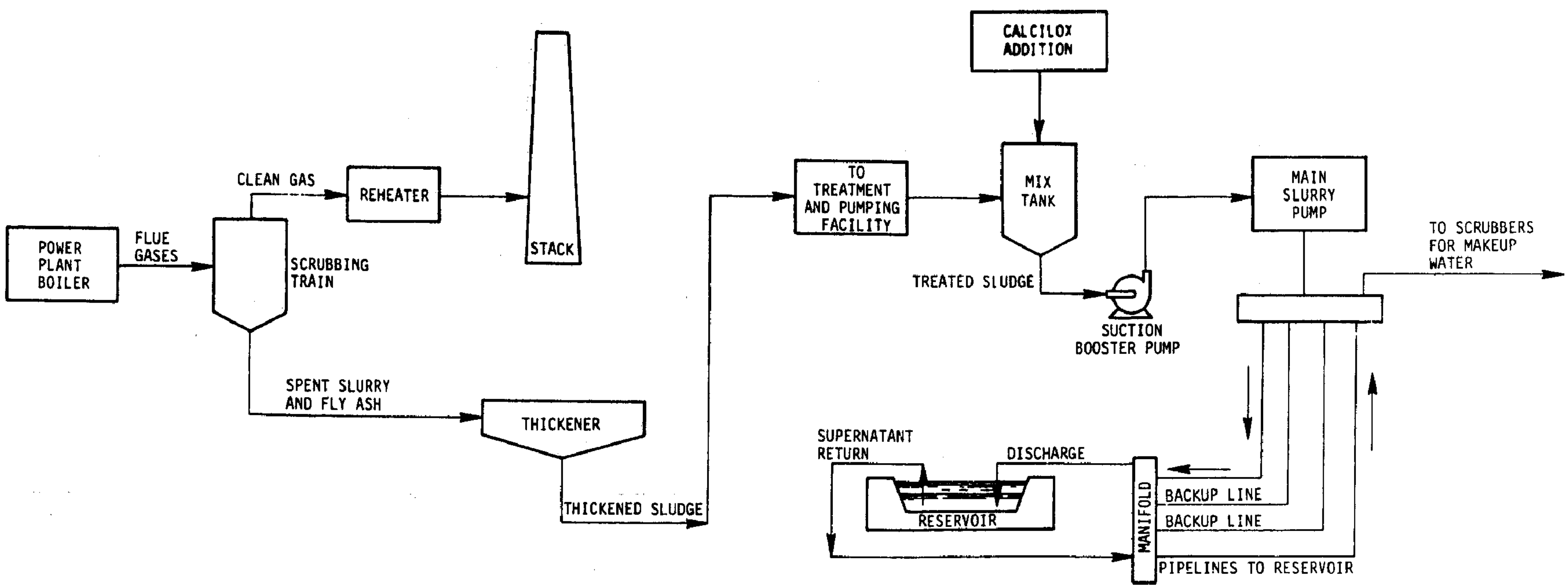

Figure 3. Simplified process flow diagrams of Bruce Mansfield air quality and waste disposal systems.

TABLE 3. DESIGN, OPERATION, AND EMISSION DATA: BRUCE MANSFIELD 1, 2, and 3

Description	Unit 1	Unit 2	Unit 3
Generating capacity, MW:			
Gross	917	917	917
Net without scrubbing	880[a]	880[a]	880[a]
Net with scrubbing	825[b]	825[b]	825[b]
Maximum coal consumption,			
Mg/h	301	301	301
(tons/h)	(332)	(332)	(332)
Maximum heat input, GJ/h	8,498	8,498	8,498
(10^6 Btu/h)	(8,055)	(8,055)	(8,055)
Maximum flue gas rate, m^3/s	1,580	1,580	1,560
(10^3 acfm)	(3,350)	(3,350)	(3,308)
Flue gas temperature, °C	140	140	140
(°F)	(285)	(285)	(285)
Unit heat rate, kJ/net kWh	13,190	13,190	N/A[c]
(Btu/net kWh)	(12,500)	(12,500)	N/A
Unit capacity factor, percent (1977)	40.09[a]	40.09[a]	N/A
Emission controls:			
Particulate and Sulfur dioxide	Variable-throat venturi scrubbers	Variable-throat venturi scrubbers	ESP's and spray chamber absorbers
Sulfur dioxide	Fixed-throat venturi absorbers	Fixed-throat venturi absorbers	Spray chamber absorbers
Particulate emission rate:			
Allowable, ng/J (lb/10^6 Btu)	15(0.035)[d]	15(0.035)[d]	32(0.075)
Actual, ng/J (lb/10^6Btu)	13(0.03)	13(0.03)	N/A
Sulfur dioxide emission rate:			
Allowable, ng/J (lb/10^6 Btu)	258(0.6)	258(0.6)	258(0.6)
Actual, ng/J (lb/10^6Btu)	65(0.15)[e]	65(0.15)[e]	NA

[a] Net rating including plant auxiliary power requirement.

[b] Net rating including plant auxiliary power requirement, scrubbing system power requirement, and cooling tower power requirement.

[c] N/A- Not applicable; unit under construction.

[d] Based upon maximum inlet fly ash loading of 6.9 g/MJ (16 lb/10^6 Btu) and a maximum rate of 0.019 g/m^3 (0.0175 gr/scf).

[e] Results of emission tests performed by Pennsylvania Department of Environmental Resources and an independent test firm hired by the utility.

SECTION 3

FLUE GAS DESULFURIZATION SYSTEM

BACKGROUND INFORMATION

On September 10, 1969, the CAPCO consortium announced the construction of the Bruce Mansfield plant. The plant was to contain two units, each having a net generating capacity of 880 MW. These units would fire high-sulfur, eastern bituminous coal obtained from local mines. Pennsylvania Power, a subsidiary of the Ohio Edison Company and a member company of the CAPCO consortium, was responsible for design, construction, and operation of the plant.

Engineering design was begun in late 1969. Plans for air quality control were developed in early 1970. Because Pennsylvania had no statewide standard applicable to sulfur oxide emissions at that time, the original air quality control plans considered only electrostatic precipitators for control of particulate emissions.

In November 1970, the Pennsylvania Department of Environmental Resources (DER) advised Pennsylvania Power that it was doubtful that a construction permit would be granted because no sulfur dioxide controls were included in the preliminary design of the plant. This precipitated an intensive investigation of applicable sulfur dioxide removal systems by Pennsylvania Power Company. Approximately 31 potential sulfur dioxide control systems, offered by both domestic and foreign suppliers, were evaluated. Fourteen were rejected immediately because they were in the early developmental stage or because the guaranteed removal efficiency was too low. Thirteen of the remaining 17 systems were rejected because they had not been developed to the point of reliable application to 800-MW generating units and/or they could not achieve the anticipated Pennsylvania statewide sulfur dioxide emission standard.

This elimination process left four systems for closer examination, three regenerable (i.e., the sulfur dioxide is recovered in a usable, marketable form) and one nonregenerable:

- Regenerable magnesium oxide process.
- Nonregenerable lime slurry process.
- Regenerable catalytic oxidation process.
- Regenerable electrolytic cell process.

The three regenerable processes were rejected because of lack of commercial experience. Only the Chemico venturi lime slurry wet scrubbing process was given serious consideration for two reasons: (1) it was the only system that had been used commercially for particulate control at an electric utility station (Arizona Public Service, Four Corners 1, 2, and 3); and (2) Chemico had design experience in sulfur dioxide removal from exhaust gases in the chemical industry to make its system the most promising candidate to meet the Pennsylvania statewide sulfur dioxide emission standard.

Because further investigations revealed that the technology associated with sulfur dioxide control had not reached the level of development necessary for reliable full-scale application, Pennsylvania Power proposed that a single module be built to treat part of the flue gas (20 to 25 percent of the total gas flow) from Bruce Mansfield 1. This module was to be an experimental prototype that would provide key design data and operating information in the areas of chemical, mechanical, and disposal problems. A 290-m (950-ft) stack was to be constructed to prevent ground-level concentrations from exceeding ambient air quality standards. This proposal was rejected by DER and the U.S. EPA.

In July 1972, Pennsylvania Power resubmitted its application for a construction permit to DER and included a lime flue gas scrubbing system for the control of particulate and sulfur dioxide in accordance with air emission regulations (Chapters 123.21, 123.22). A construction permit was granted in October 1972. In January 1973, Chemico was authorized to proceed with detailed design and engineering work for the installation of two full-scale venturi lime slurry scrubbing systems. During this design period a 0.7-m^3/s (1500-acfm) pilot plant was installed at Ohio Edison's R. E. Burger plant. Pilot plant testing was conducted from February to May 1973 and from August to September 1973. Flue gases of composition similar to those of the Mansfield plant were passed through the pilot unit, and various limes were tested to determine what type would be best suited for the high removal efficiencies required (99.8 percent for particulate and 92.1 percent for sulfur dioxide). Parameters for closed-water-loop operation were determined, as were the means of disposing of waste products from the flue gas cleaning system. As a result of the pilot programs, the Dravo Corporation was awarded contracts (1) to design and install a waste disposal system that used their proprietary additive, Calcilox, and (2) to supply the lime reagent, Thiosorbic lime, also a proprietary material.

PROCESS DESCRIPTION

The lime slurry scrubbing systems on Bruce Mansfield 1 and 2 were supplied by Chemico. Each consists of six scrubbing trains designed to treat the total boiler flue gas stream of 1580 m^3/s (3.35×10^6 acfm) at 140°C (285°F). The design efficiencies of the systems are 99.8 percent removal of the inlet particulate matter and 92.1 percent removal of the inlet sulfur dioxide when the boiler fires coal with sulfur and ash contents as high as 4.75 and 19.7 percent. The flue gas cleaning system was installed as an integral part of the power-generating facilities. Duct work is arranged so that flue gases cannot bypass the scrubbing trains.

The flue gas cleaning wastes produced by the scrubbing systems are discharged from the air quality control plants as thickener underflow at approximately 8.2 Mg (9000 tons) per unit per day. The thickener underflow, which contains 25 to 35 percent solids, is pumped to an onsite sludge treatment facility, where a stabilization material (Calcilox) is added before the mixture is pumped 11 km (7 mi) to an offsite containment area for final disposal.

Because of the size and complexity of the air quality and waste disposal systems, each is described in a separate subsection. The air quality control system can be described in terms of three basic operations: (1) lime handling and preparation, (2) gas treatment, and (3) solids/ liquid separation. The waste disposal system can be described in terms of four basic operations: (1) additive handling and preparation, (2) pumping and treatment, (3) transportation, and (4) containment. A schematic of the Bruce Mansfield air quality and waste disposal system, including all major components and process lines, is provided in Figure 4.

Air Quality Control System

Lime Handling and Preparation--

Lime for the scrubbing operation is supplied by Dravo Corporation under a long-term contract with Pennsylvania Power. This reagent, known as Thiosorbic lime, contains 2 to 6 weight percent magnesium oxide. The lime comes from a deep mine and preparation plant operated by Dravo in Maysville, Kentucky. A captive fleet of three towboats and numerous covered barges transports the reagent upriver to the Bruce Mansfield plant.

The lime is unloaded from the barges by a clamshell-type unloader. A conveying system transports the lime either into 30-day, 14,500-Mg (16,000-ton) bulk storage silos or two 3-day, 2270-Mg (2500-ton) storage silos. The 3-day silos are arranged so that lime can be discharged directly by belt, scale-type, weigh feeders into the lime slakers. One feeder and one slaker is provided for each 3-day storage silo.

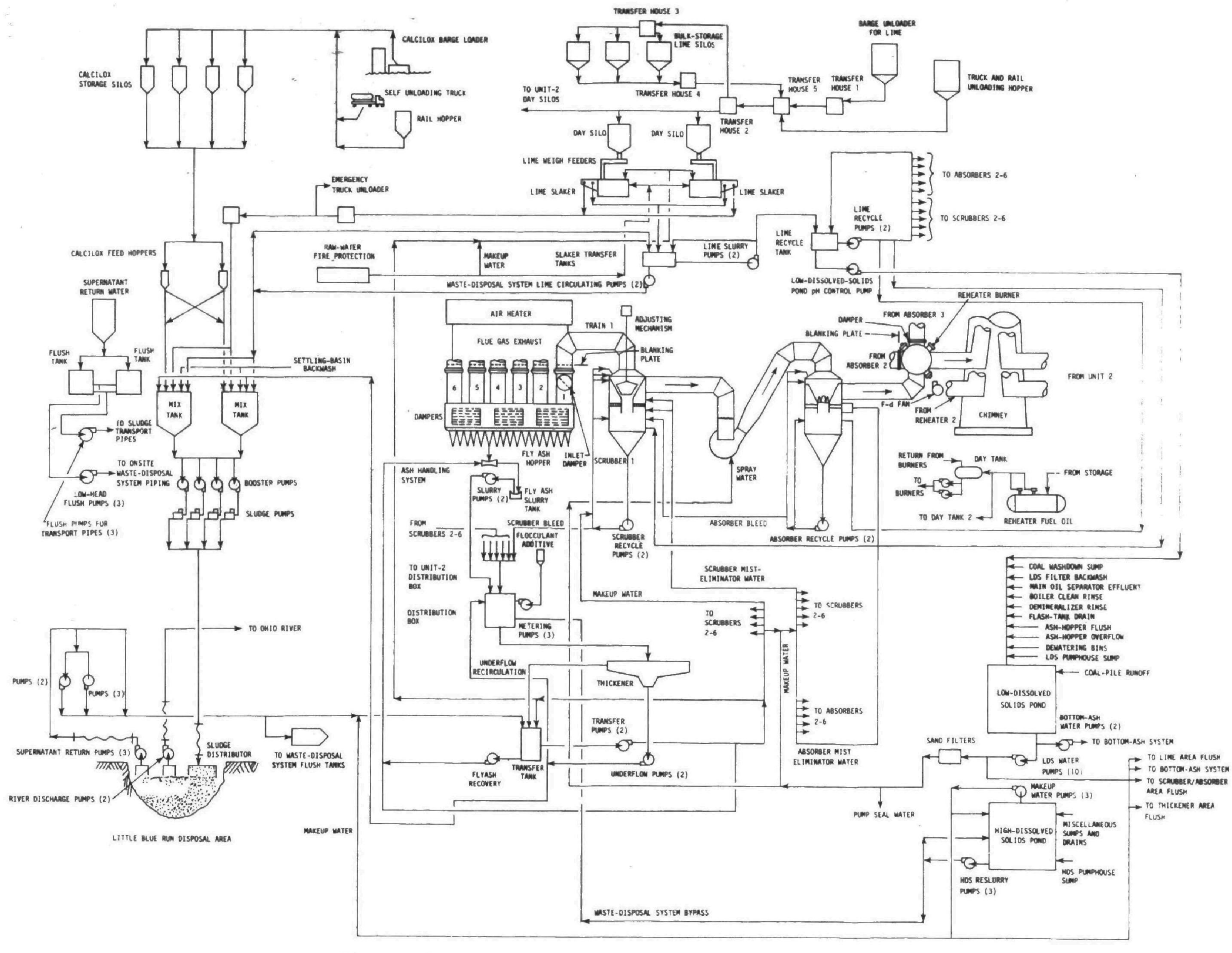

Figure 4. Bruce Mansfield flow diagram.

The slurry from the slakers is allowed to stabilize (completion of chemical slaking process) for approximately 30 minutes in an 11-m (36-ft)-diameter transfer tank. It is then pumped approximately 900 m (3000 ft) to a 3.7-m (12-ft)-diameter recycle tank directly adjacent to the absorbers. The recycle tank feeds a local recycle loop, which branches off into individual lines feeding each separate scrubber and absorber module. The lime feed, which is distributed equally between the scrubbers and absorbers, is transferred directly into the bottom of each scrubber and absorber for circulation through the vessel.

Gas Treatment--

Flue gas exits from the two air heaters of each boiler at 1580 m^3/s (3.35 x 10^6 acfm) and approximately 140°C (285°F), then enters a manifold that distributes it to six separate 4.6m (15-ft)-diameter inlet ducts. Each duct serves one scrubbing train consisting of a variable-throat venturi scrubber module, a 6700-kW (9000-hp) induced-draft fan, and a fixed-throat venturi absorber module. Six scrubbing trains are required on each unit for full boiler load operation. They are arranged in two groups of three, and the treated gas discharged from the three trains in each group flows together into a 7.6-m (25-ft)-diameter, oil-fired reheat chamber. The heated exhaust gas is then discharged to the atmosphere through a 290-m (950-ft) stack. The stack, which serves both units, contains four separate carbon steel flues, each of which receives the reheated gas stream discharged from one reheat chamber.

The flue gas first enters the top of the venturi scrubber, then passes down and around the adjustable plumb bob and accelerates to a velocity of approximately 61 m/s (200 ft/s) through the throat area. The gas is contacted in a cocurrent fashion with lime slurry that is recycled from the base (internal recycle tank) of the scrubber. A tangential-feed arrangement of the slurry feed nozzles atop each scrubber provides the primary sprays that wet the plumb bob and throat area. The incoming gas impacts upon this curtain of slurry spray, forming fine droplets, which intimately mix with the gas stream as they pass through the throat area. The gas-slurry stream separates in the lower section of the scrubber. The gas turns 180 degrees and passes upward through mist eliminator. The spent slurry droplets from the sprays are collected in the internal recycle tank for recirculation through the scrubbing circuit. The cleaned gases pass through the single-stage mist eliminator and then flow through the discharge duct to the induced-draft fan. Figure 5 provides a simplified diagram of a Bruce Mansfield scrubber module.

The induced-draft fan, which overcomes draft losses in the boiler and scrubbing system, receives the saturated gases from the scrubber. The gases then enter the top of the venturi absorber and pass down through the fixed-throat area. In a manner similar to that described for the venturi scrubber, the gas accelerates to a velocity of 30 m/s (100 ft/s) through the throat area, where it is contacted with lime slurry in a co-current fashion. The slurry, which is recycled from the absorber's internal recycle tank, is sprayed into the gas stream through a tangential-feed arrangement of the slurry feed nozzles. The nozzles spray slurry onto the convering throat area, gas baffles, and center cone of the absorber. The gas-slurry stream separates in the lower section of the absorber. The gas turns 180 degrees and passes upward through the mist eliminator. The spent slurry droplets from the primary and secondary sprays are collected in the internal recycle tank for recirculation through the scrubbing circuit. The cleaned, saturated gases then pass through another mist elimination stage, from which they are sent to the reheat chamber for temperature elevation before discharge to the atmosphere through the stack. Figure 6 provides a simplified diagram of a Bruce Mansfield absorber module.

Figure 7 provides a simplified diagram of a Mansfield scrubbing train, including inlet and outlet ducting, fan, reheater, and stack.

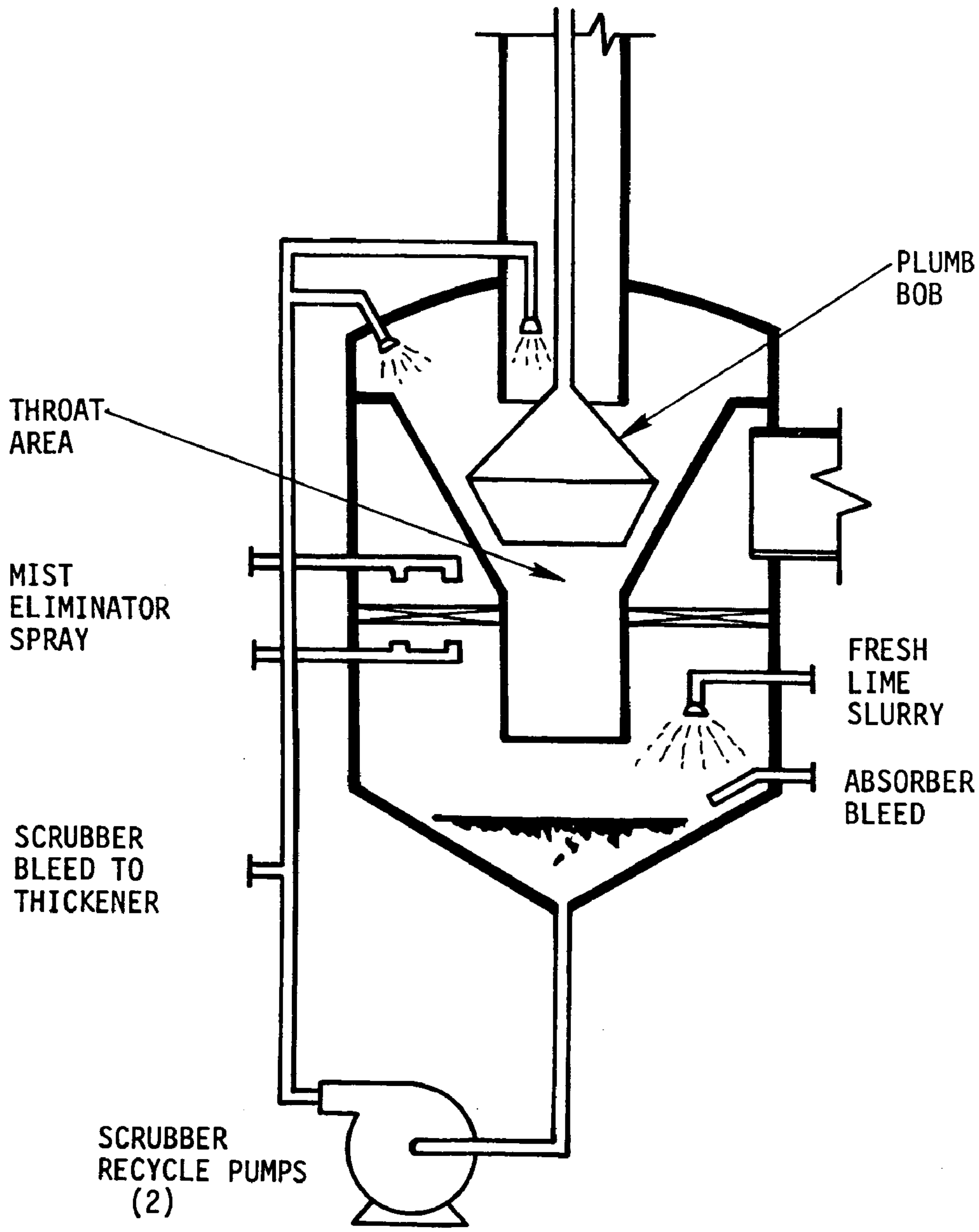

Figure 5. Simplified diagram of the Bruce Mansfield venturi scrubber.

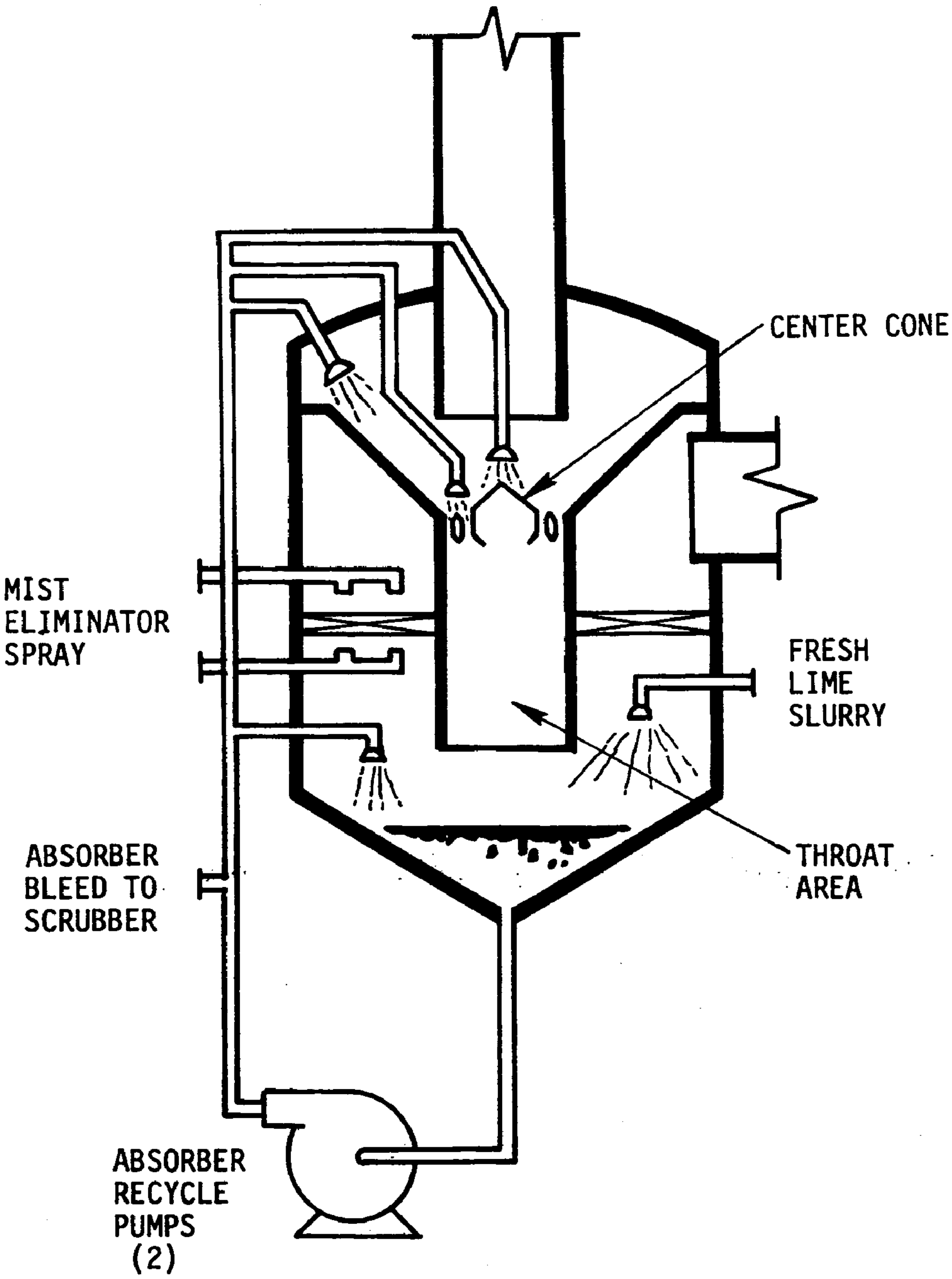

Figure 6. Simplified diagram of the Bruce Mansfield venturi absorber.

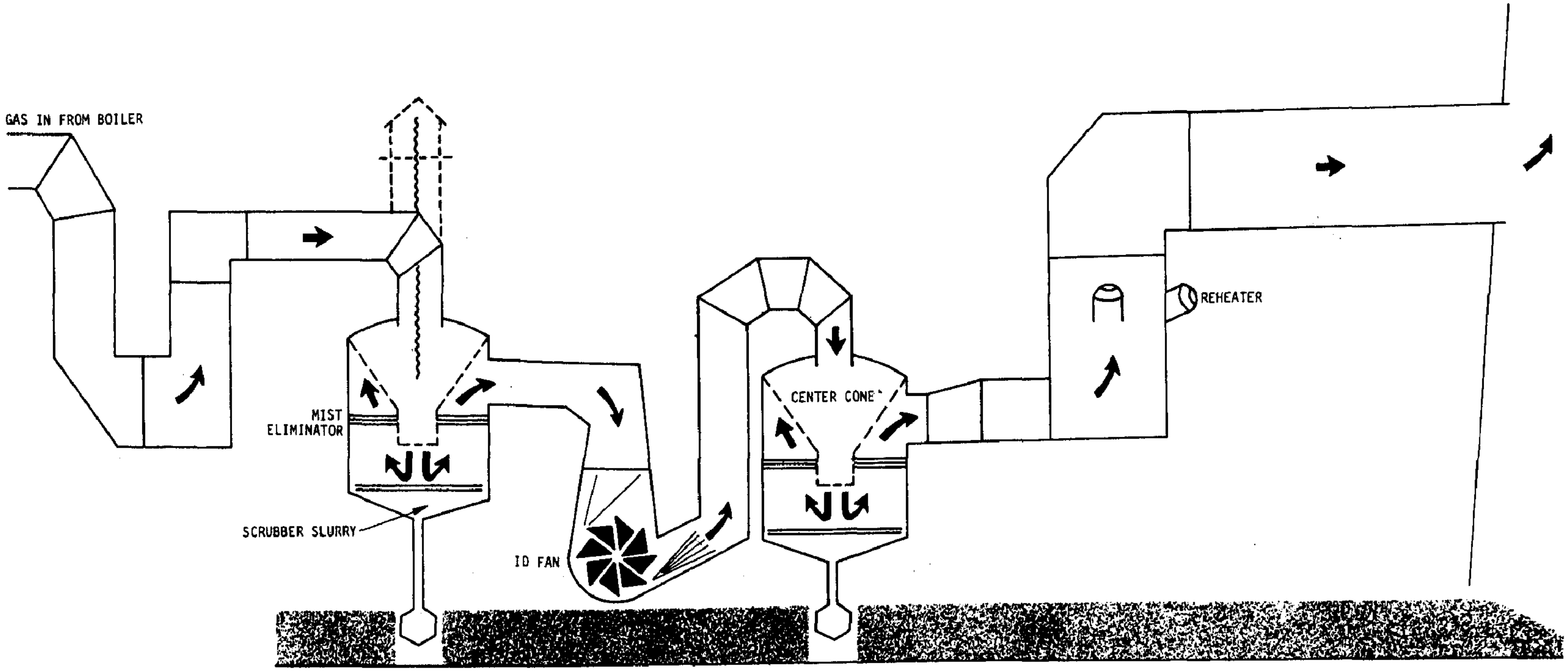

Figure 7. Simplified diagram of the Bruce Mansfield scrubbing train, duct work, and reheater.

Solids/Liquid Separation--

The spent slurry from the venturi absorber is discharged as a continuous bleed stream off the recycle line to the venturi scrubber. The absorber bleed stream enters directly into the internal recycle tank of the scrubber, where it is combined with the scrubber recycle stream and then recirculated through the scrubbing circuit. The spent slurry from the venturi scrubber is also discharged as a continuous bleed stream off the recycle line to a thickener. The spent slurry, which is 8 to 10 percent solids, combines with fly ash slurry from the boiler and then flows into a 61-m (200-ft)-diameter thickener.

The underflow from the thickener, which is 25 to 35 percent solids, is then pumped to the waste disposal system for treatment and ultimate disposal. The thickener overflow is used to maintain liquid levels in the scrubber and absorber vessels.

Waste Disposal System

Additive Handling and Preparation--

The additive (Calcilox) for the waste disposal system operation is supplied to Pennsylvania Power by the Dravo Corporation under a long-term contract. This cementitious stabilizing agent sets up the sludge to the strength of soil. Calcilox is transported to the plant harbor in totally enclosed, self-unloading barges. The stabilizer is unloaded pneumatically into four 4100-Mg (4500-ton) concrete storage silos. The storage silos feed pneumatically into two 91-Mg (100-ton) feed hoppers, which distribute Calcilox directly to two 666,000-liter (176,000-gal) mix tanks.

Pumping and Treatment--

The thickener underflow is pumped to the mix tanks to be mixed with the Calcilox. A 40-minute retention time and agitators assure adequate mixing of the waste stream with the Calcilox. The mixed sludge is discharged from the mix tanks and piped through one of two pump suction manifolds that supply four centrifugal booster pumps. The discharge from each booster pump feeds one of four 746-kW (1000-hp), positive-displacement, sludge transport pumps. Each pump can discharge from 1500 to 4500 liters/s (400 to 1200 gpm) of sludge at 7.7 MPa (1100 psig).

Transportation--

The waste slurry is pumped approximately 12 km (7 mi) downriver to the Little Blue Run ravine impoundment area. The slurry pipeline network consists of four underground pipes connecting the treatment plant and impoundment area. The pipeline network serves the dual function of transporting sludge to the impoundment area and returning supernatant to the plant. The four lines consist of two 20-cm (8-in.) and two 30-cm (12 in.)-diameter pipes, which can accommodate waste slurry flows ranging from 25 to 230 liters/s (400 to 3600 gpm).

The pipeline network is equipped with a high-pressure flushing system and a series of vents and drain boxes situated at high and low points of the pipe lines. The purpose of the flushing system is to purge the pipeline of sludge in the event a shutdown lasts longer than 24 hours, because the sludge will eventually solidify and plug the pipe if not cleared. Two 1,460,000-liter (385,000-gal) storage tanks, located next to the sludge mix tanks, provide the water needed for flushing. Three flush pumps [centrifugal type, 115 liter/s (1800 gpm) total capacity] direct flush water to the selected pipeline(s). The discharge from the flushing operation is routed to the impoundment area.

Containment--

The sludge disposal site is located in the Little Blue Run Valley lying on the Pennsylvania/West Virginia State line approximately 12 km (7 mi) west of the power plant. An earth and rockfill dam with an impervious core was constructed across the mouth of the valley, creating a reservoir for placement of the sludge. The embankment is 128 m (420 ft) high, 67 m (2200 ft) long at the crest, 518 m (1700 ft) thick at the base, and is composed of 6.5×10^6 m^3 (8.5 million yd^3) of fill.

The impoundment area covers approximately 5.7 x 10^6 m^2 (1400 acres) in area. The reservoir has a surface area of 3.6 x 10^6 m^2 (890 acres) and a total storage volume of 90 x 10^6 m^3 (118 million yd^3). It extends more than 3.2 km (2 mi) from the embankment and has over 22 km (13 mi) of shoreline.

The sludge transported through the pipelines is deposited in the reservoir through a tremie system, which distributes the sludge uniformly on the reservoir bottom. Supernatant is pumped from the reservoir surface by pumps on floating rafts. Water can either be returned to the plant or discharged to the Ohio River. The water recycled to the plant is either stored in the flush water storage tanks or routed to a transfer tank for use as makeup, mist eliminator wash, or slurry water.

Figures 8, 9 and 10 provide several diagrams of the basic operations of the waste disposal system. Figure 8 presents a simplified process diagram of the waste treatment system, including additive handling and storage. Figure 9 presents a cross-sectional view of the embankment. Figure 10 presents an overview of the Little Blue Run sludge disposal reservoir.

PROCESS DESIGN

Air Quality Control System

Fuel--

The scrubbing systems were designed to process flue gas resulting from the combustion of pulverized coal in two supercritical steam generators. Table 4 presents fuel specifications and consumption rate of the performance coal.

TABLE 4. SPECIFICATIONS AND CONSUMPTION RATE OF PERFORMANCE COAL

Heating value, kJ/kg (Btu/lb)	27,700 (11,900)
Ash, percent	12.5
Moisture, percent	8.0
Sulfur, percent	4.3
Maximum firing rate, Mg/h per unit (tons/h per unit)	301 (332)

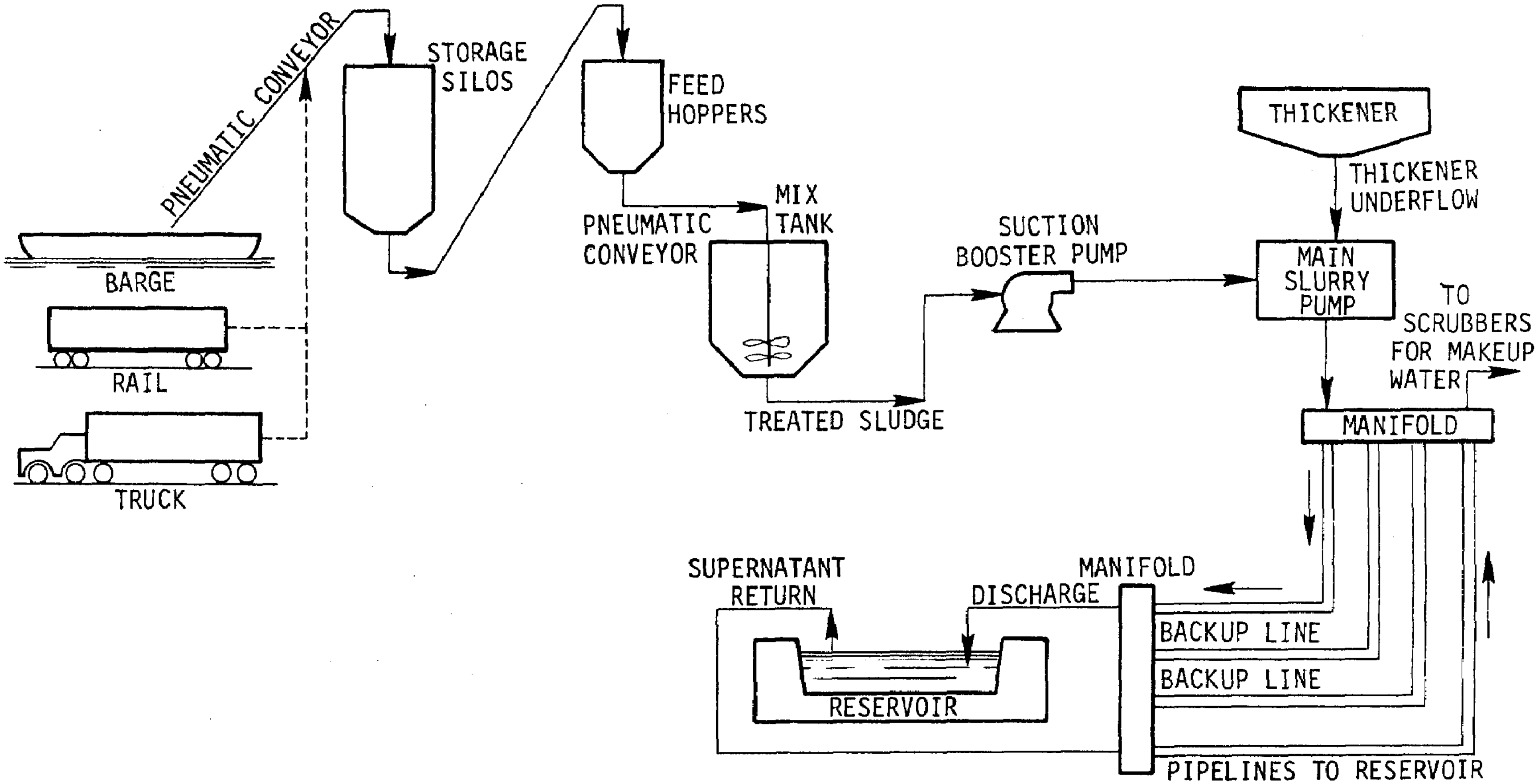

Figure 8. Simplified process diagram of the Bruce Mansfield waste treatment system.

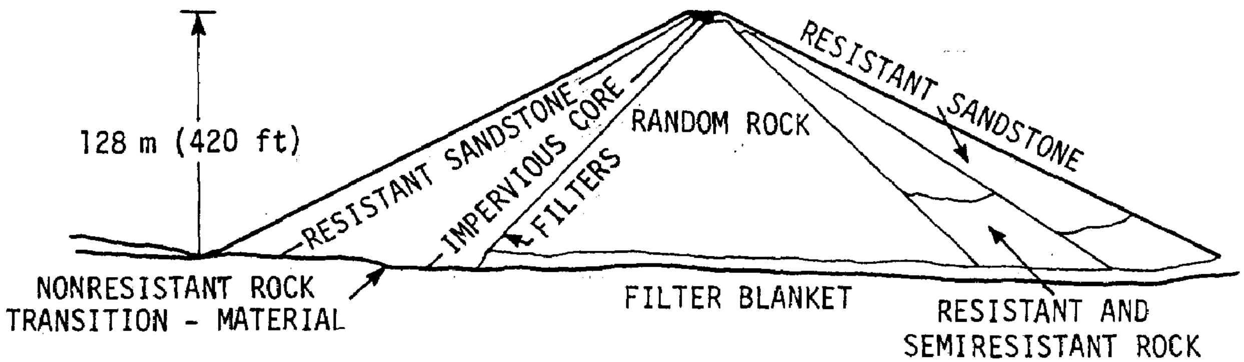

Figure 9. Cross-sectional view of the Little Blue Run Ravine embankment.

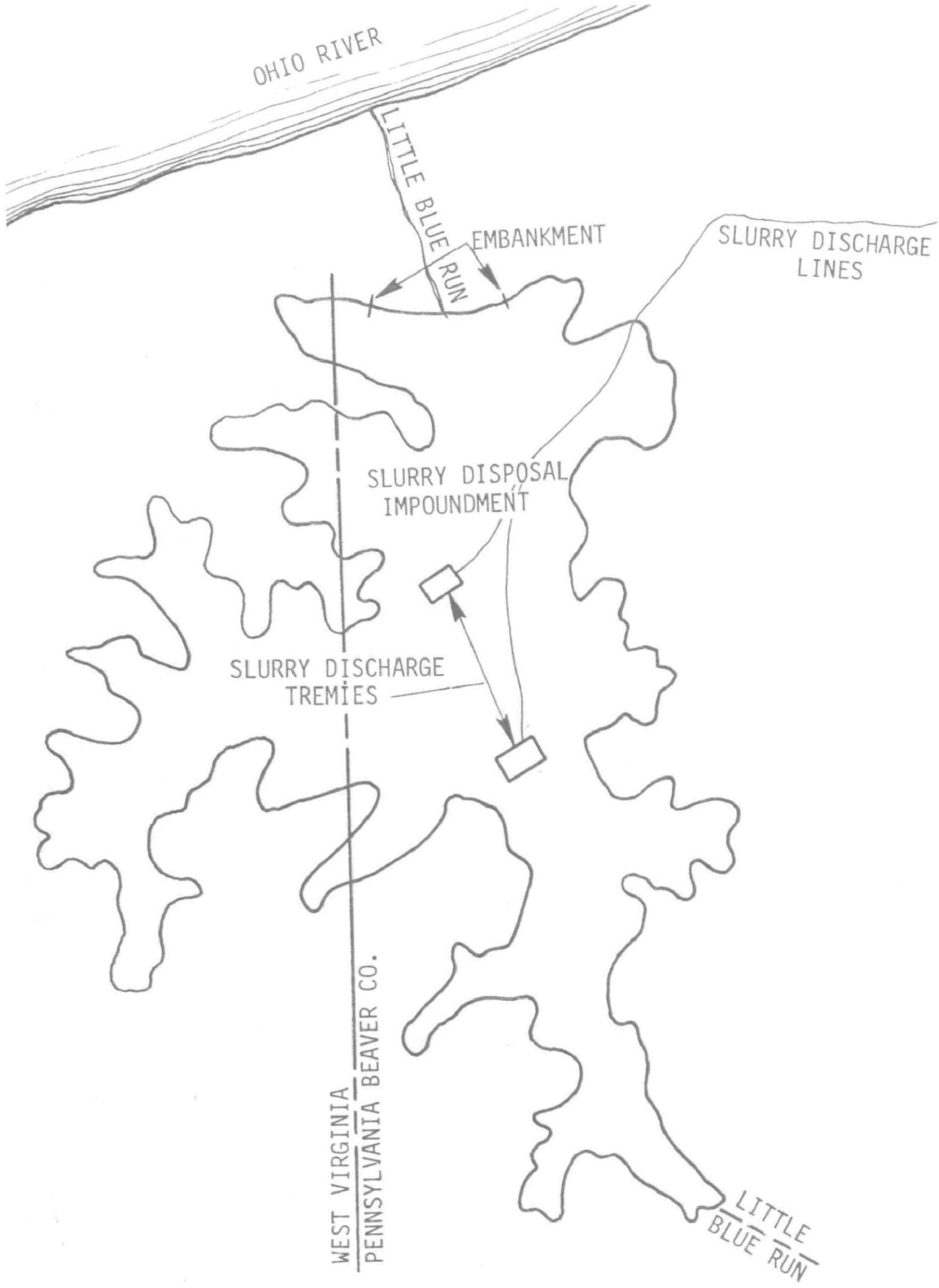

Figure 10. Overview of the Little Blue Run sludge disposal reservoir.

Inlet Gas Conditions and Removal Efficiency--

The inlet gas conditions to the scrubbing systems and design particulate and sulfur dioxide removal efficiencies are summarized in Table 5. The design values presented are based on the specifications and consumption rate of the performance coal.

Venturi Scrubbers--

The venturi scrubbers in the scrubbing systems provide primary particulate and sulfur dioxide control. Virtually all the particulate and 70 percent of the inlet sulfur dioxide is removed during this first venturi stage. Table 6 summarizes design parameters and operating conditions.

Venturi Absorbers--

The absorbers in the scrubbing systems are second-stage venturi modules designed to provide any additional particulate removal required (virtually all of the inlet particulate is removed in the venturi scrubber) and to remove an additional 70 percent of the inlet sulfur dioxide. The 70 percent sulfur dioxide removal efficiency in each stage gives a combined removal efficiency of approximately 92 percent, the level required to meet the 258 ng/J (0.6 lb/10^6 Btu) emission standard when the sulfur content of the coal is 4.75 percent (maximum). Table 7 summarizes the design parameters and operating conditions of the venturi absorbers.

Mist Eliminators--

Each module has its own separate mist eliminator, which is placed horizontal to the flue gas stream. Mist elimination is aided by a 180-degree reversal of the direction of the gas-slurry stream before it passes through the mist eliminator. This direction change effects removal of many of the medium-to-large liquid and solid particles before the stream reaches the mist eliminator. Table 8 summarizes design parameters and operating conditions. Figures 5 and 6, which provide simplified diagrams of the venturi scrubber and absorber modules, also illustrate the mist eliminator arrangements.

TABLE 5. INLET GAS CONDITIONS AND SYSTEM REMOVAL EFFICIENCY

Parameter	Average	Maximum
Inlet gas:		
Volume, m^3/s (10^3 acfm)	1580 (3350)	
Temperature, °C (°F)	140 (285)	
Particulate,		
μg/J (lb/10^6 Btu)	6.9 (16)	
g/m^3 (gr/scf) (dry basis)	10.27 (4.49)	28.93 (7.75)[a]
Sulfur dioxide,		
μg/J (lb/10^6 Btu)	3.1 (7.2)	3.4 (7.9)[b]
ppm	2940	3090
Outlet gas		
Volume, m^3/s (10^3 acfm)	1210 (2560)	
Temperature, °C (°F)	52 (125)	
Particulate,		
ng/J (lb/10^6 Btu)	15 (0.035)	
mg/m^3 (gr/scf)(dry basis)	40 (0.0175)	
Sulfur dioxide,		
ng/J (lb/10^6 Btu)	258 (0.6)	
ppm	242	
Particulate removal efficiency, percent	99.8	
Sulfur dioxide removal efficiency, percent	92.1	

[a] Based on a maximum coal ash content of 19.7 percent.

[b] Based on a maximum coal sulfur content of 4.75 percent.

TABLE 6. VENTURI SCRUBBER DESIGN PARAMETERS AND OPERATING CONDITIONS

Total number of modules	12
Number of modules per unit	6
Type	Variable-throat (plumb bob) venturi scrubber
Dimensions:	
Diameter, m(ft)	10.8 (35.5)
Height, m(ft)	15.8 (52.0)
Materials of construction	
Plumb bob	317 SS, flake-glass lining[a]
Throat	316 SS, flake-glass lining[a]
Internals	Carbon steel, flake-glass lining[a]
Shell	Carbon steel
Flue gas volume, m^3/ (acfm)	263 (558,300)
Flue gas temperature:	
Maximum, °C (°F)	149 (300)
Design, °C (°F)	140 (285)
Flue gas velocity, m/s (ft/s)	61 (200)
Pressure drop:	
Design, kPa (in. H_2O)	6 (23)
Liquid recirculation rate, liters/s (gpm)	1,390 (22,000)
Liquid-to-gas ratio (L/G), liters/m^3 (gal/10^3 acf)	5.3 (40)

[a] The flake-glass lining used in the scrubbers was supplied and applied by Heil; 80 mils of Rigiline 413GS and 410 was used for stainless steel surfaces; 80 mils of Rigiline 4850 was used for carbon steel surfaces.

TABLE 7. VENTURI ABSORBER DESIGN PARAMETERS AND OPERATING CONDITIONS

Total number of modules,	12
Number of modules per unit	6
Type	Fixed-throat venturi
Dimensions:	
Diameter, m(ft)	10.4 (34)
Height, m(ft)	15.7 (51.5)
Materials of construction:	
Center cone	316 SS, flake-glass lining
Throat	316 SS, flake-glass lining
Internals	Carbon steel, flake-glass lining
Shell	Carbon steel
Flue gas volume, m^3/s (acfm)	201 (426,600)
Flue gas temperature:	
Maximum, °C (°F)	66 (150)
Design, °C (°F)	53 (127)
Flue gas velocity, m/s (ft/s)	30 (100)
Pressure drop:	
Maximum, kPa (in. H_2O)	4 (16)
Design, kPa (in. H_2O)	2 (8)
Liquid recirculation rate, liters/s (gpm)	1220 (19,400)
L/G,[a] liters/m^3 (gal/10^3 acf)	5.3 (40)[b]

[a] Liquid-to-gas ratio.

[b] Actual operating L/G ratio is 2.6 liters/m^3 (20 gal/10^3 acf).

TABLE 8. MIST ELIMINATOR DESIGN PARAMETERS AND OPERATING

Total number	24
Number per module	1
Type	Chevron
Configuration	Horizontal
Materials of construction	Fiber-reinforced plastic
Number of stages	1
Number of passes per stage	4
Shape	Chemico open chevron design
Spacing between lanes, cm (in.)	7.6 (3.0)
Mist carryover, g/m^3 (gr/acf)	2.3 (1.0)[a]
Wash system:	
Water source	Transfer water
Wash direction	Overspray/underspray
Frequency	Overspray - once per shift; Underspray - continuous sequence spray on each quadrant.
Duration	Overspray - 1 h/shift Underspray - continuous
Rate	Overspray - 7.9 liters/s (125 gpm); Underspray - 4 liters/s (63.5 gpm)
Pressure	Overspray - 379 kPa (40 psig) Underspray - 241 kPa (20 psig)

[a] Actual measured value is 1.2 g/m^3 (0.5 gr/acf).

Reheaters--

Each scrubbing system is equipped with two oil-fired, direct-combustion reheaters. These reheaters were intended to elevate the discharge gas temperature to avoid downstream condensation and corrosion, suppress plume visibility, and enhance plume rise and dispersion of pollutants. Because experience has shown that the reheaters are incapable of operating at temperatures high enough to reheat the flue gas sufficiently and they require extensive maintenance, they will not be used. Table 9 summarizes reheater design and operating parameters.

Fans--

In each scrubbing train, a wet-type, induced-draft fan is situated between the venturi scrubber and venturi absorber. These fans are designed to operate in tandem with the boiler forced-draft fans and overcome the draft losses in the boiler and scrubbing system. Table 10 summarizes the design and operating parameters.

Pumps--

Each air quality control system has approximately 35 pumps, within the liquid circuit battery limits from the lime slurry feed to the thickener underflow discharge. Table 11 summarizes pump design parameters and operating conditions.

Lime Storage and Preparation--

One lime storage and preparation facility meets the reagent needs for scrubbing systems. Table 12 summarizes design parameters and operating conditions.

Waste Disposal System

The four basic operations of the waste disposal system are additive handling and preparation, pumping and treatment, transportation, and containment. Tables 13 and 14 summarize the design parameters and operating conditions for additive treatment and slurry transportation, Tables 15 and 16 list the embankment and reservoir design parameters.

TABLE 9. REHEATER DESIGN PARAMETERS AND OPERATING CONDITIONS

Total number	4
Number per scrubbing system	2
Type	Direct combustion
Manufacturer	Thermal research and engineering
Combustion chamber location	In-line
Combustion chamber type	Vortex type, mechanical atomization
Number of burners per chamber	3
Fuel	No. 2 fuel oil
Heating value, M /liter (10^3 Btu/gal)	39 (140)
Sulfur content, percent	0.3
Combustion rate per chamber, liters/s (gpm)	0.5 (7.9)
Heat input, GJ/h (Btu/h)	29.5 (28.0)
Gas temperature, °C (°F)	1650 (3000)
Reheated gas temperature, °C (°F)	74 (165)

TABLE 10. INDUCED-DRAFT FAN DESIGN PARAMETERS AND OPERATING CONDITIONS

Total number	12
Number per scrubbing train	1
Manufacturer	Green Fan Company
Service	Wet
Specifications:	
Type	Radial tip, inlet damper control
Rating, kW(hp) and rpm	6700 (9000) and 1300
Pressure drop:	
Design, kPa (in. H_2O)	19 (75)
Maximum continuous, kPa (in. H_2O)	16 (63)
Motor, kV	13.2
Capacity, m^3/s (ft^3/min)	263 (558)
Gas temperature, °C (°F)	48 (118)
Gas density, kg/m^3 (lb/ft^3)	0.913 (0.057)
Materials of construction:	
Housing	Rubber-lined carbon steel*
Scrolls	Inconel 625
Blades	Inconel 625
Shaft	Carbon steel clad with Carpenter 20

* The rubber-lined carbon steel has been extremely unsatisfactory and is being replaced with housing fabricated from Inconel 625.

TABLE 11. PUMP DESIGN PARAMETERS AND OPERATING CONDITIONS

Number	Service	Manufacturer	Type	Model	Capacity: Flow, liters/s (gpm)	Capacity: Head, meters (ft)	Capacity: Power, kW (hp)	Capacity: Speed, rpm	Size, cm (in.)	Materials of construction
24	Scrubber recycle	Allen-Sherman-Hoff	Centrifugal, single-stage, V-belt	DG-9-5	695 (11,000)	35 (107)	335 (450)	1200	4 x 4 x 99 (16 x 16 x 39)	Rubber-lined impellers and linings
24	Absorber recycle	Allen-Sherman-Hoff	Centrifugal, single-stage, V-belt	DG-9-5	610 (97,000)	35 (116)	335 (450)	1200	4 x 4 x 99 (16 x 16 x 39)	Rubber-lined impellers and linings
4	Thickener underflow	Joy/Denver	Centrifugal, single-stage, V-belt		95 (1500)	20 (70)	55 (75)	1200		Rubber-lined impellers and linings
4	Thickener transfer	Goulds	Centrifugal, single-stage, V-belt		440 (7000)	45 (140)	260 (350)	1180		Carbon Steel
4	Lime slurry transfer	Joy/Denver	Centrifugal, single-stage, V-belt		145 (2300)	30 (98)	95 (125)			Rubber-lined impellers and linings
4	Lime slurry recycle	Joy/Denver	Centrifugal, single-stage, V-belt		240 (3800)	190 (63)	95 (125)	1800		Rubber-lined impellers and linings

TABLE 12. LIME STORAGE AND PREPARATION FACILITY DESIGN PARAMETERS AND OPERATING CONDITIONS

Lime storage:	
Bulk storage silos:	
Number	3
Capacity, Gg (10^3 ton)	14.5 (16)
Retention time, days	30
Short term storage silos:	
Number	2
Capacity, Gg (10^3 ton)	2.3 (2.5)
Retention time, days	2
Lime preparation:	
Slakers:	
Number	2
Manufacturer	Dorr-Oliver
Capacity, Mg/h (tons/h)	20 (22)
Feed rate, liters/s (gpm)	63 (1000)
Solids, percent	9
Stoichiometric, percent	130
Point of addition	Recycle tank[a]
Maximum feed rate, liters/s (gpm)	125 (2000)[b]

[a] One common recycle tank is provided for each scrubbing system. The recycle tank, which is situated adjacent to the absorbers, receives the lime slurry stream and feeds a local recycle loop that has individual branches feeding the internal recirculation tank of each module.

[b] Per scrubbing system.

TABLE 13. ADDITIVE TREATMENT DESIGN PARAMETERS AND OPERATING CONDITIONS

Thickener underflow characteristics:	
Solids, percent (wt.)	25 to 35
Temperature, °C (°F)	38 to 52 (100 to 125)
Specific gravity	1.2 to 1.29
Particle size	250
pH	10.5 to 11.0
Treatment processing rates:	
12.5 percent station load factor, Mg/h (tons/h)	45 (50)
25 percent station load factor, Mg/h (tons/h)	91 (100)
50 percent station load factor, Mg/h (tons/h)	180 (200)
75 percent station load factor, Mg/h (tons/h)	270 (300)
100 percent station load factor, Mg/h (tons/h)	360 (400)
Additive requirements:	
Calcilox, kg/s (lb/min)	5.3 (700)
Lime grits, kg/s (lb/min)	0.7 (93)
Additive feed rates:	
Normal:	
Calcilox, percent of total flow	7
Maximum:	
Calcilox, percent, on dry basis of material being pumped	10
Retention time, minutes	40

TABLE 14. SLURRY TRANSPORTATION DESIGN PARAMETERS AND OPERATING CONDITIONS

Slurry pumping characteristics	20-cm (8-in) pipe	30-cm (12-in) pipe
25 percent solids and 1.2 specific gravity:		
Minimum conditions:		
Velocity, m/s (ft/s)	1.22 (3.99)	1.08 (3.54)
Flow rate, liters/s (gpm)	39 (619)	78.1 (1238)
Total capacity, Mg/h (tons/h)	168 (185)	336 (371)
Maximum conditions:		
Velocity, m/s (ft/s)	2.41 (7.92)	3.10 (10.18)
Flow rate, liters/s (gpm)	78.1 (1238)	226 (3590)
Total capacity, Mg/h (tons/h)	336 (371)	976 (1076)
30 percent solids and 1.24 specific gravity:		
Minimum conditions:		
Velocity, m/s (ft/s)	0.97 (3.20)	0.87 (2.85)
Flow rate, liters/s (gpm)	31.5 (500)	63.1 (1000)
Total capacity, Mg/h (tons/h)	140 (155)	281 (309)
Maximum conditions:		
Velocity, m/s (ft/s)	1.95 (6.41)	2.50 (8.20)
Flow rate, liters/s (gpm)	63.1 (1000)	183 (2904)
Total capacity, Mg/h (tons/h)	281 (309)	816 (890)
35 percent solids and 1.24 specific gravity:		
Minimum conditions:		
Velocity, m/s (ft/s)	0.80 (2.63)	0.73 (2.38)
Flow rate, liters/s (gpm)	26.1 (415)	52.4 (830)
Total capacity, Mg/h (tons/h)	121 (133)	242 (268)
Maximum conditions:		
Velocity, m/s (ft/s)	1.59 (5.21)	2.07 (6.78)
Flow rate, liters/s (gpm)	52.4 (830)	152 (2410)
Total capacity, Mg/h (tons/h)	242 (268)	705 (777)

TABLE 15. EMBANKMENT DESIGN PARAMETERS

Height, m (ft)	128 (420)
Crest length, m (ft)	670 (2200)
Base thickness, m (ft)	472 (1550)
Composition, 10^6 m^3 (10^6 yd^3)	6.5 (8.5)

TABLE 16. RESERVOIR DESIGN PARAMETERS

Total area, 10^6 m^2 (acre)	5.7 (1400)
Surface area, 10^6 m^2 (acre)	3.6 (890)
Depth, m (ft)	110 (350)
Shoreline, km (mi)	21 (13)
Total storage volume, 10^6 m^3 (10^6 yd^3)	90 (118)

PROCESS CHEMISTRY: PRINCIPAL REACTIONS

The chemical reactions involved in the Bruce Mansfield wet lime scrubbing processes are highly complex. Although details of these processes are beyond the scope of this discussion, the principal chemical mechanisms are described below.

The first and most important step in the wet-phase absorption of sulfur dioxide from the flue gas stream is diffusion from the gas to the liquid phase. Sulfur dioxide is an acidic anhydride that reacts readily to form an acidic species in the presence of water.

(1) $SO_2 \uparrow \rightleftharpoons SO_2(aq.)$

(2) $SO_{2(aq.)} + H_2O \rightleftharpoons H_2SO_3$

In addition, some sulfur trioxide is formed from further oxidation of the sulfur dioxide in the flue gas stream.

(3) $2SO_2 \uparrow + O_2 \uparrow \rightleftharpoons 2SO_3 \uparrow$

Because conditions are thermodynamically but not kinetically favorable, only small amounts of sulfur trioxide are formed. This species, like sulfur dioxide, is an acidic anhydride that reacts readily to form an acid in the presence of water.

(4) $SO_3 \uparrow \rightleftharpoons SO_3(aq.)$

(5) $SO_{3(aq.)} + H_2O \rightleftharpoons H_2SO_4$

The sulfurous and sulfuric acid compounds are polyprotic species. The sulfurous species is weak; and the sulfuric species, strong. Their dissociation into ionic species occurs as follows:

$$(6)\quad H_2SO_3 \rightleftharpoons H^+ + HSO_3^-$$

$$(7)\quad HSO_3^- \rightleftharpoons H^+ + SO_3^=$$

$$(8)\quad H_2SO_4 \rightleftharpoons H^+ + HSO_4^-$$

$$(9)\quad HSO_4^- \rightleftharpoons H^+ + SO_4^=$$

Analogous to the oxidation of sulfur dioxide to form sulfur trioxide, oxidation of sulfite ion by dissolved oxygen (DO) in the scrubbing slurry is limited.

$$(10)\quad 2SO_3^= + O_2(aq.) \rightleftharpoons 2SO_4^=$$

This reaction occurs in the aqueous phase like the gas-phase oxidation of sulfur dioxide. Formation of sulfate is a second-order reaction that is directly proportional to the concentrations of DO and sulfite ion. Since the DO content of the scrubbing solution should be relatively constant because of the excess oxygen in the flue gas, the formation of sulfate ion in the aqueous phase depends primarily on sulfite ion concentration. Since sulfite solubility increases as pH decreases, sulfate ion production occurs more readily in the acidic pH range.

The Thiosorbic lime reagent supplied by Dravo is burned lime containing primarily calcium oxide (94 to 98 percent) and a small quantity of magnesium oxide (2 to 6 percent). When slaked with water, the calcium and magnesium oxides are converted to hydroxides.

$$(11)\quad CaO + H_2O \rightleftharpoons Ca(OH)_2$$

$$(12)\quad MgO + H_2O \rightleftharpoons Mg(OH)_2$$

The calcium and magnesium hydroxides produced during the slaking process are soluble to different extents in the aqueous phase.

$$(13)\quad Ca(OH)_2 \rightleftharpoons Ca^{++} + 2OH^-$$

$$(14)\quad Mg(OH)_2 \rightleftharpoons Mg^{++} + 2OH^-$$

Because of the superior solubility of the magnesium, this species dominates in the absorption step, whereas calcium dominates in the regeneration step. This chemical behavior, similar in nature to double-alkali chemistry that utilizes a soluble medium (e.g., sodium) for absorption and calcium (lime or limestone) for regeneration in a reactor outside the scrubbing loop, has given rise to the phrase "dirty double alkali" for describing magnesium-lime scrubbing chemistry.

During absorption the magnesium cations react with the predominate sulfur dioxide anions of sulfite and bisulfite in the following manner:

$$(15)\quad Mg^{++} + SO_3^{=} \rightleftharpoons MgSO_3$$

$$(16)\quad Mg^{++} + 2HSO_3^- \rightleftharpoons Mg(HSO_3)_2$$

The magnesium sulfite formed in reaction (15) is a highly soluble ion pair, which is capable of further reacting with sulfur dioxide ions in the following manner:

$$(17)\quad MgSO_3 + H^+ + HSO_3^- \rightleftharpoons Mg(HSO_3)_2$$

Thus, the predominate species formed during absorption is magnesium bisulfite. The spent absorbing medium is collected at the base of the venturi modules in the internal recirculation tank. Fresh slaked lime is added to the internal recirculation tank, resulting in regeneration of the absorbing medium and formation of the waste products.

$$(18)\quad Mg(HSO_3)_2 + Ca(OH)_2 \rightleftharpoons MgSO_3 + CaSO_3 + 2H_2O$$

$$(19)\quad Mg(HSO_3)_2 + Mg(OH)_2 \rightleftharpoons 2MgSO_3 + 2H_2O$$

The calcium sulfite precipitates out as a hemihydrate crystal.

$$(20)\ CaSO_3 + 1/2\ H_2O \rightleftharpoons CaSO_3 \cdot 1/2\ H_2O \downarrow$$

Sulfate ions formed by reactions (9) and (10) also constitute a waste product, which is purged from the system as either a soluble component of the sludge liquor or an insoluble calcium sulfate dihydrate (gypsum).

$$(21)\ CaSO_4 + 2\ H_2O \rightleftharpoons CaSO_4 \cdot 2\ H_2O \downarrow$$

The gypsum formed in the system is present in small quantities because of the subsaturated mode provided by the magnesium species.

The waste products collected in the scrubbing system, which include fly ash, calcium sulfite, and calcium sulfate, as well as some unused reagent, are discharged to the thickener for separation and disposal.

PROCESS CONTROL

The process con ol network of the Bruce Mansfield air quality and waste disposal systems focuses on the regulation of reagent feed, slurry solids, and water balance. The major variables measured for process control include solution pH, slurry solids, liquid level, and liquid flow. The principal features of the control network are described and summarized as follows:

Reagent Feed

Control signals are provided by pH sensors, which modulate the flow of lime slurry to the scrubbing systems in a feedback control mode. The sensor feeds a signal back to the controller, and regulation is effected by correcting for any deviation between the response valve and set point after the fact. Each venturi scrubber and venturi absorber in these scrubbing systems has lime slurry circulated through it. Therefore each module regulates the amount of lime slurry fed to each scrubber and absorber by monitoring slurry pH in each recirculation line. A short-coupled, flow-through system takes a sample at the fresh-slurry injection point and returns the sample directly to the scrubber vessel at a location directly above the liquid level. The pH sensors are a Universal Uniloc model equipped with ultrasonic cleaners that do not work and are being removed. The signal is relayed to an air-operated, pinch-type, flow-control valve installed in each individual feed line that branches off the local recycle loop of the lime recycle tank. The pH control range of the lime slurry feed is 7.0 ± 0.2. As the pH swings above or below this control bank, the amount of fresh slurry is automatically reduced or increased to maintain slurry pH within this bank. This permits optimum removal efficiency while preventing loss of chemical control, which can lead to scale formation or plugging.

Slurry Solids

The slurry solids content in the scrubbing solution is manually controlled by maintaining a constant slurry solids content in the purge stream to the thickener. The solids content of this purge stream is 10 percent; it keeps the solids content of the absorber purge that flows to the venturis at 8 percent.

The solids content of the thickener underflow is also controlled manually. Maintaining a slurry solids content of 30 percent in the underflow stream provides several benefits: (1) plugging and erosion are minimized; (2) chemical control is maintained; and (3) the waste disposal system operates more efficiently.

Water balance

Water balance in the scrubbing system is monitored and controlled by the use of diaphragm and static-head level indicators situated in each scrubber and absorber internal recirculation tank and lime slurry transfer tank. Thickener overflow is used to maintain liquid levels in these and other tanks in the scrubbing systems.

SECTION 4

FGD SYSTEM PERFORMANCE

BACKGROUND INFORMATION

Bruce Mansfield air quality and waste disposal systems represent the largest and most sophisticated applications of scrubbing and waste disposal technology in the world today. The air quality control systems, which represent first-generation design philosophy, are an integral part of the power production systems. Because these systems provide primary control of both sulfur dioxide and particulates, the duct work design does not permit flue gas to bypass the system. At the time they were designed, pilot-tested, and developed, flue gas desulfurization (FGD) was still in the early stage of development. Much of the design philosophy of FGD technology at that stage was "borrowed" from other fields and applications. Specifically, the ultimate choice of a system supplier to design, fabricate, and supply the scrubbing systems was based on their previous experience with a fly ash scrubbing application at one utility station and sulfur dioxide removal in the chemical industry. Many of the advances in second- and third-generation design philosophies over the last 5 years are not evident in these two systems, but they are reflected in the one now under construction for Bruce Mansfield 3. (This is discussed at length in the latter part of this section.)

The operating history and performance of the air quality and waste disposal systems, including removal efficiencies, dependability, and problems and solutions, are summarized in the following paragraphs.

OPERATING HISTORY AND PERFORMANCE

Air Quality Control System

Bruce Mansfield Unit 1 was first fired on November 3, 1975. Initial operation of the unit began on December 11, 1975, and commercial operation followed approximately 6 months later on July 1, 1976. Initial operation of Bruce Mansfield 2 began in July 1977, and commercial operation followed approximately 2 months later on October 1, 1977.

Many major design-, mechanical-, and chemical-related problems accompanied the initial and subsequent operation of the air quality control systems. These included corrosion, scale, mist eliminator inefficiency, reheater vibration, pH control failures, stack liner failures, and induced-draft fan problems.

Although many of the problems plaguing the systems have been resolved, problems with the chimney liners and induced-draft fans have severely limited system availability. The former problem, severe stack liner failures, has especially limited operations, requiring each of the units to operate at half-load capacity for 1 year. The availability of the scrubbing trains that have been kept in service, however, has been adequate. Tables 17 and 18 summarize the performance of the Bruce Mansfield boilers and scrubbing systems.

Waste Disposal System

When Bruce Mansfield 1 was first fired, the waste disposal system was completed to the extent that a minimum manual system was available to process waste slurry. This allowed a slurry flow path to be maintained between the plant and reservoir while the balance of the system was completed. This final phase of construction, which involved the installation of backup elements and all automatic controls, lasted approximately 18 months. Halfway through this final construction phase the utility fully

TABLE 17. MANSFIELD 1 BOILER AND SCRUBBING SYSTEM PERFORMANCE

Period	Boiler operating hours	System dependability factors, percent			
		Total system availability	Total system operability[a]	Total system reliability[b]	Total system utilization[c]
May 76	595	80	100	100	80
June 76	720	100	100	100	100
July 76	673	90	100	100	90
August 76	705	95	100	100	95
Sept. 76	720	100	100	100	100
Oct. 76	720	99	100	100	99
Nov. 76	277	100	100	100	100
Dec. 76	722	100	100	100	97
Year	5,132	96	100	100	95
Jan. 77	675	90	91		83
Feb. 77	540	80	85		69
March 77	264[d]	88	88		
April 77	0	0	0		0
May 77	121[e]	82[f]	70[f]		39[f]
June 77	669	93[f]	99[f]		93[f]
July 77	473	100[f]	100[f]		65[f]
Aug. 77	692	70	73		67
Sept. 77	558	66	74		58
Oct. 77	720	93[f]	95[f]		93[f]
Nov. 77	720	95[f]	95[f]		95[f]
Dec. 77	626	97[f]	98[f]		86[f]
Year	6,058	80[g]	81[g]		62[g]
Jan. 78	331	67[f]	67[f]		39[f]
Feb. 78	514	74[f]	93[f]		74[f]

[a] Operability index: the number of hours the FGD system is operational divided by the boiler operating hours, expressed as a percentage.

[b] Reliability index: the number of hours the FGD system is operational divided by the number of hours the FGD system is called upon to operate, expressed as a percentage.

[c] Utilization index: the number of hours the FGD system is operational divided by the number of hours in the period, expressed as a percentage.

[d] The unit operated 12 days because of a scheduled 10-week turbine overhaul. Repairs commenced on the stack flue liners.

[e] Unit started up on May 23, 1977, and remained in service at half load during the remainder of the month.

[f] Dependability factors calculated for operation of half the system.

[g] Annual averages of dependability factors include monthly values when half the system was in service.

TABLE 18. MANSFIELD 2 BOILER AND SCRUBBING SYSTEM PERFORMANCE

Period	Boiler operating hours	System dependability factors, percent			
		Total system availability	Total system operability	Total system reliability	Total system utilization
Oct. 77	595	80	79		66
Nov. 77	581	72	74		58
Dec. 77	469	93	93		77
Year	1645	82	82		67
Jan. 78	391	97	85		53
Feb. 78	672	89	75		75

assumed the responsibility of operating and maintaining the system.

PROBLEMS AND SOLUTIONS

Startup and subsequent operation of the Bruce Mansfield scrubbing and waste disposal systems have been accompanied by several design-, mechanical-, and chemical-related problems, especially in the scrubbing systems and related equipment. The utility, in conjunction with system supplier, has conceived and implemented solutions to many of these problems. The major problems encountered with scrubbing and waste disposal systems and their solutions are summarized and discussed by generic type (design, mechanical, chemical) in the following paragraphs.

Air Quality Control System

Design-related Problems--

The scrubbing systems were orginally designed so that five of the six scrubbing trains installed on each unit could handle total boiler gas flow at a slightly reduced particulate and sulfur dioxide col..ction efficiency. Actual operation has shown, however, that all six scrubbing trains are necessary when the unit is operating at full load. This has eliminated the option of servicing one train over a short period of time without the necessity of load cutbacks.

The reheaters have never worked properly. At maximum operating conditions a resonance pattern was created by the oil burners, and severe duct vibration occurred. The shock wave created by the oil injection nozzle matched the reasonance frequency of the ducts. This vibration was so severe that, if permitted to continue, it would have cracked the ducts and shaken them loose. The oil injection nozzles were modified by the manufacturer to eliminate this shock wave. Although this modification was successful, the reheaters are only able to operate at 80 percent capacity and provide a ΔT of 17 to 19°C (30 to 35°F).

Mist eliminator performance has been a major problem area in system operation. The problems encountered resulted from a complex combination of chemical-, mechanical-, design-related factors, as well as from operating the mist eliminators above design gas volume and from continuous use of thickener overflow water or work water without intermittent use of fresh water. Mist eliminator scaling was encountered very early, prompting modification to the mist eliminator wash system. Moreover, tests conducted in late 1976 indicated that mist carryover from the mist eliminators was on the order of 7 g/m^3 (3 gr/scf), higher than the maximum design value by a factor of three. Pennsylvania Power and Chemico experimented with second-stage vertical mist eliminators. Duct diameter and spatial restrictions caused these mist eliminators to experience high flow velocities, on the order of 15 m/s (50 ft/s). One experimental vertical mist eliminator was installed and collapsed because of structural failure. Another vertical configuration was developed that would operate at lower gas velocities. Concurrently with this research, model studies performed by Chemico indicated that excessive carryover resulted when pressure drops exceeding 3 kPa (0.75 in. H_2O) developed across horizontal mist eliminators. No carryover was evident when pressure drops were maintained at 2 kPa (0.5 in. H_2O) or less. Where the problem is not corrected and pressure drop continues to rise, the module is taken out of service, and the mist eliminator is manually cleaned.

Failure of chimney liners is also considered a design-related problem. Failure of the original coating material applied to the carbon steel (Cor-Ten) flues has resulted in half-load operation for 1 year on both units. Originally, the two flues on Unit 1 were coated with flake-glass. The first 61-m (200-ft) section of each flue was coated with a troweled-on flake-glass material approximately 60 mils thick. The remaining 213-m (700-ft) section was coated with a sprayed-on flake-glass material approximately 20 mils thick. Widespread failure and resulting corrosion were most severe in the top section. For want of other viable alternatives, the utility replaced the sprayed-on coating with the troweled-on material. Several test patches were also inserted in one of the flues of Bruce Mansfield 2. An inspection of the flues in the spring of 1978 revealed that one of the flues for Bruce Mansfield 2 had developed a crack approximately three-quarters of the way around because of coating failure and acid corrosion attack. This crack had extended to 90 percent of the circumference by the time the utility repaired it by applying metal cladding to the failed area. The utility contracted Carnegie Mellon Institute to investigate this problem thoroughly. Their findings and the results of the test patch program indicate that a completely suitable coating material does not exist. Of all the material evaluated, CXL-2000, developed by Pullman Kellogg, holds the most promise for long-term service. The utility may use this material when making future repairs or coating.

Another design-related problem concerns the operation of the wet induced-draft fans. Although these fans have been beset by a number of problems that are a combination of chemical-, mechanical-, and design-related factors, the major problem encountered has been failure of the construction materials. The pH at this location has been measured at approximately 2.0. The fan housings (constructed of rubber-lined carbon steel) and the scrolls (constructed of rubber-lined carbon steel) have been damaged extensively by corrosion and/or erosion. The utility is now replacing many of these with components constructed of more sophisticated alloys, such as Carpenter 20 or Inconel 625.

Chemical-related Problems--

Many of the chemical-related problems that beset the scrubbing system and related equipment were caused by a faulty pH monitoring network during the early phases of operation. Primary difficulties involved flow sampling location and glass probe breakage, causing pH to be controlled manually during much of the initial operation stage. This manual control in turn caused subsequent problems such as scale formation, plugging, and acid corrosion. The pH monitors were relocated to a different position in the recirculation circuit, and sampling procedures were modified. The results have been excellent. The pH is controlled within a very narrow band of 7.0 ± 0.2. Magnesium ion concentration is maintained at approximately 1500 ppm in the liquid circuit. Sulfur dioxide removal efficiency levels are consistently above the 92.1 percent design value. Finally, the modules are operating without any substantial development of hard scale (gypsum) or plugging, which often affected mist eliminator performance.

Mechanical-related Problems--

Although the system has been plagued by a number of minor problems such as pump and valve failures, they have caused very little outage time.

Waste Disposal System

Generally, the operation of the waste disposal system has proceeded without major incident; however, the problems that have been encountered are summarized briefly in the following paragraphs.

Closed loop operation has never been achieved; supernatant from the reservoir is being discharged into the Ohio River. One major reason is the greater requirement of fresh makeup water in scrubbing operations (e.g., mist eliminator wash); another is the quality of the supernatant resulting from the stabilization process. The pH of the supernatant is approximately 9.0 to 9.2 instead of the design value of 8.0; thus, less supernatant is returned for slurrying and washing.

Core samplings of the stabilized waste material covering the reservoir floor indicate different strata of material with varying physical characteristics. This resulted from not varying the Calcilox feed rate with varying thickener underflow characteristics, especially during the initial operation when stabilizer was added on a manual control basis.

Future Operations

Bruce Mansfield 3, a 917-MW (gross) coal-fired unit is currently under construction alongside Units 1 and 2. Commercial operation is scheduled for October 1980. The emission control system for this unit, which is designed and supplied by Pullman Kellogg, is different from those on Bruce Mansfield 1 and 2. In many respects the design strategy for Bruce Mansfield 3 (compared with that for Units 1 and 2) is representative of the change in FGD design philosophy that has occurred over the past 5 years. Most notably, electrostatic precipitators will provide particulate removal upstream of a lime-based, spray chamber FGD system. Dry type fans will be located upstream of the spray towers. A high degree of component redundancy will increase overall system reliability. Redundant components include one spare fan, one spare precipitator, one spare spray chamber, and one spare stage per spray chamber. The electrostatic precipitators are designed for 95 percent particulate removal, and the spray chambers will collect additional particulate simultaneously with the sulfur dioxide. The lower-efficiency electrostatic precipitators offer substantial capital savings and permit a simpler, more efficient design. Another important feature of this system involves the chimney liner. Currently, the utility is planning to use an Inconel 625 alloy liner in the 183-m (600-ft) high chimney. This choice of an exotic alloy stems from the nearly disastrous results encountered in Bruce Mansfield 1 and 2. The flue gas cleaning wastes produced by this system will be disposed of in the existing waste disposal system. Table 19 summarizes the Bruce Mansfield 3 emission control system.

TABLE 19. SUMMARY OF MANSFIELD 3 EMISSION CONTROL SYSTEM

Unit capacity, MW (gross)	917
Design coal specifications	
Heating value, kJ/kg (Btu/lb)	27,700 (11,900)
Sulfur content, percent	2.6 - 4.75
Ash content, percent	9.5 - 19.7
Particulate emission rate, ng/J (lb/10^6 Btu)	32 (0.075)
Sulfur dioxide emission rate, ng/J (lb/10^6 Btu)	258 (0.6)
Emission controls:	
Particulate	Electrostatic precipitators and spray tower absorbers
Sulfur dioxide	Spray tower absorbers
Process	Lime
Supplier	Pullman Kellogg
Absorber type	Spray tower
Number of absorbers	5 (1 spare)
Number of ESP's	4 (1 spare)
Gas capacity, m^3/s	1110 (2355)
Pressure drop, kPa (in. H_2O)	7.0 (28.0)
Gas reheat:	
Type	Oil-fired
ΔT, °C (°F)	22 (40)
Gas bypass capability	No
Commercial startup date	October 1980
Total capital cost, $/kW	243[a]

[a] Cost includes ash handling system, electrostatic precipitators, spray tower absorbers, fans, stack, one-third of the waste disposal system, and all necessary auxilliary equipment.

SECTION 5

FGD ECONOMICS

INTRODUCTION

The cost of FGD systems for the control of sulfur dioxide emissions is an area of intense interest and substantial controversy. For this reason, reported and adjusted economic data have been incorporated into this report.

The rationale for including adjusted costs stems primarily from the incomparability of the reported costs. Many of the reported cost figures for operational FGD systems, both capital and operating, are largely site-sensitive and cannot be compared accurately because they involve different FGD battery limits and the expenditures were made in different years. To allow for these differences, ıe cost data for these systems were analyzed, and adjustments were made so that cost data for the sulfur dioxide portion of the emission control system would be accurate and comparable.

APPROACH

PEDCo forwarded Pennsylvania Power a cost form containing all available cost information in the PEDCo files with the request that Pennsylvania Power verify the data and fill in any missing information. PEDCo then arranged for a followup visit to assist in data acquisition and to ensure completeness and reliability of the information.

The sole intent of this adjusting procedure was to establish accurate costs of FGD systems on a common basis, not to critique the design or reasonableness of the costs reported by the utility. Adjustments focused primarily on the following items:

- Capital costs were adjusted to July 1, 1977, dollars using the Chemical Engineering Index. Capital costs, represented in dollars/kilowatt ($/kW), were expressed in terms of gross megawatts (MW).
- Gross unit capacity was used to express all FGD capital expenditures because the capital requirement of an FGD system is dependent on actual boiler size before derating for auxiliary and air quality control power requirements.
- Particulate control costs were deducted in an effort to estimate the incremental cost for sulfur dioxide control.
- Capital costs associated with the modification or installation of equipment that is not part of the FGD system but is needed for its proper functioning were included (e.g., chimney lining, modification to existing duct work or fans).
- Indirect charges were adjusted to provide adequate funds for engineering, field expenses, legal expenses, insurance, interest during construction, allowance for startup, taxes, and contingency.
- Annual costs, represented in mills/kilowatt-hour (mills/kWh), were expressed in terms of net megawatts (MW).
- Net unit capacity was used to express all FGD annual expenditures, because the annual cost requirement of an FGD system is dependent on the actual amount of kilowatt-hours (kWh) produced by the unit after derating for auxiliary and air quality control power requirements.
- Annual costs were adjusted to a common capacity factor (65 percent).
- Replacement power costs were not included.
- Sludge disposal costs were adjusted to reflect the costs of sulfur dioxide waste disposal only (i.e., excluding fly ash disposal).
- A 30-year life was assumed for all process and economic considerations.

DESCRIPTION OF COST ELEMENTS

Capital costs consist of direct costs, indirect costs, contingency costs, and other capital costs. Direct costs include the "bought-out" cost of the equipment, the cost of installation, and the cost of site development. Indirect costs include interest during construction, contractor's fees and expenses, engineering, legal expenses, taxes, insurance, allowance for startup and shakedown, and spares. Contingency costs include those costs resulting from malfunctions, equipment alterations, and similar unforeseen sources. Other capital costs include the nondepreciable items of land and working capital.

Annual costs consist of direct costs, fixed costs, and overhead costs. Direct costs include the cost of raw materials, utilities, operating labor and supervision, and maintenance and repairs. Fixed costs include depreciation, interim replacement, insurance, taxes, and interest on borrowed capital. Overhead costs include those of plant and payroll expenses.

RESULTS

The complete results of the capital and annual cost analysis for Bruce Mansfield 1 and 2 are presented in Appendix C of this report. The reported and adjusted capital cost data are summarized in the following paragraphs.

Reported and Adjusted Capital and Annual Costs

The reported capital and annual variable costs provided by the utility are summarized in Tables 20 and 21. The total reported capital cost of both systems is $221,278,000, which is equivalent to $120.65/kW (gross). The annual cost of both systems is $47,730,357, which is equivalent to 13.18 mills/kWh.

The adjusted capital and annual costs are summarized in Tables 22 and 23. The total adjusted capital cost of both systems is $187,417,900, which is equivalent to $102.19/kW (gross). The annual adjusted cost of both systems is $83,250,212, which is equivalent to 8.96 mills/kWh.

TABLE 20. MANSFIELD 1 AND 2 REPORTED CAPITAL COSTS (dollars)

Equipment	
Air quality control systems:	
Scrubbers and absorbers	
Induced-draft fans	
Flue-gas reheaters	
Concrete chimney with coated steel flues	
Duct work	
Barge, truck, and rail lime unloading facilities	
Lime slaking and lime slurry pumping and recycling equipment and facilities	
Thickeners	
Pumping facilities for transporting thickened wastes to the waste disposal system	
Waste holding pond and reslurry pumps and piping facilities	
Water pumps and associated piping and filtration equipment	
Instrumentation and control	
Electric power supply equipment and cabling	
Piping and pipe rack systems	
Pump houses and electrical houses	
Control rooms	
Fuel-oil supply and storage for flue-gas reheaters	
Steam supply for lime slaking	
Protective linings in the duct work and other related equipment	
Associated sumps and sump pumps	
Subtotal	137,607,000
Waste disposal system:	
Barge, truck, and rail unloading facilities for additive	
Additive transporting, handling, and storage facilities	
Waste and additive mixing equipment	
Pumping equipment for pumping treated wastes to the disposal area	
Pipelines between pumping station and disposal area	
Equipment	
Waste disposal and dam pumping equipment for supernatant return to plant	
Instrumentation and control	
Electric power supply equipment and cabling	
Pump house building	
Control room	
Associated sumps and sump pumps	
Subtotal	83,761,000
Total, air quality and waste disposal	221,278,000

TABLE 21. MANSFIELD 1 AND 2 REPORTED 1977 ANNUAL VARIABLE COSTS (dollars)

Category		
Supervision and engineering		106,282
Fuel:		
Reheater oil	$ 535,255	
Calcilox	$ 699,122	
Other	$1,104,292	
Total		2,338,669
Steam operating expenses:		
Lime	$6,819,411	
Other	$1,423,470	
Total		8,242,881
Miscellaneous operati expenses		212,856
Maintenance supervision and engineering		155,717
Maintenance of structures		59,994
Maintenance of boiler plant		3,643,536
Total air quality control system and waste disposal system operating and maintenance expenses		14,759,935

TABLE 22. MANSFIELD 1 AND 2 ADJUSTED CAPITAL COSTS
(dollars)

Adjustments	
Total reported capital	221,278,000
Particulate control deduction	-27,338,185
Partial stack deduction	- 2,500,000
Particulate control waste disposal	-37,651,950
Conversion to July 1, 1977, dollars	+33,630,035
Total adjusted capital	187,417,900

TABLE 23. MANSFIELD 1 AND 2 ADJUSTED 1977 ANNUAL COSTS
(dollars)

Category	
Operation and maintenance	38,296,450
Power	13,467,555
Fixed charges	31,486,207
Total annual	83,250,212

APPENDIX A

PLANT SURVEY FORM

A. Company and Plant Information

1. Company name: Pennsylvania Power Co.[a]
2. Main office: New Castle, Pennsylvania
3. Plant name: Bruce Mansfield
4. Plant location: Shippingport, Pennsylvania
5. Responsible officer: W.F. Reeher
6. Plant manager: K.H. Workman
7. Plant contact: R. Forsythe
8. Position: Engineer
9. Telephone number: (412) 652-5531
10. Date information gathered: July 7, 1976, and Mar. 22, 1978

Participants in meeting	Affiliation
Russ Forsythe	Pennsylvania Power
Dale Billheimer	Pennsylvania Power
T.O. Flora	Pennsylvania Power
B.A. Laseke, Jr.	PEDCo Environmental
R.W. Gerstle	PEDCo Environmental
M. Melia	PEDCo Environmental

[a] Bruce Mansfield is owned by the Central Area Power Coordination Group (CAPCO), a consortium consisting of five Pennsylvania and Ohio power companies: Pennsylvania Power, Ohio Edison, Duquesne Light, Cleveland Electric Illuminating, and Toledo Edison. Pennsylvania Power has design, construction, and operation responsibility.

B. Plant and Site Data

1. UTM coordinates: ______

2. Sea Level elevation: Plant grade elevation is 730 ft. Normal Ohio River pool elevation is 664.5 ft.

3. Plant site plot plan (Yes, No): Yes
(include drawing or aerial overviews)

4. FGD system plan (yes, No): Yes

5. General description of plant environs: Sparsely populated, highly industrialized section of the Ohio River.

6. Coal shipment mode: Primary coal transportation is via jumbo and standard river barges to the plant barge harbor. Truck is a secondary means, employed only during emergencies.

C. FGD Vendor/Designer Background (Units 1 and 2)

1. Process name: Lime

2. Developer/licensor name: Chemico

3. Address: One Penn Plaza, New York, New York 10001

4. Company offering process:

Company name: Chemico

Address: One Penn Plaza

Location: New York, New York

Company contact: Mr. Feller

Position: Manager, Bruce Mansfield Project

Telephone number: (212) 239-5100

5. Architectural/engineers name: Gilbert/Commonwealth Assoc.

Address: 209 E. Washington Avenue

Location: Jackson, Michigan 49201

Company contact: Mr. W.E. Richards

Position: Project Engineer

Telephone number: (517) 788-3580

D. Boiler Data

1. Boiler: Bruce Mansfield 1 and 2

2. Boiler manufacturer: Foster Wheeler

3. Boiler service (base, standby, floating, peak): Base load

4. Year boiler placed in service: 4/1/76 (Unit 1), 10/1/77 (Unit 2)

5. Total hours operation: 4655 (Unit 1)

6. Remaining life of unit: 30-yr service life

7. Boiler type: Pulverized coal-fired

8. Served by stack no.: One chimney for both units

9. Stack height: 290 m (950 ft)

10. Stack top inner diameter:

11. Unit ratings (MW): Bruce Mansfield 1 and 2

Gross unit rating: 1834 MW

Net unit rating without FGD: 1760 MW

Net unit rating with FGD: 1650 MW

Name plate rating: 1834 MW

12. Unit heat rate: ____

Heat rate without FGD: ____

Heat rate with FGD: ____

13. Boiler capacity factor, (1977): 40.09% (station)

14. Fuel type (coal or oil): Coal

15. Flue gas flow: 1570 m^3/s (3,350,000 acfm)

Maximum: 1570 m^3/s (3,350,000 acfm)

Temperature: 140°C (285°F)

16. Total excess air: 18-20%

17. Boiler efficiency: 92.5%

E. Coal Data (Units 1 and 2)

1. Coal supplier: (Major supplier)

Name: North American Coal Co.

Location: Belmont County, Ohio

Mine location: ____

County, State: Belmont, Ohio

Seam: ____

2. Gross heating value: 26,700 kJ/kg (11,500 Btu/lb)

3. Ash (dry basis): 12.5%

4. Sulfur (dry basis): 3.0%

5. Total moisture: 7.0%

6. Chloride: Not available

7. Ash composition (See Table A1) Not available

Table A-1

Constituent	Percent weight
Silica, SiO_2	
Alumina, Al_2O_3	
Titania, TiO_2	
Ferric oxide, Fe_2O_3	
Calcium oxide, CaO	
Magnesium oxide, MgO	
Sodium oxide, Na_2O	
Potassium oxide, K_2O	
Phosphorous pentoxide, P_2O_5	
Sulfur trioxide, SO_3	
Other	
Undetermined	

F. Atmospheric Emission Regulations (Units 1 and 2)

1. Applicable particulate emission regulation

   a) Current requirement: 43 ng/J (0.1 lb. per 10^6 Btu heat input)

      AQCR priority classification: ____

      Regulation and section No.: Pittsburgh Interstate AQCR, Chap. 123.11

   b) Future requirement (Date:): ____

      Regulation and section No.: ____

2. Applicable SO_2 emission regulation

   a) Current requirement: 263 ng/J (0.6 lb/10^6 Btu heat input)

      AQCR Priority Classification: ____

      Regulation and section No.: Pittsburgh Interstate AQCR, Chap. 123.21, 123.22

   b) Future requirement (Date:) ____

Regulation and section No.: ______________________

G. Chemical Additives: (Includes all reagent additives - absorbents, precipitants, flocculants, coagulants, pH adjusters, fixatives, catalysts, etc.)

1. Trade name: Thiosorbic lime

   Principal ingredient: Calcium oxide and magnesium oxide (2-6%)

   Function: Absorbent

   Source/manufacturer: Dravo Lime Co.

   Quantity employed: 227 Mg/yr per unit (250,000/yr per unit)

   Point of addition: Scrubber and absorber recirculation tanks

2. Trade name: Calcilox

   Principal ingredient: Confidential

   Function: Sludge stabilization agent

   Source/manufacturer: Dravo Lime Co.

   Quantity employed: 23.5 Mg/h (26 tons/h) (projected full capacity, both units)

   Point of addition: Sludge treatment facility

3. Trade name: ______________________

   Principal ingredient: ______________________

   Function: ______________________

   Source/manufacturer: ______________________

   Quantity employed: ______________________

   Point of addition: ______________________

4. Trade name: Not applicable

   Principal ingredient: ______________________

   Function: ______________________

   Source/manufacturer: ______________________

   Quantity employed: ______________________

Point of addition: ______

5. Trade name: Not applicable

Principal ingredient: ______

Function: ______

Source/manufacturer: ______

Quantity employed: ______

Point of addition: ______

H. Equipment Specifications (Units 1 and 2)

1. Electrostatic precipitator(s)

Number: ______

Manufacturer: ______

Particulate removal efficiency: ______

Outlet temperature: ______

Pressure drop: ______

2. Mechanical collector(s) Not applicable

Number: ______

Type: ______

Size: ______

Manufacturer: ______

Particulate removal efficiency: ______

Pressure drop: ______

3. Particulate scrubber(s)

Number: 12, 6 per unit

Type: Adjustable-throat vertical venturi

Manufacturer: Chemico

Dimensions: 10.8 m ϕ x 15.8 m ht. (35.5 ft ϕ x 52.0 ft.ht)

Material, shell: Carbon steel

Material, shell lining: Polyester flake glass

Material, internals: 316 SS (Plumb bob and throat area)

No. of modules: 1 per train, 6 per unit

No. of stages: Two

Nozzle type: Not available

Nozzle size: Not available

No. of nozzles: Four primary spray heads per module

Boiler load: 100% for all 6 modules/unit

Scrubber gas flow: 259 m^3/s @ 140°C (558,300 acfm @ 285°F)

Liquid recirculation rate: 1390 liters/s (22,000 gpm)

Modulation: 50%

L/G ratio: 5.3 liters/m^3 (40 gal/10^3 acf)

Scrubber pressure drop: Design: 167 kPa (67 in. H_2O)
Actual: 6 kPa (23 in. H_2O)

Modulation:

Superficial gas velocity: 61 m/s @ 140°C (200 ft/s @ 285 °F)

Particulate removal efficiency: 99.8% (design)

Inlet loading: 17.7 g/m^3 (7.75 gr/scf) (dry, maximum)

Outlet loading: 0.0354 g/m^3 (0.0155 gr/scf) (dry, maximum)

SO_2 removal efficiency: 92.1% (design)

Inlet concentration: 3,090 ppm (maximum design)

Outlet concentration: 930 ppm (maximum design)

4. SO_2 absorber(s)

Number: 12, 6 per unit

Type: Fixed-throat vertical venturi

Manufacturer: Chemico

Dimensions: 10.4 m ϕ x 15.7 m ht. (34 ft ϕ x 51.5 ft ht)

Material, shell: Carbon steel

Material, shell lining: Polyester flake glass

Material, internals: 316 SS (center cone and throat area)

No. of modules: 1 per train, 6 per unit

No. of stages: Two

Packing type: None

Packing thickness/stage: Not applicable

Nozzle type: Not available

Nozzle size: Not available

No. of nozzles: Five primary spray heads per module

Boiler load: 100% for all 6 modules/unit

Absorber gas flow: 201 m^3/s @ 52°C (426,000 acfm @ 127°F)

Liquid recirculation rate: 1,220 liters/s (19,400 gpm)

Modulation: 50%

L/G ratio: 6.1 liter/m^3 (45 gal/10^3 acf)

Absorber pressure drop: 2 kPa (8 in. H_2O)

Modulation: None

Superficial gas velocity: 30 m/s (100 ft/s)

Particulate removal efficiency: 99.8% (scrubber & absorber design)

Inlet loading:

Outlet loading: 0.0354 g/m^3 (0.0155 gr/scf) (dry, maximum)

SO_2 removal efficiency: 92.1% (design)

Inlet concentration: 930 ppm (maximum design)

Outlet concentration: 240 ppm (maximum design)

5. Clear water tray(s) None

Number: __________

Type: __________

Materials of construction: __________

L/G ratio: __________

Source of water: __________

6. Mist eliminator(s)

Number: 24, 1 per module

Type: Chevron

Materials of construction: FRP

Manufacturer: Chemico

Configuration (horizontal/vertical): Horizontal

Distance between scrubber bed and mist eliminator: Not available

Mist eliminator depth: Not available

Vane spacing: 7.6 cm (3.0 in.)

Vane angles: __________

Type and location of wash system: Overspray/underspray; intermittent overspray (once/shift) & continuous underspray

Superficial gas velocity: 3.1 m/s @ 52°C (10.0 ft/s @ 127°F)

Pressure drop: 1.2 kPa (0.3 in. H_2O)

Comments: 1-stage, 4-pass, Z-shape, 90-deg sharp-angle bend design; 2nd vertical stage was installed and tested intermittently

7. Reheater(s): 4 reheat chambers, 2 per unit

Type (check appropriate category): __________

- [ ] in-line
- [ ] indirect hot air
- [x] direct combustion
- [ ] bypass
- [ ] exit gas recirculation
- [ ] waste heat recovery
- [ ] other

Gas conditions for reheat:

Flow rate: 201 m^3/s (426,000 acf)

Temperature: 51°C (125°F)

SO_2 concentration: 240 ppm

Heating medium: Combustion products

Combustion fuel: No. 2 fuel oil

Percent of gas bypassed for reheat: None

Temperature boost (ΔT): 22°C (51 to 73) [40°F (124 to 164)]

Energy required:

Comments: Three burners/reheat chamber. Each chamber is rated at (28 x 10^6 Btu/h, vortex type, mechanical atomization injection. Total reheat fuel consumption per boiler is 1200 gph.

8. Fan(s)

Total number	12
Manufacturer	Green Fan Company
Service	Wet
Specifications:	
Type	Radial-tip, inlet damper control
Rating, kW (hp) and rpm	6700 (9000) and 1300
Pressure drop:	
Design, kPa (in. H_2O)	19 (75)
Maximum continuous[2]	16 (63)
Motor, kV	13.2
Capacity, m^3/s (ft^3/min)	263 (558)
Gas temperature, °C (°F)	48 (118)
Gas density, kg/m^3 (lb/ft^3)	0.913 (0.057)
Materials of construction:	
Housing	Rubber-lined carbon steel
Scrolls	Inconel 625
Blades	Inconel 625
Shaft	Carbon steel clad with Carpenter 20

9. Tank(s) 24 internal recirculation tanks, one per module

Materials of construction: Carbon steel, flake glass lining

Function: Collection of spent solution/lime makeup addition

Configuration/dimensions: Contained in venturi modules

Capacity: 136,000 liters (36,100 gal)

Retention times: 1.5 min

Covered (yes/no): Yes (internal)

Agitator description: None

10. Recirculation/slurry pump(s) (See Table A-2 on following page.)

Type: ____

Manufacturer: ____

Materials of construction: ____

Head: ____

Capacity: ____

11. Thickener(s)/clarifier(s)

Number: Two, one per unit

Type: Rake drive

Manufacturer: Koppers Co.

Materials of construction: Carbon steel and concrete

Configuration: Cylindrical

Diameter: 61 m (200 ft)

Depth: 3.7 m (12 ft)

Rake speed: Variable

12. Vacuum filter(s) Not applicable

TABLE A-2. RECIRCULATION/SLURRY PUMPS

Number	Service	Manufacturer	Type	Model	Capacity: Flow, liters/s (gpm)	Capacity: Head, meters (ft)	Capacity: Power, kW (hp)	Capacity: Speed, rpm	Size, cm (in.)	Materials of construction
24	Scrubber recycle	Allen-Sherman-Hoff	Centrifugal, single-stage, V-belt	DG-9-5	695 (11,000)	35 (107)	335 (450)	1200	4 x 4 x 99 (16 x 16 x 39)	Rubber-lined impellers and linings
24	Absorber recycle	Allen-Sherman-Hoff	Centrifugal, single-stage, V-belt	DG-9-5	610 (97,000)	35 (116)	335 (450)	1200	4 x 4 x 99 (16 x 16 x 39)	Rubber-lined impellers and linings
4	Thickener underflow	Joy/Denver	Centrifugal, single-stage, V-belt		95 (1500)	20 (70)	55 (75)	1200		Rubber-lined impellers and linings
4	Thickener transfer	Goulds	Centrifugal, single-stage, V-belt		440 (7000)	45 (140)	260 (350)	1180		Carbon Steel
4	Lime slurry transfer	Joy/Denver	Centrifugal, single-stage, V-belt		145 (2300)	30 (98)	95 (125)			Rubber-lined impellers and linings
4	Lime slurry recycle	Joy/Denver	Centrifugal, single-stage, V-belt		240 (3800)	190 (63)	95 (125)	1800		Rubber-lined impellers and linings

Number: None

Type:

Manufacturer:

Materials of construction:

Belt cloth material:

Design capacity:

Filter area:

13. Centrifuge(s) Not applicable

Number: None

Type:

Manufacturer:

Materials of construction:

Size/dimensions:

Capacity:

14. Water balance system:

Number: 4 onsite storage ponds.

Description: Two low dissolved solids (LDS) ponds and two high dissolved solids (HDS) ponds

Capacity: 38 million liters (10 million gal) per pond

Service: The LDS ponds receive raw river water, miscellaneous sump runoffs, coal storage area drainage; LDS water is used for bottom ash transport, I.D. fan sprays, sealing, cooling, and slurry pipe flushing. The HDS ponds, receive acid, boiler cleaning wastes, seal-water return, sump discharges, and emergency thickener underflow; HDS pond supernatant is used as makeup water for the scrubbing system.

15. Final disposal site(s): Little Blue Run ravine landfill

Number: One

Description: Earth and rockfill embarkment area

Area: 5.7 km^2 (1400 acres)

Depth: Maximum dam height is 128 m (420 ft)

Location: Approximately 11.3 km (7 mi) from plant site

Transportation mode: 4 underground transport pipes

Typical operating schedule: Continuous, semiautomatic basis; maximum feed capacity is 302 m^3/s (4800 gpm) of fixated slurry to the Little Blue Run

16. Raw materials production

Type: Lime storage/preparation

Number: Three bulk storage silos (30-day storage); Two 2-day silos per unit

Manufacturer: Dorr-Oliver

Capacity: 20 Mg/h (22 tons/h) maximum feed rate; 63 liters/s (1000 gpm) maximum slurry output; two 14.9-kW (20-hp) slaking mixers

I. Equipment Operation, Maintenance, and Overhaul Schedule

1. Scrubber(s)

Design life: 30 yr

Elapsed operation time:

Cleanout method:

Cleanout frequency: Maintenance performed as needed

Cleanout duration:

Other preventive maintenance procedures:

2. Absorber(s)

Design life: 30 yr

Elapsed operation time: ____

Cleanout method: ____

Cleanout frequency: Maintenance performed as needed

Cleanout duration: ____

Other preventive maintenance procedures: ____

3. Reheater(s)

Design life: 30 yr

Elapsed operation time: ____

Cleanout method: ____

Cleanout frequency: ____

Cleanout duration: ____

Other preventive maintenance procedures: ____

4. Scrubber fan(s)

Design life: 30 yr

Elapsed operation time: Approximately 33,000 h for all six trains

Cleanout method: ____

Cleanout frequency: Maintenance performed as needed

Cleanout duration: ____

Other preventive maintenance procedures: ____

5. Mist eliminator(s)

Design life: 30 yr

Elapsed operation time: ____

Cleanout method: Washwater sprays

Cleanout frequency: Continuous/intermittent

Cleanout duration: Intermittent overspray once/shift

Other preventive maintenance procedures: Clean out when ΔP exceeds 1.2 kPa (0.3 in. H_2O)

6. Pump(s) Not determined

Design life: ______

Elapsed operation time: ______

Cleanout method: ______

Cleanout frequency: ______

Cleanout duration: ______

Other preventive maintenance procedures: ______

7. Vacuum filter(s)/centrifuge(s) Not applicable

Design life: ______

Elapsed operation time: ______

Cleanout method: ______

Cleanout frequency: ______

Cleanout duration: ______

Other preventive maintenance procedures: ______

8. Sludge disposal pond(s)

Design life: ______

Elapsed operation time: ______

Capacity consumed: ______

Remaining capacity: ______

Cleanout procedures: ______________________________

____

J. Cost Data (see Appendix C)

1. Total installed capital cost: ______________________

2. Annualized operating cost: ______________________

3. Cost analysis

4. Unit costs

   a. Electricity: ______________________

   b. Water: ______________________

   c. Steam: ______________________

   d. Fuel (reheating/FGD process): ______________

   e. Fixation cost: ______________________

   f. Raw material: ______________________

   g. Labor: ______________________

____

______ ______________________

5. Comments ______________________

____

____

____

____

____

____

____

____

____

K. <u>Instrumentation</u> See text of report, Section 3, Process Control subsection

A brief description of the control mechanism or method of measurement for each of the following process parameters:

- Reagent addition: ______________________________

  ____

- Liquor solids content: ______________________________

  ____

- Liquor dissolved solids content: ______________________________

  ____

- Liquor ion concentrations

  Chloride: ______________________________

  ____

  Calcium: ______________________________

  ____

  Magnesium: ______________________________

  ____

  Sodium: ______________________________

  ____

  Sulfite: ______________________________

  ____

  Sulfate: ______________________________

  ____

  Carbonate: ______________________________

  ____

  Other (specify): ______________________________

  ____

- Liquor alkalinity: ______________________

____

- Liquor pH: ______________________

____

- Liquor flow: ______________________

____

- Pollutant (SO_2, particulate, NO_x) concentration in flue gas: ______________________

____

- Gas flow: ______________________

____

- Waste water ______________________

____

- Waste solids: ______________________

____

Provide a diagram or drawing of the scrubber/absorber train that illustrates the function and location of the components of the scrubber/absorber control system.

Remarks: See text of report concerning specific instrumentation information and the process control scenario.

____

____

____

L. Discussion of Major Problem Areas:

1. Corrosion: See the main body of the report concerning problem areas.

____

2. Erosion: See the main body of the report concerning problem areas.

3. Scaling: See the main body of the report concerning problem areas.

4. Plugging: See the main body of the report concerning problem areas.

5. Design problems: See the main body of the report concerning problem areas.

6. Waste water/solids disposal: See the main body of the report concerning problem areas.

7. Mechanical problems: See the main body of the report concerning problem areas.

M. General comments:

APPENDIX B

PLANT PHOTOGRAPHS

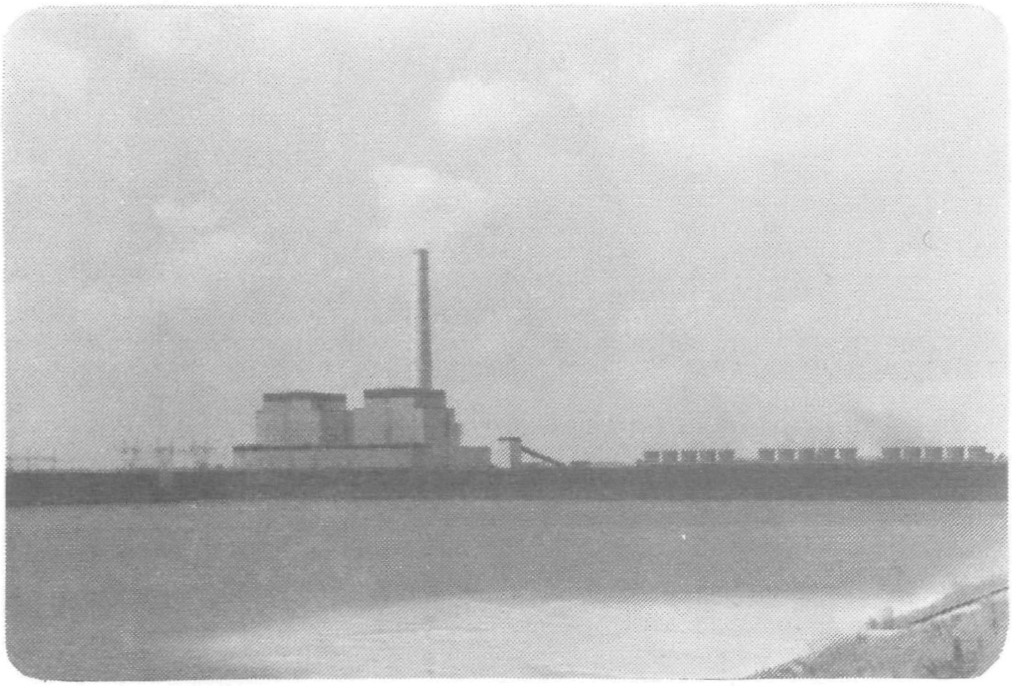

Photo No. 1. View of Sherburne County generating station. Featured are the boiler and turbine house, stack, mechanical draft cooling towers, and fly ash pond.

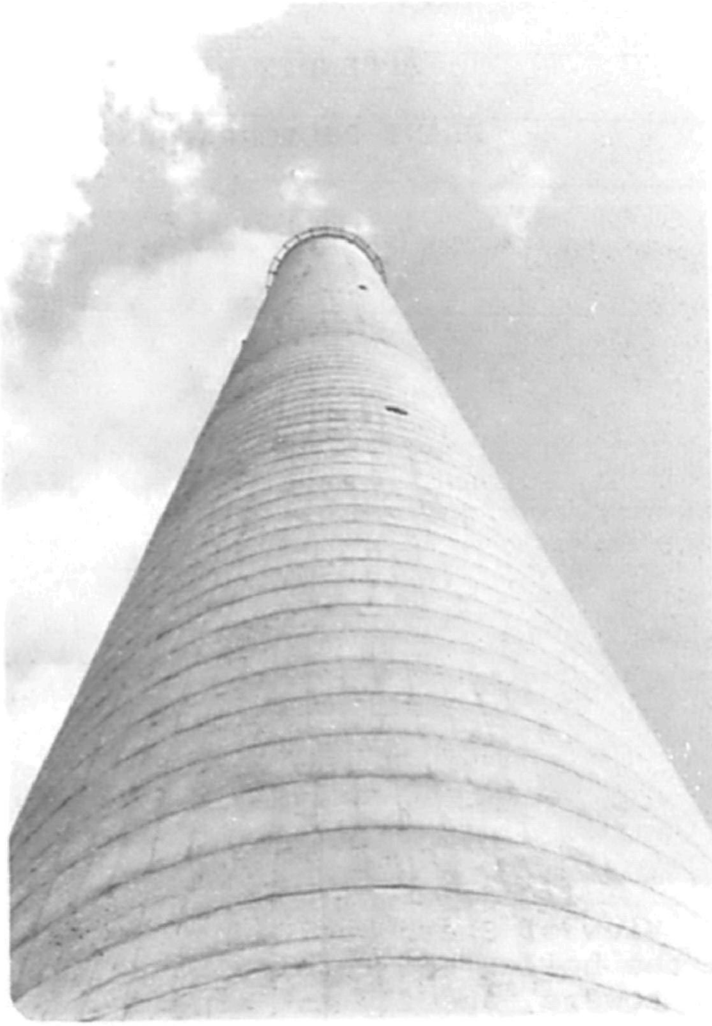

Photo No. 2. Upward view of stack as seen from its base.

Photo No. 3. View of one of the rod sections used in the venturi scrubber.

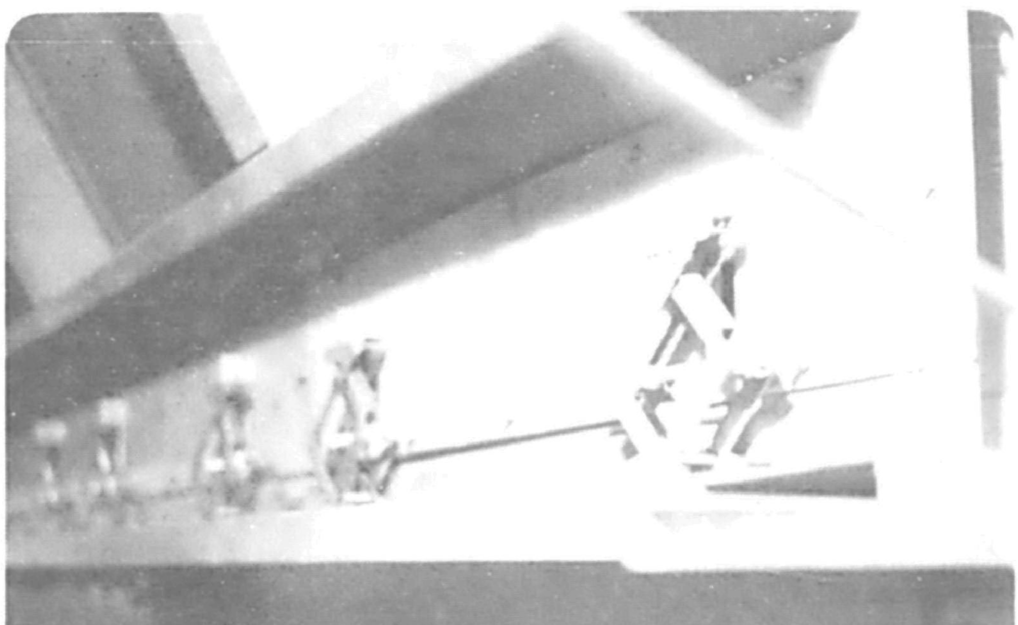

Photo No. 4. Close-up view of the scissor jacking arrangement used to control the position of the rod decks.

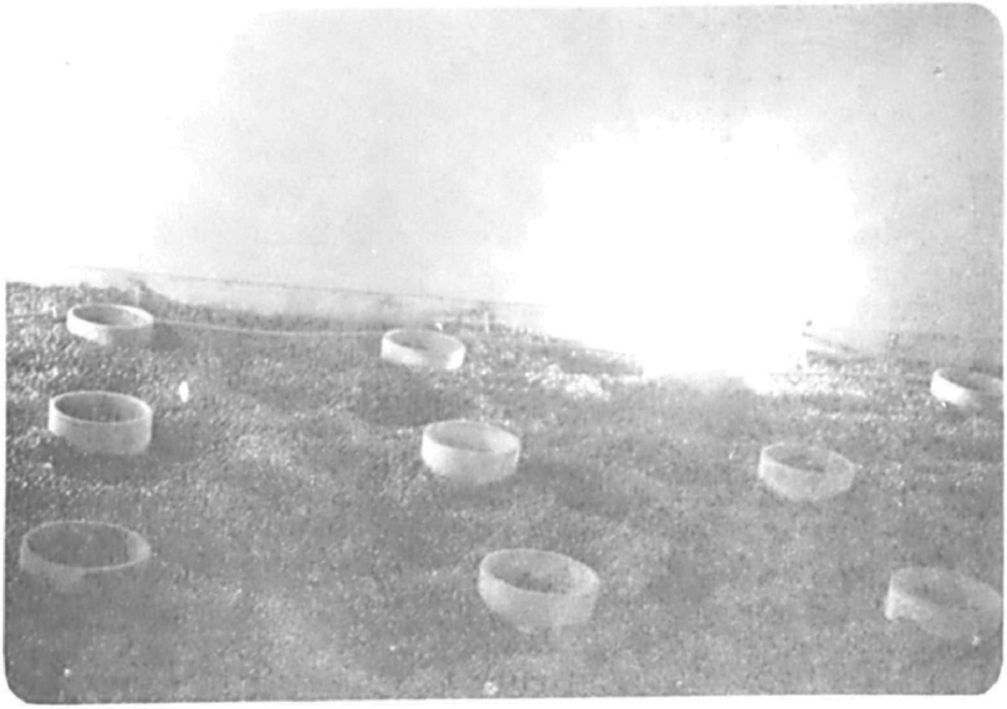

Photo No. 5. View of a marble bed inside a scrubber module. Featured are the overflow pots surrounded by the glass sphere packing (marbles).

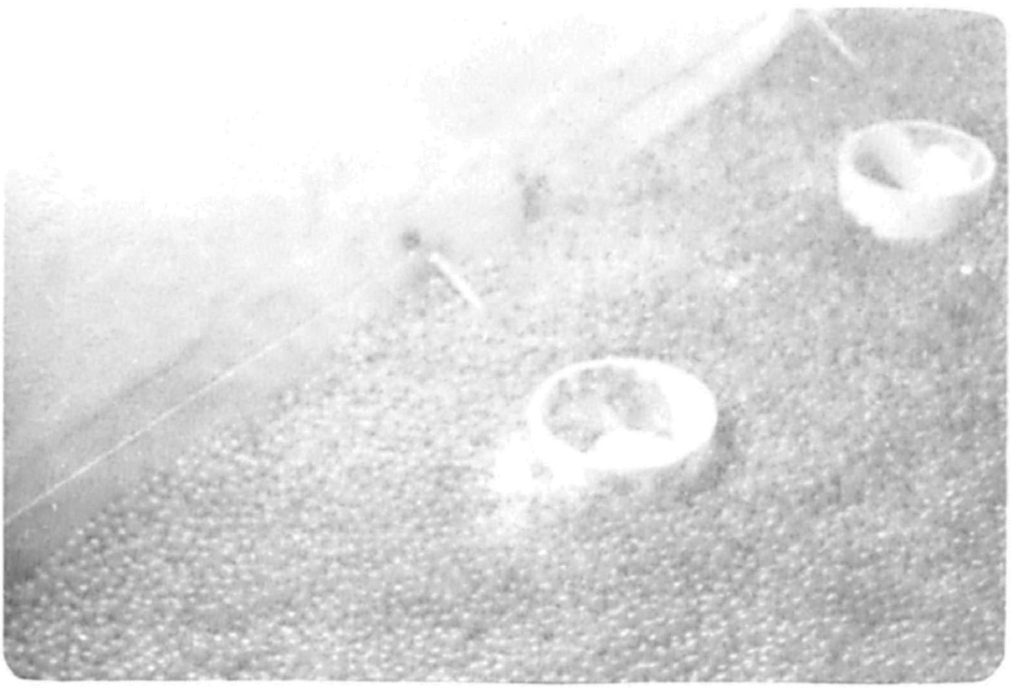

Photo No. 6. Close-up view of marble-bed packing and overflow pots.

Photo No. 7. View of top section of second stage mist eliminator. Top right-hand portion of photo features the reheater inlet of the in-line, hot-water reheater.

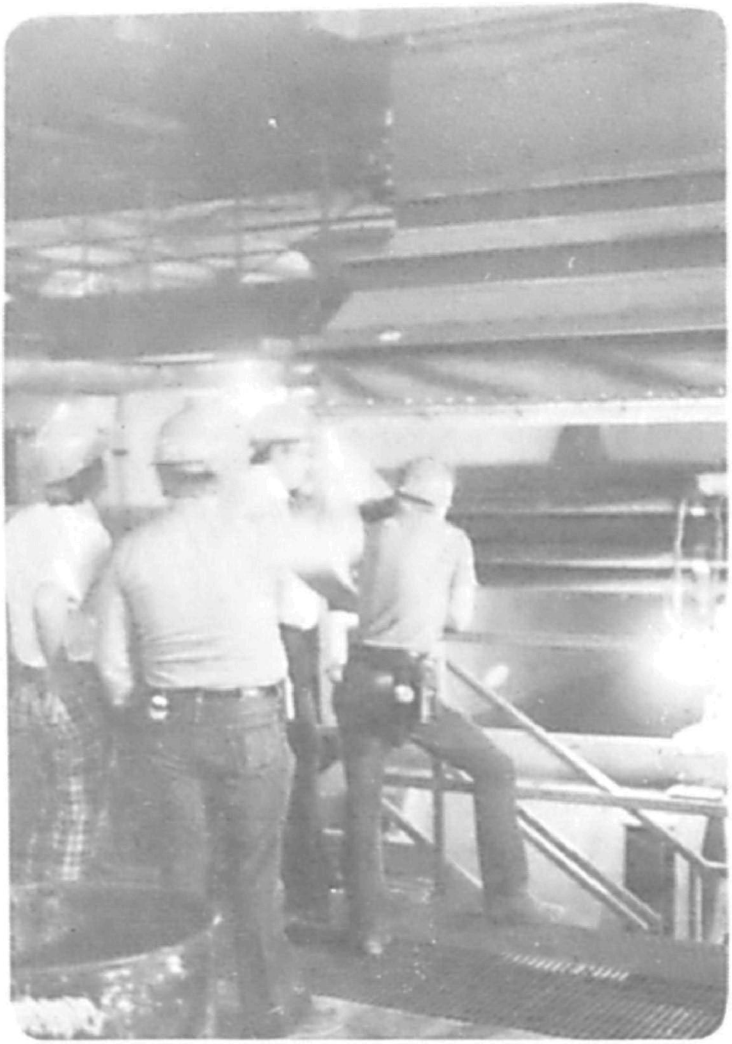

Photo No. 8. Side view of reheat tube bundles situated in top portion of scrubber module.

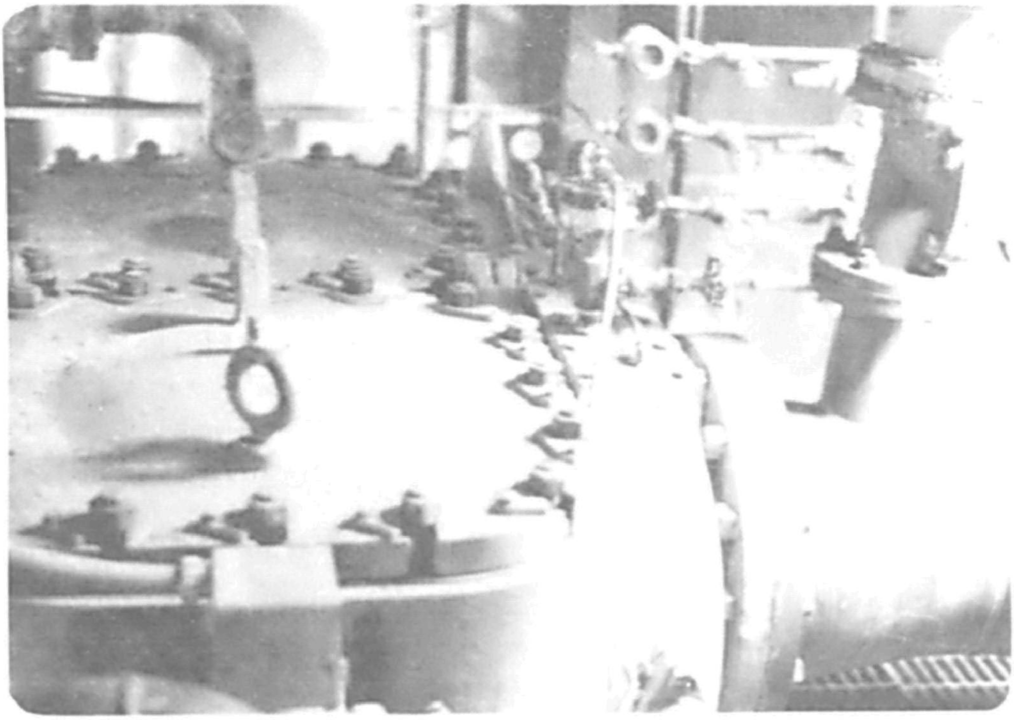

Photo No. 9. View of original duplex strainer situated in the slurry spray discharge line.

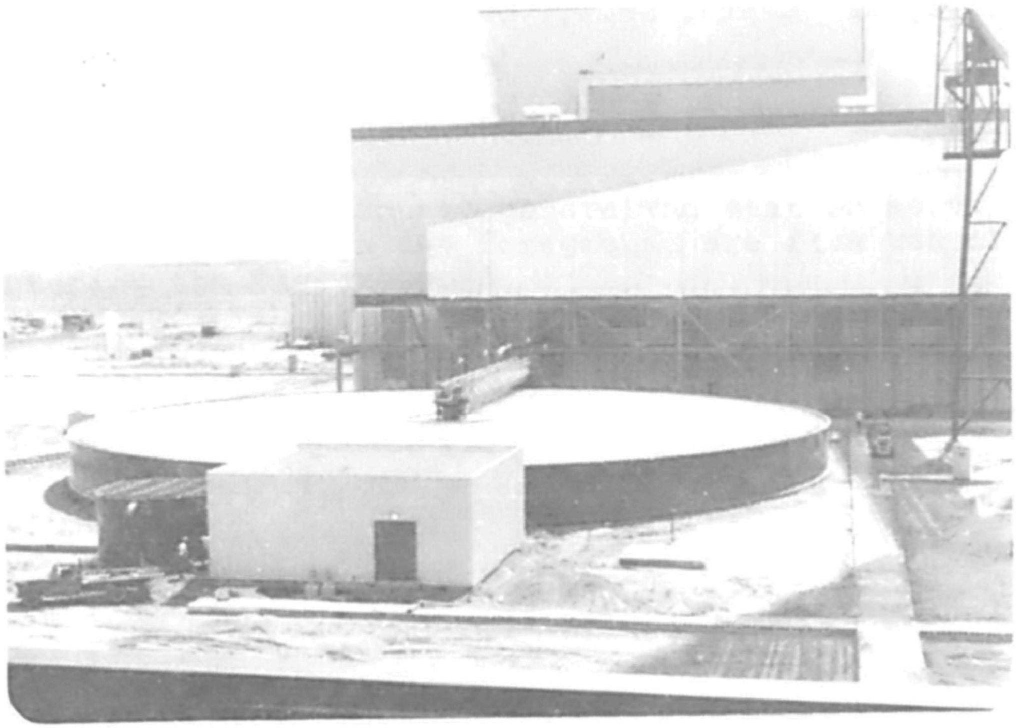

Photo No. 10. View of one of the two main thickeners used for concentrating the solids of the waste stream prior to disposal.

Photo No. 11. Side view of thickener water surface featuring walkway and center well.

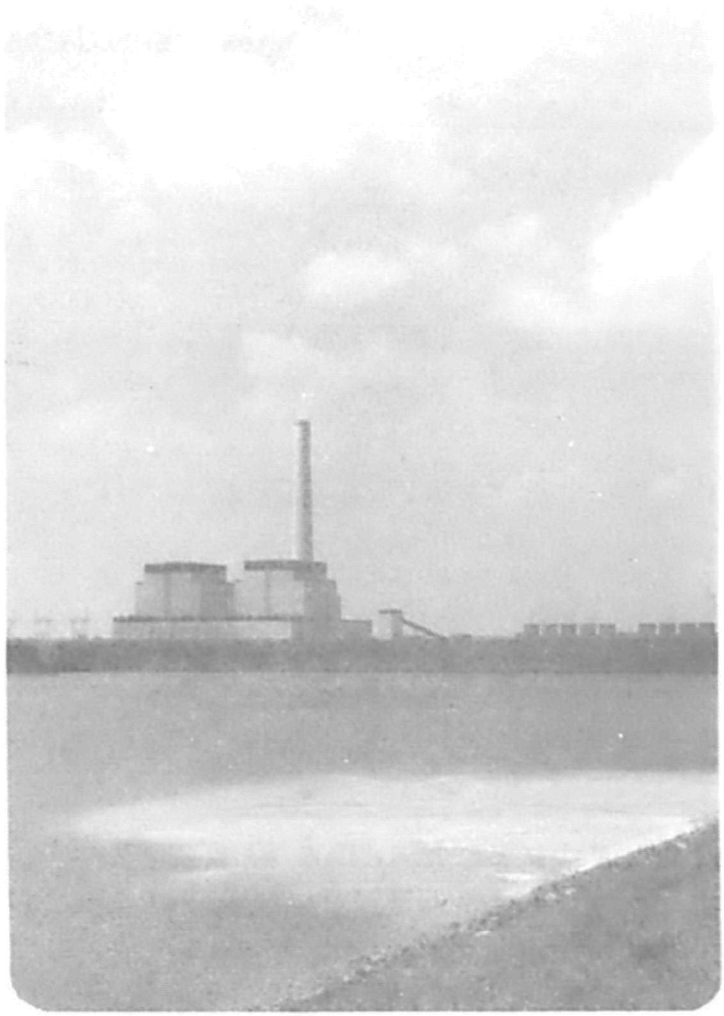

Photo No. 12. Sherburne County generating station as viewed from the fly ash pond. In the foreground are flue gas cleaning wastes entering the fly ash pond.

Photo No. 13. View of holding and recycle basins used for plant water distribution, recycling, monitoring, and discharge.

APPENDIX C

OPERATIONAL FGD SYSTEM COST DATA

Date June 26, 1978

Utility Name Pennsylvania Power Company

Address 1 East Washington Street, New Castle, Pa.

Name of Contact - Title Russ C. Forsythe - Engineer

Phone No. (412)/652 - 5531

Station Bruce Mansfield

Unit Identification No. 1 and 2

Unit Size, 1834 gross MW, 6.7 MM acfm @ 285 °F

Net MW w/o FGD 1760

Net MW w/FGD 1650

FGD System Size, 1834 MW

6.7 MM acfm @ 285 °F

Footnote No.

COST BREAKDOWN

I. CAPITAL COSTS OF FGD SYSTEM INSTALLATION

A. Year(s) to which estimates below apply: 1973-1977

B. Year of greatest capital expenditure: 1975

C. Month and year estimates made: April 1978

D. Date FGD contract awarded: October 1973

Date FGD construction began: April 1973

Date of initial FGD system start-up: Dec. 1975 (Unit 1) Jul. 1977 (Unit 2)

Date of commercial FGD system start-up: June 1, 1976 (Unit 1) Oct. 1, 1977 (Unit 2)

E. Expected FGD system life: 30 years

F. Cost adjustment made by: B. A. Laseke, Jr.

G. Cost adjustment checked by: B. A. Laseke, Jr.

Footnote No.		Included in reported total cost Yes	No	Capital cost, $
	H. Direct capital cost			
1	1. Particulate collection			
	Equipment cost	X		
	Installation cost	X		
	Total cost	X		Included in item 3
2	2. Facilities for reagent handling and preparation			
	Equipment cost	X		
	Installation cost	X		
	Total cost	X		11,700,000
3	3. SO_2 absorber and related equipment			
	Equipment cost	X		31,800,000
	Installation cost	X		42,500,000
	Total cost	X		74,300,000
4	4. Fans installed for FGD			
	Equipment cost	X		
	Installation cost	X		
	Total cost	X		Included in item 3
5	5. Reheat			
	Equipment cost	X		
	Installation cost	X		
	Total cost	X		Included in item 3

Foot-note No.		Included in reported total cost Yes	No	Capital cost, $
6	6. Solids disposal: site			
	Equipment cost	X		
	Installation cost	X		
	Total cost	X		40,000,000

Location of interim and final disposal site(s) 6.5 to 7 miles from the plant site.

When was site(s) acquired or year of expected acquisition 1973 and 1974

Cost when acquired or at time of expected acquisition $2,700,000

Life span 30 yr for all three Mansfield units.

Required site treatment (lining, surface preparation, etc.) 420-ft high hydraulic dam

Composition of disposed material (flyash 15 %, bottom ash 0 %, SO_2 waste 15 %, unreacted reagent ___ %, fixative 2.5% water 67.5%).

Foot-note No.		Yes	No	Capital cost, $
7	7. Solids disposal: transport system			
	Contract cost		X	
	Equipment cost	X		
	Installation cost	X		
	Total cost	X		34,858,465

Footnote No.		Included in reported total cost: Yes	No	Capital cost, $
8	8. Solids disposal: treatment system			
	Equipment cost	X		
	Installation cost	X		
	Total cost	X		8,812,530
	9. By-product recovery: regenerative system			
	Equipment cost		X	
	Installation cost		X	
	Total cost		X	N/A
	10. By-product recovery plant			
	Equipment cost		X	
	Installation cost		X	
	Total cost		X	N/A
	11. Instrumentation and controls			
	Equipment cost	X		
	Installation cost	X		
	Total cost	X		Included in items 3 and 7
	12. Utilities and services			
	Equipment cost	X		
	Installation cost	X		
	Total cost	X		

N/A - Not Applicable.

Foot-note No.		Included in reported total cost Yes	No	Capital cost, $
9	13. Stack requirements due to FGD			
	Equipment cost	X		______
	Installation cost	X		______
	Total cost	X		______
	14. Additional system modifications			
	Equipment cost	X		______
	Installation cost	X		______
	Total cost	X		______
10	15. Other			
	Equipment cost	X		______
	Installation cost	X		______
	Total cost	X		______
	16. Other			
	Equipment cost		X	______
	Installation cost		X	______
	Total cost		X	______
	17. Other			
	Equipment cost		X	______
	Installation cost		X	______
	Total cost		X	______

Footnote No.		Included in reported total cost: Yes	Included in reported total cost: No	Capital cost, $
	18. Ot[illegible]			
	Equipment cost		X	
	Installation cost		X	
	Total cost		X	
	19. Other			
	Equipment cost		X	
	Installation cost		X	
	Total cost		X	
	20. Other			
	Equipment cost		X	
	Installation cost		X	
	Total cost		X	
	Direct cost s[illegible]total			
	Equipment cost	X		
	Installation cost	X		
11	Total cost	X		221,278,000
	I. Indirect Costs			
	1. Engineering			
	In-house	X		
12	A-E	X		
	2. Construction expenses			
	In-house	X		
12	Contractor	X		

Footnote No.		Included in reported total cost Yes	Included in reported total cost No	Capital cost, $
	3. Contractor fees	X		
	4. Subcontractor fees	X		
13	5. Allowance for funds used during construction	X		
	6. Allowance for start-up	X		
	7. Contingency	X		
14	8. Escalation	X		
	9. Spares, offsite, taxes, freight, etc.	X		
	10. Research and development		X	
	11. Other		X	
	Indirect cost subtotal	X		Included in direct cost

J. Total Direct and Indirect Costs $221,278,000

$/kW (gross) 120.65

II. ANNUAL OPERATING COST

See Attachment A: breakdown of all operation and maintenance costs for B. Mansfield 1 and 2 scrubbing systems

Footnote No.		Included in reported total cost Yes	Included in reported total cost No	Cost, $
	A. Variable Costs			
	1. Particulate removal			
	a. Operating	X		
	(1) Labor	X		
	(2) Supervision	X		
	b. Electricity	X		
	c. Other utilities			
	(1) Water	X		

Footnote No.		Included in reported total cost: Yes	No	Cost, $
	d. Maintenance			
	Labor	X		
	(2) Supplies	X		
	Subtotal particulate	X		Included in total variable cost
	2. SO_2 absorber			
	a. Operating	X		
	(1) Labor	X		
	(2) Supervision	X		
	b. Electricity consumption			
	(1) Feed preparation	X		
	(2) Reheat		X	
	(3) Fans	X		
	(4) SO_2 absorber	X		
	(5) Other	X		
	c. Fuel			
15	(1) Reheat	X		
	(2) Other		X	
	d. Other Utilities			
	(1) Water	X		
	(2) Other		X	
	e. Maintenance			
	(1) Labor	X		
	(2) Supplies	X		

Footnote No.		Included in reported total cost: Yes	Included in reported total cost: No	Cost, $
	Subtotal absorber	X		Included in total variable cost
3.	Raw materials			
	a. Lime	X		
	b. Limestone		X	
	c. Fuel for process needs		X	
	d. Sodium hydroxide		X	
	e. Magnesium oxide		X	
	f. Sodium carbonate		X	
	g. Flocculant		X	
	h. Other	X		
	Subtotal raw materials	X		Included in total variable cost
4.	Solid and liquid waste disposal			
	a. Operating			
	(1) Labor	X		
	(2) Supervision	X		
	b. Electricity consumption	X		
	c. Other utilities			
	(1) Water	X		
	(2) Other		X	
	d. Maintenance			
	(1) Labor	X		
	(2) Supplies	X		
	e. Other	X		
	f. Credit for by-product recovery		X	

Footnote No.		Included in reported total cost: Yes	No	Cost, $
	g. Wa[illegible]water treatment	X		
	Subtotal disposal	X		Included in total variable cost
	5. Overhead			
	a. Plant	X		
	b. Administrative	X		
	Subtotal	X		Included in total variable cost
	Total Variable Costs	X		14,759,935
16	B. Fixed Charges			
	1. Interest	X		17,923,518
	2. Annual depreciation	X		6,859,618
	3. Insurance	X		2,212,780
	4. Taxes	X		10,178,788
	5. Other, specify		X	
	Total Fixed Costs	X		37,174,704
	C. Total Variable and Fixed Costs	51,934,639		
	mills/kWh(net)	14.34		

FOOTNOTES

Line	Page	Comments
1	2	Each unit is equipped with 6 parallel 2-stage scrubbing trains for the wet phase removal of particulate and SO_2. Each train includes a variable-throat venturi for particulate and SO_2 removal and a fixed-throat venturi for primary SO_2 removal. The cost of particulate control is included in the cost of SO_2-removal equipment.
2	2	Included is the additional reagent preparation equipment. Charges are not included in the original contract with Chemico.
3	2	The cost of the contract for engineering and procurement includes all 24 scrubbing vessels and related equipment, including reagent handling, equalling approximately $3,100,000 per module.
4	2	Twelve wet fans are provided for both units. Each fan is a 9000-hp unit capable of overcoming a maximum gas side pressure drop of 75 in. H_2O (62 in. H_2O on a maximum continuous basis). The cost of the fans is included in the scrubbing equipment and related components (Item 3).
5	2	Four direct fuel-oil-fired reheat chambers boost the gas discharge temperature 40°F. The cost of the reheater is included in the scrubbing and related equipment (Item 3).
6	3	The Little Blue Run ravine waste disposal area is located approximately seven miles from the plant. A manmade dam impounds a disposal area approximately 1460 acres in area.
7	3	169,500 lineal feet of 12-inch and 8-inch piping, 41 pumps, and supernatant return equipment are provided to transport 18,000 tons/day of sludge to the waste disposal area.
8	4	Dravo's Calcilox/Synearth stabilization process is used. All associated transportation, mixing, storage, and handling equipment is included.
9	5	950-ft. concrete-shell chimney contains four steel (Corten) sleeves, two for each unit. Flake-glass coating (Heil Rigiflake) is included. (NOTE: the cost of repair to failed coating and reapplication of new materials is not included.)

FOOTNOTES (continued)

Line	Page	Comments
10	5	Included are the ductwork, thickeners, waste holding ponds, piping and pipe racks, pump houses, electrical houses, control rooms, fuel-oil storage and supply, steam supply, protective liners, sumps, and sump pumps.
11	6	The total direct capital cost includes $137,607,000 for air quality control and $83,671,000 for waste solids disposal. These values also include all the indirect capital costs.
12	6	Gilbert/Commonwealth Associates.
13	7	Eight percent interest rate on borrowed capital during construction.
14	7	Eight percent/year for purchased and quoted material; 12 percent/year for estimated material; 5.5 percent/year on labor through June 1, 1976; 8 percent/year on labor after June 1, 1976.
15	8	No. 2 fuel oil used for direct reheat systems (140,000 Btu/gal at $2.282/10^6$ Btu).
16	10	The fixed charges provided were computed using the following rates: interest - 8.1 percent; annual depreciation - 3.1 percent; insurance - 1.0 percent; taxes - 4.6 percent; total fixed charge rate - 16.8 percent.
17	10	The station capacity factor for 1977, reported by the utility, was 40.09 percent, equaling 3.62099 x 10^9 kWh. The station capacity factor was based on one complete year of service from Unit 1 and approximately one-half year from Unit 2. (Initial startup commenced on July 1, 1977, and commercial startup commenced on October 1, 1977.)

Attachment A to Appendix C

Bruce Mansfield Plant
Units 1 and 2
Air Quality Control System
Operation and Maintenance Costs for 1977

Supervision and engineering		$ 106,282
Fuel:		
Reheater oil	$ 535,255	
Calcilox	$ 699,122	
Other	$1,104,292	
Total		$ 2,338,669
Steam operating expenses		
Lime	$6,819,411	
Other	$1,423,470	
Total		$ 8,242,881
Miscellaneous operating expenses		$ 212,856
Maintenance supervision and engineering		$ 155,717
Maintenance of structures		$ 59,994
Maintenance of boiler plant		$ 3,643,536
Total air quality control system and waste disposal system operation and maintenance expenses		$14,759,935

(Total net plant generation in 1977, at a capacity factor of 40.09 percent, was 3,620,990 MWh.)

Total operating and maintenance costs for Units 1 and 2	$62,911,541

Operating and maintenance costs in 1977, mills/net kWh:

Total operating and maintenance	17.37
Air quality control system and waste disposal system operating and maintenance	4.08
Estimated 1977 station power costs, excluding air quality control system and waste disposal system	1.89

Attachment B to Appendix C

COST ADJUSTMENTS

1. Of the estimated \$213,200,000, \$74,300,000 was allocated for the scrubber modules, reheaters, and fans. Of this total, \$2,057,750 is assessed to the reheaters, leaving \$72,242,430 for the modules (24) and fans (12). The design premises of the scrubbing system call for virtually all the particulate and 70 percent of the inlet SO_2 to be removed in the first-stage venturi. The second-stage venturi removes the remaining SO_2 (22.1 percent design efficienies). Thus, 1-(70/92.1) or 24 percent of \$72,242,430, or \$27,338,185, is subtracted for particulate control.

2. The entire 950-ft concrete-shell chimney, including four flake-glass-coated carbon steel flues, was included in the scrubber capital costs. Because a 600-ft stack was originally proposed and rejected, only a portion of the top 350 ft can accurately be assessed against the scrubber. Thus, \$2.5 million has been subtracted.

3. The total direct and indirect costs assessed against the air quality control systems are as follows:

\$137,607,000		
- 17,338,185		
- 2,500,000		
\$117,768,815	=	\$64.214/kW (gross)

4. With regard to the waste disposal system, approximately 45 percent of the wastes disposed is collected fly ash (1×10^6 tons/year of fly ash; 1.2×10^6 tons/year of SO_2 waste). Therefore, 45 percent of the capital costs assessed against the waste disposal system (\$83,671,000), or (\$37,651,950), has been subtracted.

\$ 83,671,000		
- 37,651,950		
\$ 46,019,050	=	\$25.092/kW (gross)

5. Conversion to 1977 dollars is based upon the following assumptions:

   a) Construction of the station commenced on 9/10/69.
   b) Engineering design commenced in late 1969.
   c) Plant construction began in May 1971.
   d) Origninal AQCS plans (ESP and high stack) were drawn up in 1970.

e) An intensive investigation of FGD processes was initiated in November 1970.
f) Plans for a full-scale FGD system were formulated in July 1972.
g) The plans were approved in October 1972.
h) Chemico was authorized to proceed with design engineering and fabrication in January 1973.
i) Pilot plant testing was conducted between February and May 1973, and August and September 1973.
j) B. Mansfield 1 started up initially December 11, 1975. Commercial operation commenced June 1, 1976.
k) B. Mansfield 2 started up on July 1, 1977, and went commercial October 1, 1977.

- One percent of capital expenditures for the entire AQCS and sludge disposal system occurred before January 1, 1973, or 0.5 percent in 1971 and 0.5 percent in 1972.

  $1,637,880 x 50% = $818,940 x (1.488/0.964) = $1,264,090
  $1,637,880 x 50% = $818,940 x (1.488) = $1,218,580

- Ten percent of the capital expenditures was made during the course of 1973. This figure is derived by assuming that half of the average monthly expenditures over the duration of the entire project was made during this period because the pilot plant program needed to verify process chemistry and process design.

  $16,774,135 x (1.488/1.05) = $23,771,350

- Approximately 23 percent of the expenditures was made each year in 1974, 1975, and 1976, and 19 percent in 1977. This translates into the following actual costs:

$37,924,135 x (1.488/1.206)	= $ 46,791,165	
$37,924,135 x (1.488/1.329)	= $ 42,461,335	
$37,924,135 x (1.488/1.4)	= $ 40,307,935	
$31,603,445 x 1.00	= $ 31,603,445	
	$161,163,880	(1977 dollars)
Total adjusted capital:	$187,417,900	(1977 dollars)
	$102.19/kW	(gross)

6. Annualized charges: Assume 65 percent station capacity factor (9,395,100,000 kWh).

   a) Operation and maintenance costs:

   $$\$14,759,935 \times \left(\frac{9,395,100 \text{ MWh}}{3,620,990 \text{ MWh}}\right) = \$38,296,450 = 4.076 \text{ mills/kWh}$$

   b) Power costs:

   $$(\$6,829,690)\left(\frac{9,395,100 \text{ MWh}}{3,620,990 \text{ MWh}}\right) = \$13,467,555 = 1.433 \text{ Mills/kWh}$$

   c) Fixed charges: Using 16.8 percent, a total fixed charge of $31,486,207 on a fixed investment of $187,417,900 is calculated, which equals 3.35 mills/kWh.

   d) Total annual charges: $83,250,212 = 8.96 mills/kWh

7. Summary of adjusted costs:

Capital cost:	$187,417,900	$102.19/KW (gross)
Annual cost:	$83,250,212	8.96 mills/kWh (net)

TECHNICAL REPORT DATA

(Please read Instructions on the reverse before completing)

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16. ABSTRACT

This report gives the results of a survey of operational flue gas desulfurization (FGD) systems on coal-fired utility boilers in the United States. The FGD systems installed on Units 1 and 2 at the Bruce Mansfield Station of the Pennsylvania Power Company are described in terms of design and performance. Each unit is fitted with a wet magnesium-modified lime scrubbing system consisting of six parallel, two-stage scrubbing trains arranged in two groups of three. Flue gas from each group of three scrubbing trains flows together into an oil-fired reheater and is discharged through a separate flue contained in a 290 m (950 ft) stack. The waste disposal system is a three-part process consisting of a pumping and treatment facility, transportation facility, and containment area. Bruce Mansfield 1 commenced commercial operation on June 1, 1976. Bruce Mansfield 2 commenced commercial operation on October 1, 1977. Initial operation of these FGD systems was characterized by problems with the reheaters, induced-draft fan housing, and stack flue liners.

17. KEY WORDS AND DOCUMENT ANALYSIS

a. DESCRIPTORS		b. IDENTIFIERS/OPEN ENDED TERMS	c. COSATI Field/Group	
Air Pollution	Scrubbers	Air Pollution Control	13B	
Flue Gases	Coal	Stationary Sources	21B	21D
Desulfurization	Combustion	Wet Limestone	07A,07D	
Fly Ash	Cost Engineering	Particulate		14A
Limestone	Sulfur Dioxide			07B
Slurries	Dust Control		11G	
Ponds			08H	

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