Lime FGD System and Sludge Disposal Case Study

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Prepared by
Black & Veatch
Kansas City, Missouri

ELECTRIC POWER RESEARCH INSTITUTE

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Work Completed, May 1980

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ABSTRACT

Selecting and installing a flue gas desulfurization (FGD) system and a sludge disposal system at a utility electric generation plant is no easy task. Approximately 21,000 MW of FGD and sludge disposal systems are presently operating with another 28,000 MW of FGD and sludge disposal systems under construction or planned. With the new EPA regulations requiring an FGD system on essentially every new coal-fired utility electric generation unit, the ability to decide on the most advantageous FGD and sludge disposal systems which are technically, economically, and environmentally acceptable can result in savings of $7-40/kW to the utility.

This case study describes the step-by-step design decisions and equipment selections for a hypothetical lime FGD and sludge disposal system for a new 500 MW coal-fired electric generation unit. The hypothetical FGD and sludge disposal systems are based on actual installations. This case study demonstrates the methods by which utility personnel can effectively utilize the information contained in the "Lime FGD Systems Data Book" (FP-1030) and the "FGD Sludge Disposal Manual" (FP-977) to select the most advantageous lime FGD and sludge disposal systems.

EPRI PERSPECTIVE

PROJECT DESCRIPTION

This final report presents a case study prepared under RP982-18 for use in EPRI-sponsored seminars on the application of two design guideline manuals published earlier--the Lime FGD Systems Data Book (EPRI Final Report FP-1030) and the FGD Sludge Disposal Manual (EPRI Final Report FP-977). These guideline manuals present general flue gas desulfurization (FGD) scrubber and sludge disposal concepts with specific details that must be considered in system design. The case study illustrates how these general concepts are applied to the selection and design of an FGD system. The case study also delineates the decision path to be followed by utility staff, from system selection through equipment erection and startup.

PROJECT OBJECTIVE

The objective of this study is to illustrate to utility and engineering company personnel how the Lime FGD Systems Data Book and the FGD Sludge Disposal Manual can be utilized effectively in the design of an FGD system.

PROJECT RESULTS

The Lime FGD Systems Data Book provides a central information source to help the utility design engineer specify and select a lime-based SO_2 scrubbing system. The FGD Sludge Disposal Manual provides the utility industry with an objective, technically sound state-of-the-art assessment of scrubber by-product disposal methods. The case study demonstrates how to apply the information contained in these books to the selection and design of a lime SO_2 scrubber and sludge disposal system; it was presented at several seminars on the use of both books and will provide those unable to attend the seminars with a detailed example of how to apply the information contained in the books.

The case study contains examples of material balances for both the FGD system and the sludge disposal system. The use of the material balance for developing both design and sizing criteria is addressed in detail, and alternative FGD systems, with their advantages and disadvantages, are briefly discussed. Optional sludge disposal schemes are also addressed. Throughout the case study, the decision path is clearly illustrated; one particularly useful feature is individual decision trees that show the alternatives available for both the FGD and sludge disposal systems.

The case study is addressed to utility engineers responsible for the design, evaluation, and operation of lime-based FGD systems, but can be utilized by others in the field such as architect-engineers and system suppliers. It is not a definitive FGD and sludge disposal design, but rather a hypothetical plant situation used to demonstrate how the two earlier reports can be most effectively utilized in the design of an FGD and sludge disposal system.

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LIME FGD SYSTEM AND SLUDGE DISPOSAL
CASE STUDY

1.0 INTRODUCTION

1.1 CASE STUDY PURPOSE AND SCOPE

This case study describes the rationale associated with the design of a hypothetical Flue Gas Desulfurization (FGD) system to illustrate how utility personnel can effectively benefit from the information contained in EPRI's Lime FGD Systems Data Book (EPRI FP-1030, May, 1979) and FGD Sludge Disposal Manual (EPRI FP-977, January, 1979). The ways in which utility management, generation engineering, and power production staff can benefit include the following.

- Informing utility management of the processes, alternatives, and decisions required to select the most economically advantageous flue gas desulfurization and sludge disposal systems for a specific power generating station.
- Guiding the generation engineer in evaluation of their consulting engineer's studies and recommendations related to FGD and sludge disposal systems.
- Improving the evaluation of FGD systems and predicted performance as proposed by equipment suppliers.
- Providing more definitive design and performance information routinely requested by regulatory agencies for permit applications and related regulatory questions.
- Presenting and justifying the FGD and sludge disposal design and selection decisions made by the utility to the general public.
- Establishing improved operating procedures for FGD and sludge disposal systems based on current operating experiences.

The Lime FGD Systems Data Book and FGD Sludge Disposal Manual present general lime FGD scrubber and sludge disposal concepts. In addition, they describe specific details that must be considered in system design. With the background information contained in these manuals, which is based on the accumulated experience of existing operating scrubber systems, a utility staff can better communicate their needs with their consulting engineer, the equipment suppliers, and the equipment installation contractor. Throughout this case study, references will be provided to appropriate sections of the Lime FGD Systems Data Book and FGD Sludge Disposal Manual . These references will indicate where specific information in the manuals supports the design and equipment selection decisions reached as part of the example case study.

1.2 CASE STUDY CONTENTS

Figure 1-1 illustrates a typical FGD project coordination sequence and design approach from initial assignment through commercial operation. The format of this case study follows this same basic sequence. The plant design basis is presented in Section 2.0. The FGD system preliminary study and equipment design criteria are presented in Sections 3.0 and 4.0, respectively. Similarly, the sludge disposal system preliminary study and equipment design criteria are presented in Sections 5.0 and 6.0. Section 7.0 describes the purchase specifications and Section 8.0 presents the bid evaluation. Equipment erection, startup of subsystems, and performance testing are discussed in Section 9.0. The primary objectives of each of the sections of this case study are as follows.

Section 2.0 establishes the case study design basis. The hypothetical power generation site is described and the site-related factors influencing the FGD system design are presented.

Section 3.0 presents the preliminary FGD system selection study. The objective of this section is to review the available methods for flue gas desulfurization and select the most advantageous FGD system and type of scrubber additive for the hypothetical station described in Section 2.0.

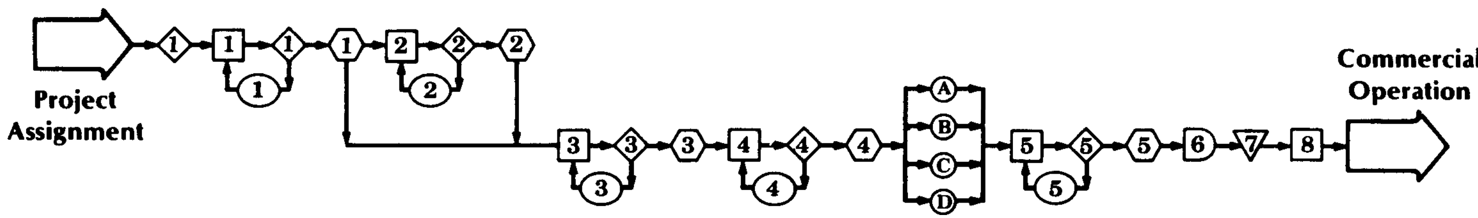
Section 4.0 presents the FGD equipment design criteria. This section includes the FGD system material balance, water balance, sizing criteria, and design criteria. The design criteria will provide the technical basis for the purchase specification which is discussed in Section 7.0.

Section 5.0 presents the sludge disposal preliminary study. The objective of this section is to define the characteristics and quantities of waste requiring treatment and disposal and select the most advantageous disposal site, sludge processing, and solid waste transport alternatives.

Section 6.0 presents the sludge disposal equipment design criteria. This section includes the sludge disposal system water balance, system design criteria, equipment sizing criteria, and disposal site seal requirements.

Section 7.0 describes the contents of a typical lime FGD system purchase specification and the approach for preparing this type of document. Examples are presented which indicate the typical format and content. This section explains how the design criteria developed in Sections 4.0 and 6.0 are incorporated into appropriate specifications and the importance of developing and using a qualified bidders list.

PROJECT COORDINATION
SEQUENCE FROM ASSIGNMENT
THROUGH COMMERCIAL OPERATION



KEY SYMBOLS

- ◇ Generation Engineering
- □ Consulting Engineer
- ⬭ Review and Comment
- ⬡ Completed Document
- ○ Equipment Suppliers (A, B, C, D)
- D Contractor
- ▽ Power Production

NUMBER DESIGNATIONS

1 - Plant Design Basis
2 - Preliminary Studies
3 - Equipment Design Criteria
4 - Purchase Specifications
5 - Bid Evaluations
6 - Equipment Erection
7 - Startup Subsystems
8 - Performance Testing

FIGURE 1-1

Section 8.0 discusses, by example, the process of evaluating bids that have been received in response to the specification developed in Section 7.0. This section demonstrates how the actual proposal prices submitted by the qualified bidders must be adjusted for noncompliance items, balance of plant costs, commercial costs, and operating costs to provide equivalent comparisons.

Section 9.0 presents a brief discussion of considerations related to FGD system construction and startup, testing, and operation. General erection guidelines are presented which emphasize the interfaces involving utility personnel, the equipment supplier, the construction contractor, and construction management. This section considers the post-contract period of the project up to and including FGD equipment startup and operation. General testing guidelines and information are presented related to demonstrating compliance with emission standards and system performance guarantees. Test parameters, sampling and analysis techniques, as well as testing procedures are described. The operational considerations discussed include operator training, record keeping, and preventative maintenance.

2.0 CASE STUDY DESIGN BASIS

2.1 OBJECTIVE

The objective of this section is to establish the design basis for the case study. The factors influencing the hypothetical FGD system design are listed in Table 2-1[1]. Each of these design factors are discussed in the following subsections.

2.2 REQUIREMENTS

(1) The hypothetical station consists of a single 500 MW net coal-fired electric generating unit.

(2) The station load model and economic criteria are presented in Table 2-2.

2.3 COAL PROPERTIES

Properties of the coal fired determines to what extent FGD controls are required. Table 2-3 presents the properties of the coals considered. Three separate coal analyses are presented. The nominal coal is the design basis coal with a sulfur content of 3.2 per cent and a heating value of 25,586 Joules per gram (11,000 Btu per pound). The typical lower sulfur coal (1.8 per cent sulfur and 27,558 Joules per gram [11,848 Btu per pound]) and typical higher sulfur coal (3.6 per cent sulfur and 26,749 Joules per gram [11,500 Btu per pound]) indicate the expected variations in coal properties. The hypothetical FGD system must be designed to accommodate any of the coals listed.

2.4 STEAM GENERATOR DESIGN

The type of steam generator determines to a large extent the amount of fly ash that the downstream particulate collection system (i.e., electrostatic precipitator or fabric filter) receives and to some extent the volume of flue gas that the FGD system must treat. Table 2-4 presents the steam generator design data. Since the FGD system is located downstream of an electrostatic precipitator (ESP), the volume of fly ash entering the scrubber is reduced to small amounts. The volume of flue gas at maximum capacity is expected to be 744 kilograms per second (5,909,000 pounds per hour). At the average annual capacity factor of 66 per cent, the expected volume of flue gas is 489 kilograms per second (3,878,000 pounds per hour).

2.5 LIME PROPERTIES

The lime additive properties are presented in Table 2-5. The range of values for the lime constituents presented in the table indicate that calcium oxide (CaO)

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[1] Lime FGD System Data Book , Table 2.2-1, Page 2.2-2.

TABLE 2-1. FACTORS OUTSIDE THE BATTERY LIMITS THAT INFLUENCE SCRUBBER SYSTEM DESIGN

- Coal properties
  - Sulfur content, type
  - Ash content
  - Fly ash composition, particle size
  - Chloride content
  - Heating value
  - Moisture content
  - Composition variability
- Steam generator design
  - Type of steam generator
  - Size of steam generator
  - Age of steam generator
  - Flue gas flow
  - Additional control equipment
  - Loading characteristics
- Lime properties
  - Per cent inert material
  - Ca and Mg content
  - Reactivity
  - Size
- Site conditions
  - Land availability
  - Soil permeability
  - Ambient humidity
  - Rainfall
  - Climate
- Regulations
  - SO_2 emission/ambient standards
  - Particulate standards
  - Plume visibility standards
  - Water/land standards
- Makeup water
  - Chemical composition
  - Source
- Flue gas
  - Temperature
  - Flow
  - Dew point
  - Particulate loading
  - Particulate alkalinity

TABLE 2-2. STATION LOAD MODEL AND ECONOMIC CRITERIA

Startup Date	January, 1985
Economic Life	30 years
Average Station Lifetime Capacity Factor	66 per cent
Fixed Charge Rate	15 per cent
Present Worth Discount Rate	8.5 per cent
Indirect Cost Rate (% of capital cost)	25 per cent
Escalation	
-Fuel	8 per cent per year for 5 years following unit startup; 6 per cent thereafter
-Additives	6 per cent per year
Levelized Annual Fuel Cost	\$3.80/kJ (\$4.01/10^6 Btu)
Levelized Annual Energy Charge	36.81 mills/kWh
Levelized Annual Demand Charge	\$91.80/kW
Additive Cost*	
-Lime	\$61/1,000 kg (\$55/ton)
-Limestone	\$12/1,000 kg (\$11/ton)
-Soda Ash	\$118/1,000 kg (\$107/ton)

*Costs are in 1980 dollars.

TABLE 2-3. COAL PROPERTIES

Parameter	Coal Properties: Typical Lower Sulfur	Typical Higher Sulfur	Nominal Coal
Sulfur Content, %	1.8	3.6	3.2
Ash Content, %	16.0	16.0	16.0
Chlorine, %	0.11	0.03	0.06
Moisture, %	6.5	5.0	8.0
Carbon, %	62.79	63.77	60.04
Hydrogen, %	4.2	4.2	4.2
Oxygen, %	7.4	6.1	7.5
Nitrogen, %	1.2	1.3	1.0
Heating Value, J/g (Btu/lb)	27,558 (11,848)	26,749 (11,500)	25,586 (11,000)

TABLE 2-4. STEAM GENERATOR DESIGN DATA

Parameter	Steam Generator Design Data
Type of Steam Generator	Pulverized coal fired, balanced draft, drum type unit with tilting tangential type burners.
Size of Steam Generator	Maximum capacity = 3,800,000 lb steam per hour.
Age of Steam Generator	New Unit
Flue Gas Flow, kg/s (lb/hr)	Maximum Capacity = 744 (5,909,000) 66% Capacity = 489 (3,878,000)
Additional Control Equipment	Electrostatic Precipitator installed upstream of the scrubber

TABLE 2-5. LIME PROPERTIES

Parameter	Lime Properties
Constituent, per cent	
CaO	85 to 90
MgO	0 to 6
Inerts	4 to 10
Size	The lime is expected to be of 4.45 by 0 cm (1-3/4 by 0 inch) size.
Reactivity	For mass balances assume 90% CaO, 10% inerts, and assume the lime slaker efficiency is 85%.

content may vary from 85 to 90 per cent and magnesium oxide (MgO) may be as high as 6 per cent. However, for mass balance calculations 90 per cent CaO and 10 per cent inerts will be assumed with no credit taken for the MgO content.

It will be shown in Section 3.0 that for this hypothetical case study lime is the most advantageous type of scrubber additive. For this reason the properties of alternate additives (i.e., limestone and soda ash) are not presented in Table 2-5.

2.6 SITE CONDITIONS

The hypothetical site selected is located in the midwestern United States adjacent to a major river. Figure 2-1 illustrates the proposed site topography and land available for site development and solid waste disposal. The area within the indicated site boundary is approximately 3,905,000 square metres (965 acres). The area available for solid waste disposal includes approximately 480 acres. Additional site design data are presented in Table 2-6.

2.7 REGULATIONS

Based on the revised New Source Performance Standards (NSPS) the regulations pertinent to FGD system design are presented in Table 2-7. For the coals considered in this case study, sulfur dioxide emissions must not exceed 0.258 kilograms per Gigajoule (0.6 pound SO_2 per million Btu) of heat input. This corresponds to an SO_2 removal efficiency of 90 per cent. In addition, the regulations require installation of a spare scrubber module if emergency bypass capabilities are required.

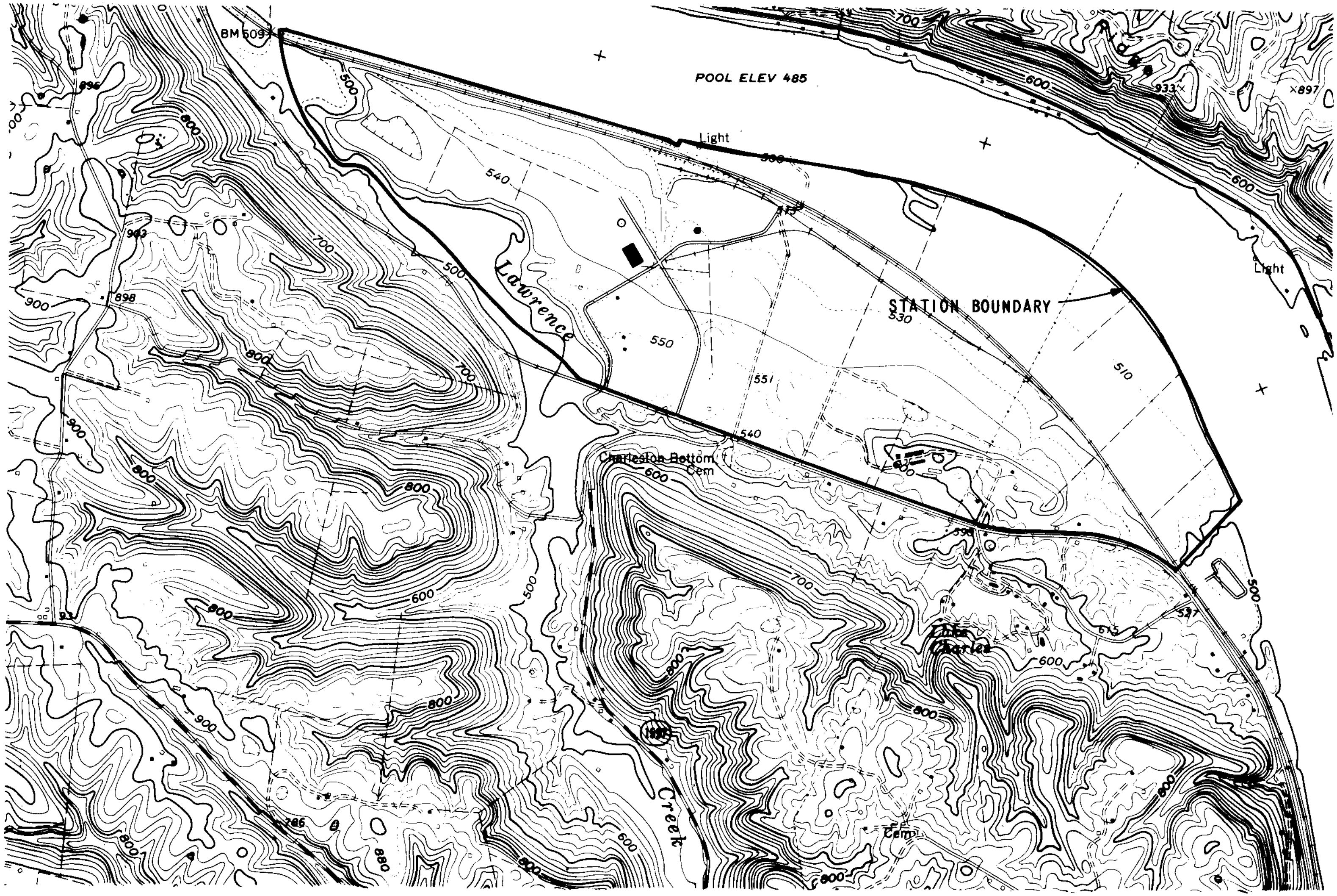
New source coal-fired boilers are required to install and maintain continuous emission monitoring systems for nitrogen oxides (NO_x), opacity, sulfur dioxide (SO_2), and oxygen (O_2) or carbon dioxide (CO_2) as listed in Table 2-7. The installed instrumentation must meet performance specifications and exhibit general characteristics as given in Appendix B of Part 60 of Title 40 of the Code of Federal Regulations.

2.8 MAKEUP WATER

The source and chemical composition of the makeup water available at the hypothetical site is presented in Table 2-8. The normal source of makeup water will be cooling tower blowdown and well water. Additional makeup will be from the recycle basin.

2.9 FLUE GAS

The flue gas characteristics are presented in Table 2-9. The average station lifetime capacity factor, as previously presented in Table 2-2, is 66 per cent. Therefore, the flue gas characteristics at both maximum capacity and the average capacity at 66 per cent of rated capacity are listed in Table 2-9.



SITE BOUNDARY AND
AREA TOPOGRAPHY

FIGURE 2-1

TABLE 2-6. SITE CONDITIONS

Parameter	Site Conditions
Land Availability	
Total Site Development, m^2 (acres)	3,905,000 (965)
Disposal Area, m^2 (acres)	1,943,000 (480)
Scrubber Module Area, m (feet)	~61 x 61 (~ 200 x 200)
Sludge Preparation Area, m (feet)	~76 x 46 (~ 250 x 150)
Sealing Requirements for Pond, $l/m^2/yr$ ($gal/ft^2/yr$)	Sealing required to ensure leakage does not exceed 306 (7.5) (equivalent to 1×10^{-6} cm/sec permeability)
Natural Clay Availability	Available near site
Grade Elevation, m (ft) msl	164.6 (540)
Barometric Pressure, Pa (in. Hg)	99,300 (29.4)
Ambient Temperature	
Minimum, C (F)	-21 (-5)
Maximum, C (F)	35 (95)
Mean Avg. Rainfall, cm/yr (in./yr)	118 (46.5)
Mean Avg. Evaporation, cm/yr (in./yr)	91 (36)

TABLE 2-7. NEW SOURCE COAL-FIRED BOILER EMISSION REGULATIONS

Parameter	New Source Performance Standards (NSPS) and Regulations
Emission Limitations for:	
- Nitrogen Oxides (NO_x)	0.258 kg NO_x per GJ (0.6 pound per MMBtu) (bituminous coal)
- Particulate Matter	0.0129 kg per GJ (0.03 pound per MMBtu) which corresponds to 99.8 per cent removal.*
- Opacity	Limited to 20 per cent
- Sulfur Dioxide (SO_2)	0.258 kg per GJ (0.6 pound per MMBtu) which corresponds to 90 per cent removal.*
-Redundancy	A spare scrubber module is required for a facility larger than 125 MW electrical output capacity if emergency bypass capabilities are desired. A spare module is defined as a separate module capable of treating an amount of flue gas equal to the total flue gas generated divided by the total number of modules required at maximum flue gas flow conditions.
NSPS Continuous Emission Monitoring Requirements for:	
- NO_x	Must be monitored if emissions are greater than 70 per cent of the standard (3 hour averaging time).
- Opacity	Continuous measurement of the attenuation of visible light by particulate matter in stack effluent with an averaging time interval of 6 minutes.
- SO_2	Continuous measurement of SO_2 in stack effluent (30 day rolling average)
- Oxygen (O_2) or Carbon Dioxide (CO_2)	Monitoring required to determine appropriate conversion factors for flue gas stream dilution.

*For the coal properties presented in Table 2-3.

TABLE 2-8. MAKEUP WATER

Parameter	Fresh Makeup Water	
Source	Normal fresh water makeup will be cooling tower blowdown and well water. Additional makeup may be obtained from the recycle basin which contains the following. o Decanted bottom ash sluice water o Plant equipment, floor, and roof drains o Coal pile runoff o Area drains	
Typical Chemical Composition, expressed in mg/ℓ as $CaCO_3$ except as otherwise noted		
	Well Water	Cooling Tower Blowdown
- Calcium	200	800
- Magnesium	55	220
- Sodium	30	120
- Total Alkalinity	225	200
- Sulfate	25	800
- Chloride	20	80
- Silica, as SiO_2	15	60
- Orthophosphate, as $PO_4^{\equiv}$	—	2
- Total phosphate, as $PO_4^{\equiv}$	—	6
- Total dissolved solids, as such	315	1,375
- Total suspended solids, as such	<1	7
- pH	7.5	7.5-8.0
-Conductivity, µmhos/cm	505	2,200

TABLE 2-9. FLUE GAS CHARACTERISTICS

Parameter	Flue Gas Characteristics 66 per cent Rated Capacity	Maximum Capacity
Temperature at scrubber inlet, C (F)		
- Nominal	121 (250)	141 (285)
- Minimum	113 (235)	132 (270)
- Maximum	129 (265)	149 (300)
Gas Flow, kg/s (lb/hr)	489 (3,878,000)	745 (5,909,000)
Gas Density at nominal temperature, kg/m^3 (lb/ft^3)	0.929 (0.058)	0.865 (0.054)
Particulate content in flue gas at inlet to scrubber, kg/s (lb/hr)		
- Expected minimum with precipitator operating at 99.8 per cent efficiency	0.0063 (50)	0.0107 (85)
- Expected maximum with precipitator operating at 99.8 per cent efficiency	0.0126 (100)	0.0189 (150)
Expected Excess Air, per cent	25	25
Expected Air Heater Leakage, per cent	10	10

3.0 PRELIMINARY FGD SYSTEM STUDY

3.1 OBJECTIVE

The objective of this section is to review available methods for flue gas desulfurization (FGD) and select the most advantageous FGD system for the hypothetical station described in Section 2.0. Figure 3-1 presents schematically the general decision alternatives required to select and design a FGD system. The present section will only consider the first two steps shown, selection of the absorber system and scrubber additive.

3.2 REQUIREMENTS

(1) The FGD systems will be evaluated based on the Case Study Design Basis presented in Section 2.0.

(2) The FGD system shall meet the following requirements.

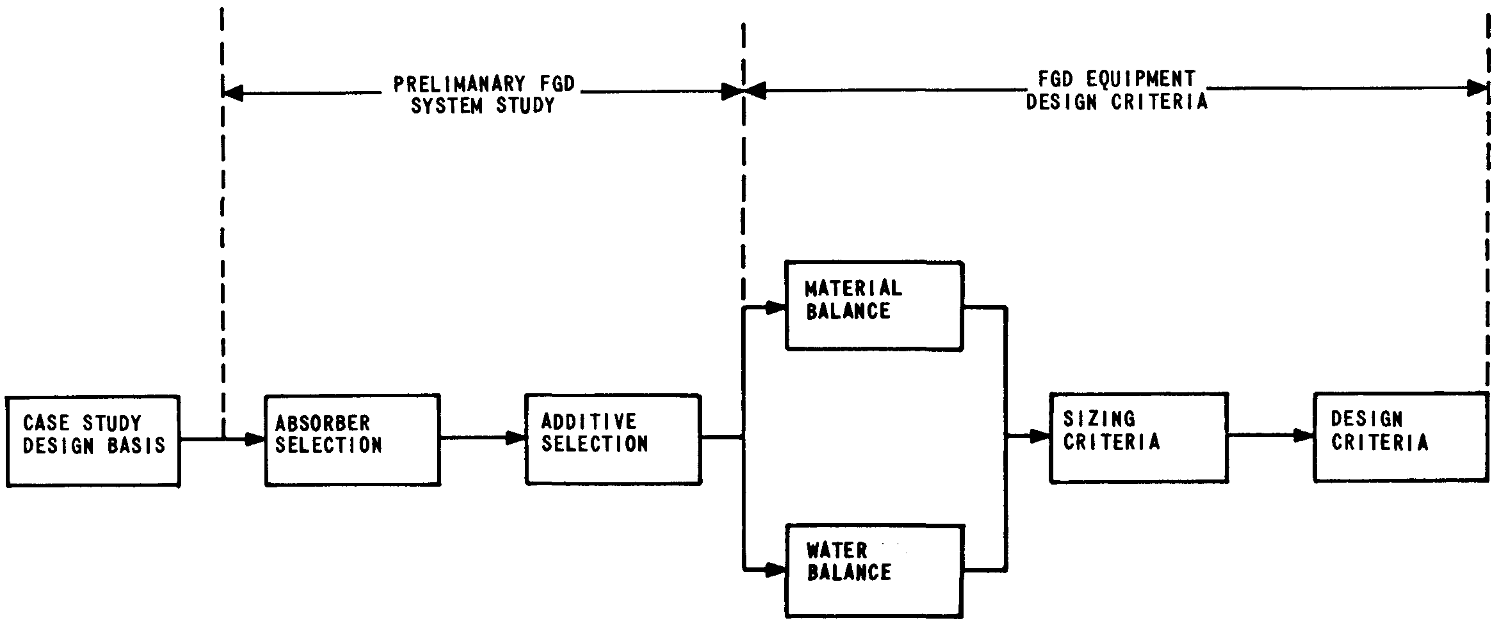
- (a) Demonstrated technical feasibility.
- (b) Advanced level of availability.
- (c) Acceptance by utility industry.
- (d) Favorable economic impact.
- (e) Acceptable environmental impact of waste disposal or a marketable end product.

3.3 AVAILABLE FLUE GAS DESULFURIZATION METHODS

The leading types of desulfurization processes for large power plants are identified in the block diagram shown on Figure 3-2. The basic divisions are recovery, throwaway, and advanced processes.

A large amount of research, testing, and development has occurred in the area of flue gas desulfurization in the past 10 years. In the United States alone, units with over 21,500 megawatts of electric generating capacity are currently equipped with FGD systems. An additional 27,500 megawatts of generating capacity are being designed or are under construction with flue gas desulfurization.

Of the over 200 desulfurization processes that have been studied, only a limited number of processes are receiving significant application or advanced development: lime, limestone, spray absorber/ dryer, soda ash (sodium carbonate/ Trona), double-alkali, Chiyoda, DOWA, magnesium oxide, and Wellman-Lord. Table 3-1 presents a summary of the current status of FGS systems in utility applications in the United States.



GENERAL DECISION ALTERNATIVES
REQUIRED TO SELECT AND DESIGN
AN FGD SYSTEM

FIGURE 3-1

SELECTED FLUE GAS DESULFURIZATION CONCEPTS

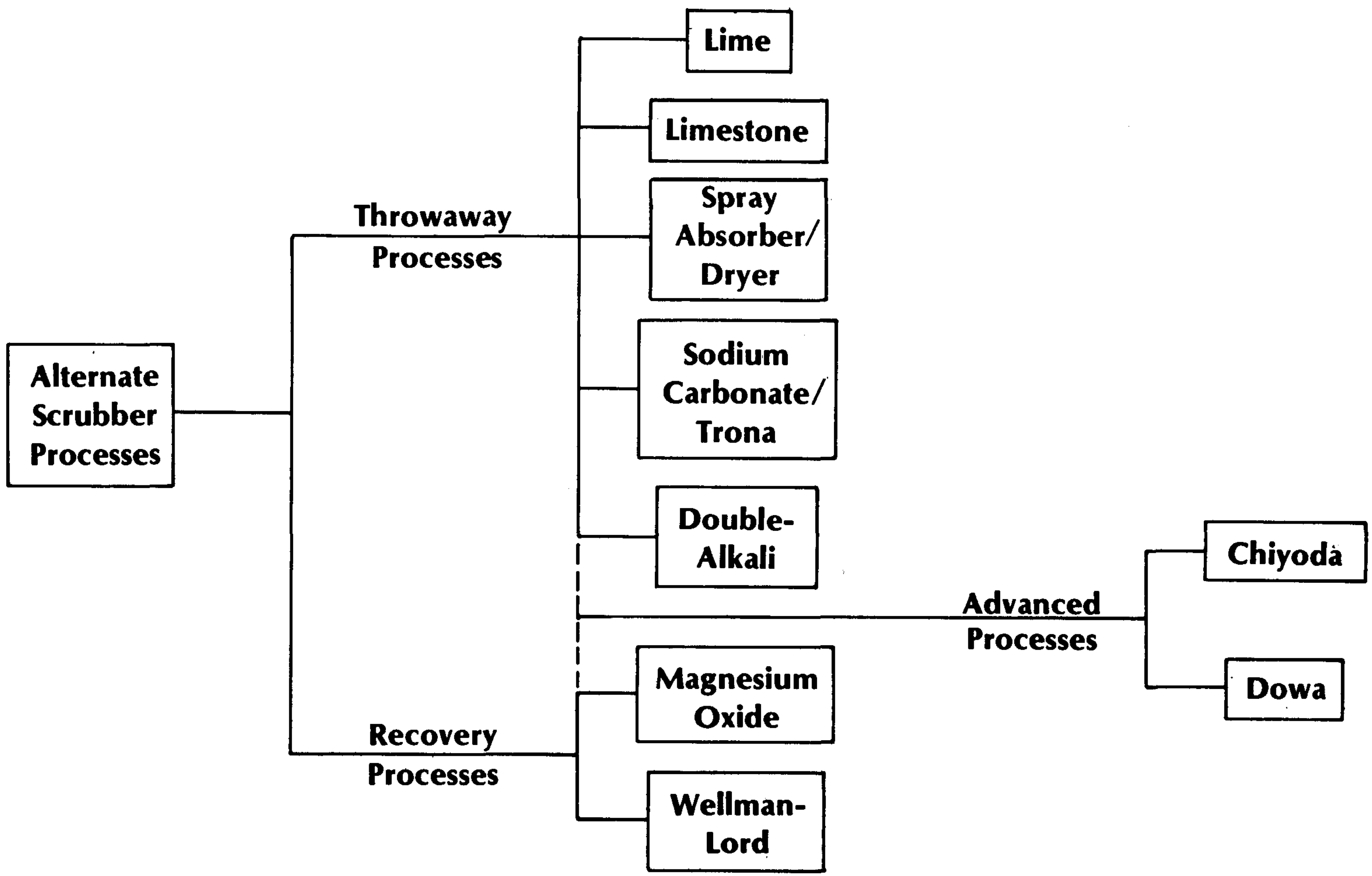


FIGURE 3-2

TABLE 3-1. SUMMARY OF SELECTED FGD SYSTEMS BY PROCESS*

Scrubber Process	Operational Units/MW	Design/ Construction Units/MW	Total Units/MW
Lime**	23/7,700	20/9,300	43/17,000
Limestone**	26/10,200	30/14,500	56/24,700
Spray Absorber/Dryer	--	6/2,300	6/2,300
Sodium Carbonate	4/900	--	4/900
Double-Alkali	3/1,200	--	3/1,200
Magnesium Oxide	1/100	3/700	4/800
Wellman-Lord	4/1,400	2/700	6/2,100

*Reference: EPA Utility FGD Survey: October-December 1979, EPA-600/7-80-029a, January 1980.

**Includes Additive/Fly Ash Systems.

Although the large majority of the FGD systems purchased and planned utilize lime or limestone technology, research is being conducted toward the development of newer, more sophisticated systems capable of recovering usable byproducts from the flue gas or which produce a waste product that minimizes waste disposal difficulties. The advanced processes, Chiyoda and DOWA are relatively new concepts. In the Chiyoda process (jet bubbling reactor) the flue gas is bubbled through a limestone slurry. The DOWA process is a packed tower scrubber system similar to a double-alkali process which uses aluminum sulfate and limestone as additives. Both of these processes have been pilot tested and will be offered commercially in the near future. However, they are not sufficiently demonstrated for application to the 500 MW unit considered in this case study.

3.3.1 Recovery Processes

In recovery processes, such as the magnesium oxide and Wellman-Lord processes, the end product is a saleable product (usually elemental sulfur, sulfuric acid, gypsum, or fertilizer base compounds). A prerequisite for consideration of a recovery process is the existence of a locally available market for the end products. To date, none of these recovery processes have been found to be economically competitive unless unusually strong markets for the end product are located nearby.

3.3.2 Throwaway Processes

Throwaway processes, such as the lime, limestone, double-alkali, soda ash, and spray absorber/dryer processes, produce a waste product with no commercial value which is disposed with the fly ash and bottom ash. The lime, limestone, double-alkali, and soda ash throwaway processes have been commercially applied to utility service. The spray absorber/dryer process has been successfully pilot tested using both lime and soda ash additives. Several full-scale units have been considered or purchased by utilities, but none are in service at this time. The first full scale utility demonstration spray absorber/dryer unit (100 MW) is scheduled to be in operation in the fall of 1980.

3.4 FGD SYSTEM SELECTION

3.4.1 Feasible FGD Systems

It is assumed that none of the possible end products from the recovery processes have a strong market near the hypothetical site location. Therefore, the recovery processes are not considered to be economically feasible alternatives. This limits the list of feasible FGD systems for this case study to the following five.

(1) Soda ash process

(2) Double-alkali process

(3) Spray absorber/dryer process

(4) Lime process

(5) Limestone process

These five processes are further discussed in the following subsections.

3.4.1.1 Soda Ash Process. The soda ash process utilizes soda ash as an SO_2 absorbent. Sodium carbonate is highly soluble and has a strong affinity for SO_2. This allows the scrubbing liquor to react quickly with the SO_2 in the spray tower at relatively low liquid-to-gas (L/G) ratios.

The soda ash process produces a soluble waste which can be difficult to dispose. The soda ash reaction with the SO_2 forms soluble sodium sulfite and sodium bisulfite. Since the waste products from this process are soluble, the disposal volumes can not be reduced by conventional dewatering techniques. In addition, the additive is not recovered in this process. Therefore, the feasibility of this process is dependent on the availability of a plentiful supply of low cost soda ash or the scarcity of other typically lower cost additives such as lime or limestone. These conditions are present only in the dry western states where soda ash is produced and high evaporation rates permit consideration of evaporation disposal ponds. Since these conditions do not exist for the hypothetical site considered in this case study and because of the potential of ground water contamination due to sodium leaching, the soda ash process will not be considered further.

3.4.1.2 Double-Alkali Process. The double-alkali process is basically a modification of the soda ash process. Soda ash is still used as the primary additive for SO_2 removal. However, lime is added to the scrubber blowdown to precipitate the calcium salts and regenerate most of the soda ash. Due to the relatively short supply and high cost of soda ash and the potential of ground water contamination due to residual sodium leaching from the waste products, this process is not considered a feasible alternative for the hypothetical site investigated in this case study.

3.4.1.3 Spray Absorber/Dryer Process. Operation of the spray absorber/ dryer process on high sulfur coals (greater than about 1.5 per cent sulfur) has been simulated by spiking the flue gas with SO_2 during pilot tests on low sulfur fuels. The results of these tests have generally indicated that the process is not economically attractive for high sulfur coals due to its low additive utilization. Therefore, the spray absorber/dryer process is not considered to be a feasible alternative when burning the coal considered in this case study.

3.4.1.4 Lime Process. The lime process has the advantages of extensive successful operating experience on the required size units and the availability of several qualified equipment suppliers. A wet spray tower type scrubber using lime additive is considered a feasible FGD process for this case study. The large amount of operating experience with this system has resulted in significant design modifications and has greatly improved the operational and maintenance performance of the present generation of systems. Turbulent contact absorbers (packed towers) and venturi scrubber-absorbers which have been installed are considered to be "first generation" type systems. Nearly all of the lime FGD systems now offered are of the improved spray tower type.

3.4.1.5 Limestone Process. The limestone process is basically a modification of the lime process. Limestone ($CaCO_3$) is used to absorb the sulfur dioxide rather than lime (CaO). The primary difference in equipment between limestone and lime usage is the additive preparation system required. For a limestone system, a wet ball mill and classification system is required; for a lime system, a lime slaker is required to develop the additive slurry.

Limestone is less reactive than lime. For this reason, a limestone process using a spray tower type scrubber would not be practical to achieve an average 90 per cent SO_2 removal required for the coal considered in this case study. The scrubber modules would be prohibitively large to provide the required liquid-to-gas contact and a large excess of limestone would be required. Consequently, packed tower type absorbers would be required to provide practical sized scrubber modules. Several qualified equipment suppliers will guarantee the limestone process for 90 per cent SO_2 removal using packed towers. For this reason, the limestone process using packed towers is considered a feasible process for this case study.

3.4.2 Process Selection

The choice between a lime and limestone FGD system is often seen as a choice between a more reactive alkaline material (lime) and a less costly one (limestone). Both of these processes are technically feasible for the coals considered in this case study. Therefore, the process selection must be based on economic and operational considerations.

3.4.2.1 Economic Considerations. A preliminary economic evaluation based on the hypothetical conditions assumed in this case study was performed. The results of this evaluation indicated that a wet spray tower type scrubber using lime additive is more economically advantageous than a packed tower type scrubber using limestone additive. This preliminary evaluation is supported by the case study bid evaluation discussed in Section 8.0. One of the bidders proposed a packed tower limestone system and the total comparative evaluated cost was significantly higher than all three lime spray tower systems proposed.

The primary reasons for the economic advantage of the spray tower lime process over the packed tower limestone process for this hypothetical case study are as follows.

(1) The additive preparation system for the lime process has lower capital costs and lower operating power requirements than for the limestone system.

(2) The open spray tower for the lime process had a lower pressure drop across the module than for the packed tower limestone process. This resulted in decreased induced draft fan power requirements.

(3) A source of high quality lime was available near the hypothetical site. River barge transportation of lime was practical and reduced the potential economic advantage of limestone.

3.4.2.2 Operational Considerations. In addition to the economic advantages of the lime process over the limestone process for this hypothetical case study, the lime process also offers the following potential operational advantages.

(1) The more reactive lime affords better FGD system control.

(2) Lime FGD systems exhibit higher additive utilizations and potentially more reliable operation with minimal gypsum scale problems.

3.4.3 Summary

In summary, a wet spray tower type scrubber using lime additive is the most advantageous FGD system for the 500 MW electric generating unit considered in this case study.

4.0 FGD EQUIPMENT DESIGN CRITERIA

4.1 OBJECTIVE

The objective of this section is to establish the lime FGD system equipment design criteria. As shown previously in Figure 3-1 this section will include the material balance, water balance, equipment sizing criteria, and design criteria. The design criteria will provide the technical basis for the purchase specification discussed in Section 7.0.

4.2 REQUIREMENTS

(1) The FGD system equipment design criteria will be established based on the Case Study Design Basis presented in Section 2.0.

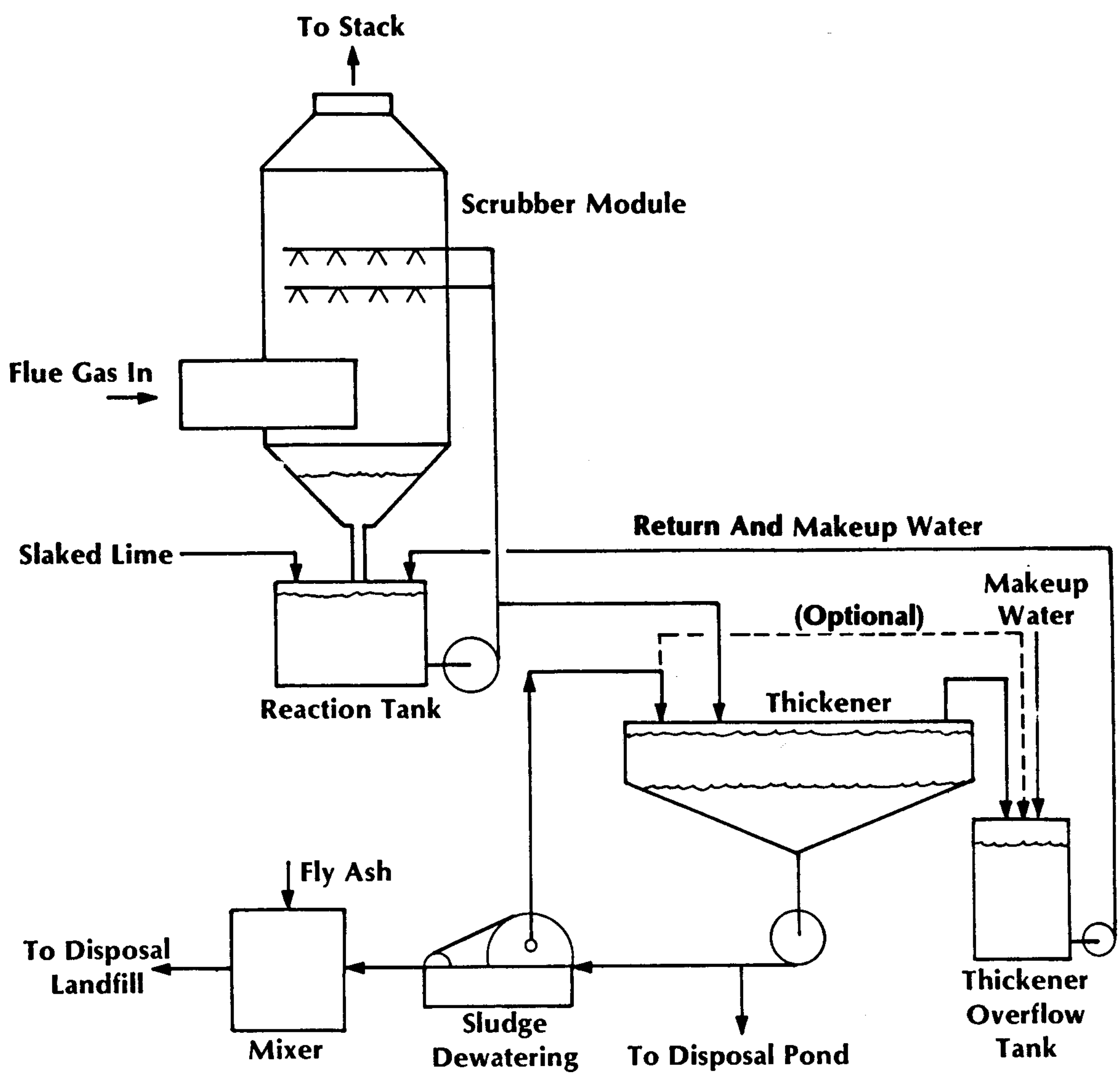
(2) Section 5.0 will establish that a stabilized landfill is the most advantageous method of sludge disposal for this case study. Therefore, in order to preserve the continuity of this section, dry sludge disposal in a stabilized landfill is assumed.

4.3 GENERAL LIME FGD SYSTEM DESCRIPTION

In a lime scrubbing system, slaked lime is used to absorb sulfur dioxide, producing a wet sludge which is stored in ponds or landfills. Figure 4-1 shows the diagrammatic processes of a lime FGD system. The lime is transferred from the additive system as a slurry to the reaction tank. The flue gas comes into contact with the spray slurry in the scrubber module where sulfur dioxide is absorbed by the slurry, and reacts with the calcium to form calcium sulfite. The spray slurry, with the captured sulfur dioxide, drains into the reaction tank where the chemical reactions continue before the slurry is recirculated back to the scrubber module.

Air is sometimes introduced into the reaction tank to convert calcium sulfite to calcium sulfate, which can be dewatered more easily than calcium sulfite. Experience with lime FGD scrubbers has shown that at the pH at which lime FGD scrubbers normally operate, forced oxidation of calcium sulfite to calcium sulfate is relatively ineffective. Therefore, none of the alternate FGD sludge processing systems will consider forced oxidation.

A portion of the spray slurry is bled off from the reaction tanks to the thickener to control the solids content of the slurry. Clarified thickener overflow water is returned to the reaction tanks. The thickener underflow which contains primarily calcium sulfite, calcium sulfate, and unreacted additive is pumped to either a disposal pond or to additional dewatering equipment. If the sludge is



LIME FGD SYSTEM

FIGURE 4-1

dewatered, it is often mixed with dry fly ash or sludge fixation additives to obtain a more stable mixture.

The alternate methods of sludge disposal will be discussed in Section 5.0.

4.4 MATERIAL BALANCE

The primary objective of the lime FGD system material balance is to establish the additive and water requirements and quantities of solid wastes generated. Two separate material balances will be considered. The first will be used for equipment sizing and will be based on burning the higher sulfur coal (3.6 per cent sulfur and 26,749 Joules per gram [11,500 Btu per pound]) at rated plant capacity. The second material balance will be used to determine average annual lime requirements and sludge disposal quantities. This material balance will be based on burning the nominal coal (3.2 per cent sulfur and 25,586 Joules per gram [11,000 Btu per pound]) at the average annual capacity factor of 66 per cent.

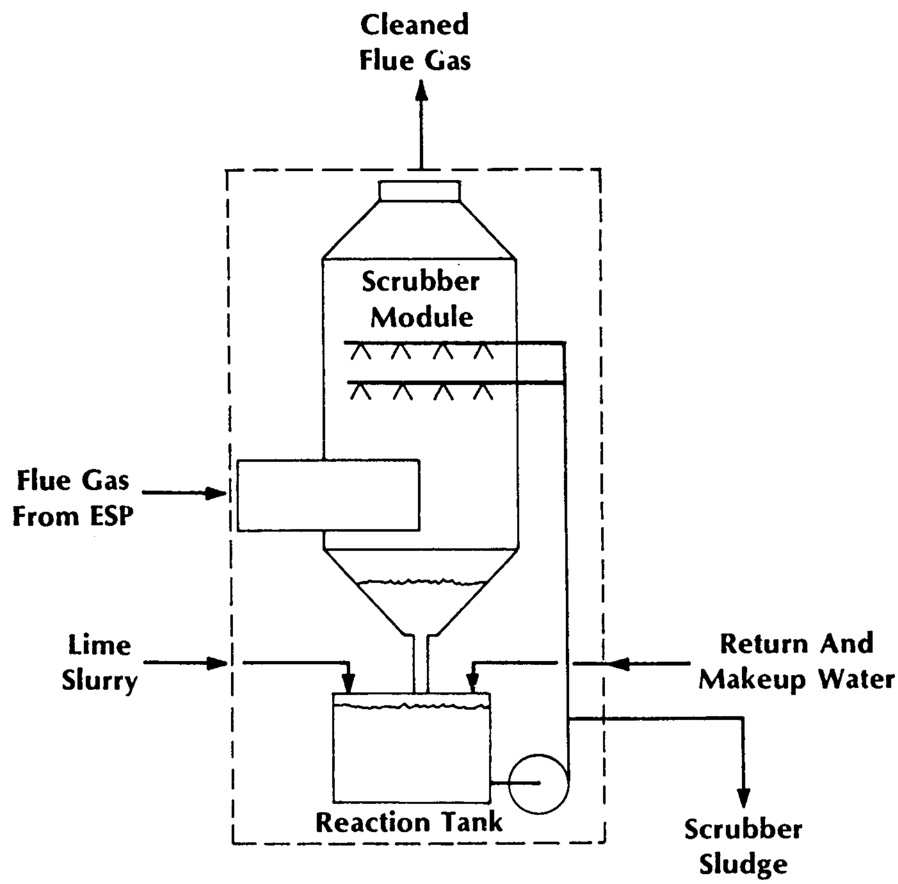
The basic material balance of the scrubber system is shown in Figure 4-2 (Refer to the "Lime FGD Systems Data Book", Figure 2.3-16, page 2.3-26). Although the lime FGD system will consist of multiple scrubber modules, a single module is assumed to simplify the calculations. The elements of the material balance shown in Figure 4-2 are summarized as follows.

- Input:
  - (1) Flue gas from the electrostatic precipitator (ESP) which introduces the SO_2 to the system.
  - (2) Lime slurry.
  - (3) Makeup water.
- Output:
  - (1) Cleaned flue gas with residual SO_2 and evaporated moisture.
  - (2) Scrubber sludge.

The information necessary to perform the two material balances is presented in Table 4-1. Information for both rated capacity and average capacity at 66 per cent of rated capacity is included. Based on this information, Table 4-2 was developed. Table 4-2 presents the maximum hourly and average annual additive requirements and quantities of solid wastes from the scrubber system. Grit from the lime slaker and ash quantities will be considered in Section 5.0.

4.5 WATER BALANCE

The objective of the water balance is to estimate the amount and quality of makeup water requirements to the FGD scrubber system. The basic water balance is shown in Figure 4-3 (Refer to the "Lime FGD Systems Data Book", Figure 2.3-23, page 2.3-69). The elements of the water balance are as follows.



FGD SCRUBBER SYSTEM MATERIAL BALANCE

FIGURE 4-2

TABLE 4-1. MATERIAL BALANCE DESIGN INFORMATION

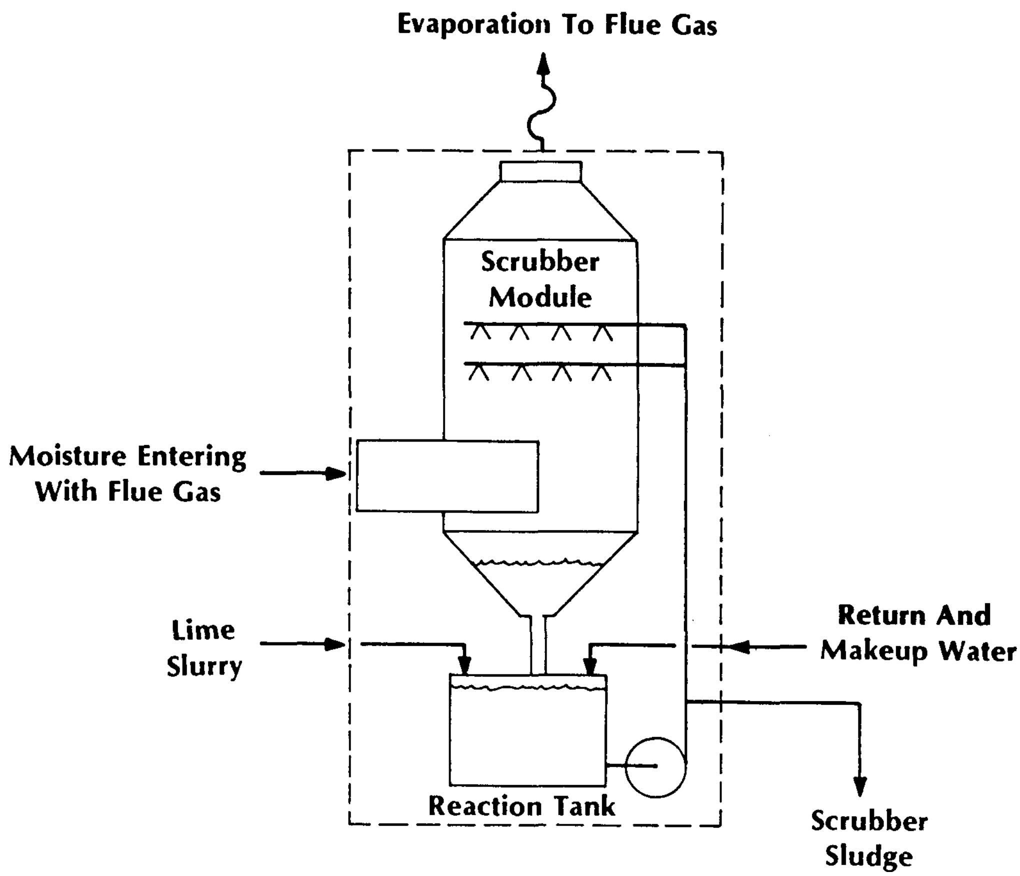
	Rated Capacity	66 Per Cent Rated Capacity
Plant Capacity, MW	500	330
Coal		
Type	Higher Sulfur	Nominal Coal
Consumption, kg/s (ton/hr)	55.9 (221.7)	38.6 (153.0)
Heating Value, Joules/gm (Btu/lb)	26,749 (11,500)	25,586 (11,000)
Moisture, per cent	5.0	8.0
Sulfur, per cent	3.6	3.2
Ash, per cent	16.0	16.0
Ash Distribution, per cent of total ash		
Fly ash	80*	76
Economizer ash	5*	4
Bottom ash	30*	20
Pulverizer Rejects, per cent of total coal burned	0.5	0.5
SO_2 Removal Efficiency, per cent	90	90
Lime Properties		
CaO, per cent	90	90
Inerts, per cent	10	10
Slaking efficiency, per cent	85	85
Stoichiometric ratio, moles of CaO/mole of SO_2 removed	1.10	1.10
Solids Concentration		
Lime slurry, per cent solids	20	20
Scrubber sludge, per cent solids	10	10
Sulfite to Sulfate Oxidation, per cent	20	20

*Based on the maximum expected ash distribution at each collection point.

TABLE 4-2. FGD SCRUBBER SYSTEM MATERIAL QUANTITIES

	Material Quantities			
	Maximum Hourly at Rated Capacity (Higher Sulfur Coal)		Average Annual at 66% Rated Capacity (Nominal Coal)	
	10^3 kg/hr	(tons/hour)	10^3 kg/yr	(tons/year)
Coal	201.1	(221.7)	1,216,600	(1,341,000)
Total SO_2 Produced	14.5	(16.0)	77,800	(85,800)
Total SO_2 Removed	13.1	(14.4)	70,000	(77,200)
Lime Consumption	16.4	(18.1)	88,100	(97,100)
Scrubber Sludge				
Sulfate sludge	7.0	(7.7)	37,700	(41,600)
Sulfite sludge	21.0	(23.2)	113,000	(124,600)
Excess additive	2.0	(2.2)	10,900	(12,000)
Total Scrubber Solids*	30.0	(33.1)	161,700	(178,200)

*Total scrubber solids do not include lime slaker grits and unreacted lime.



FGD SCRUBBER SYSTEM WATER BALANCE

FIGURE 4-3

- Input:
  - (1) Moisture entering with the flue gas.
  - (2) Lime slurry at 20 per cent solids by weight.
  - (3) Makeup water.
- Output:
  - (1) Evaporation to the flue gas.
  - (2) Scrubber sludge at 10 per cent solids by weight.

Table 4-3 presents the maximum hourly and average annual water balance for the FGD scrubber system. The estimated makeup water requirements shown in Table 4-3 represents a combination of freshwater makeup and return water from the sludge disposal system. The freshwater makeup requirement will be developed in Section 6.0 once the sludge disposal system has been selected.

4.6 EQUIPMENT SIZING CRITERIA

As explained in Section 4.4, the lime FGD scrubber system equipment will be sized based on material balances performed at the maximum design capacity when burning the higher sulfur coal. In addition, the FGD scrubber system equipment will be designed for safe and reliable operation under the following operating conditions in any combination.

(1) Daily start-up following an overnight shutdown of approximately 8 hours duration.

(2) Weekly start-up following weekend shutdown of approximately 48 hours duration.

(3) Operating at 25 per cent of rated capacity over extended periods of time.

(4) Continuous operation at rated capacity.

4.7 DESIGN CRITERIA

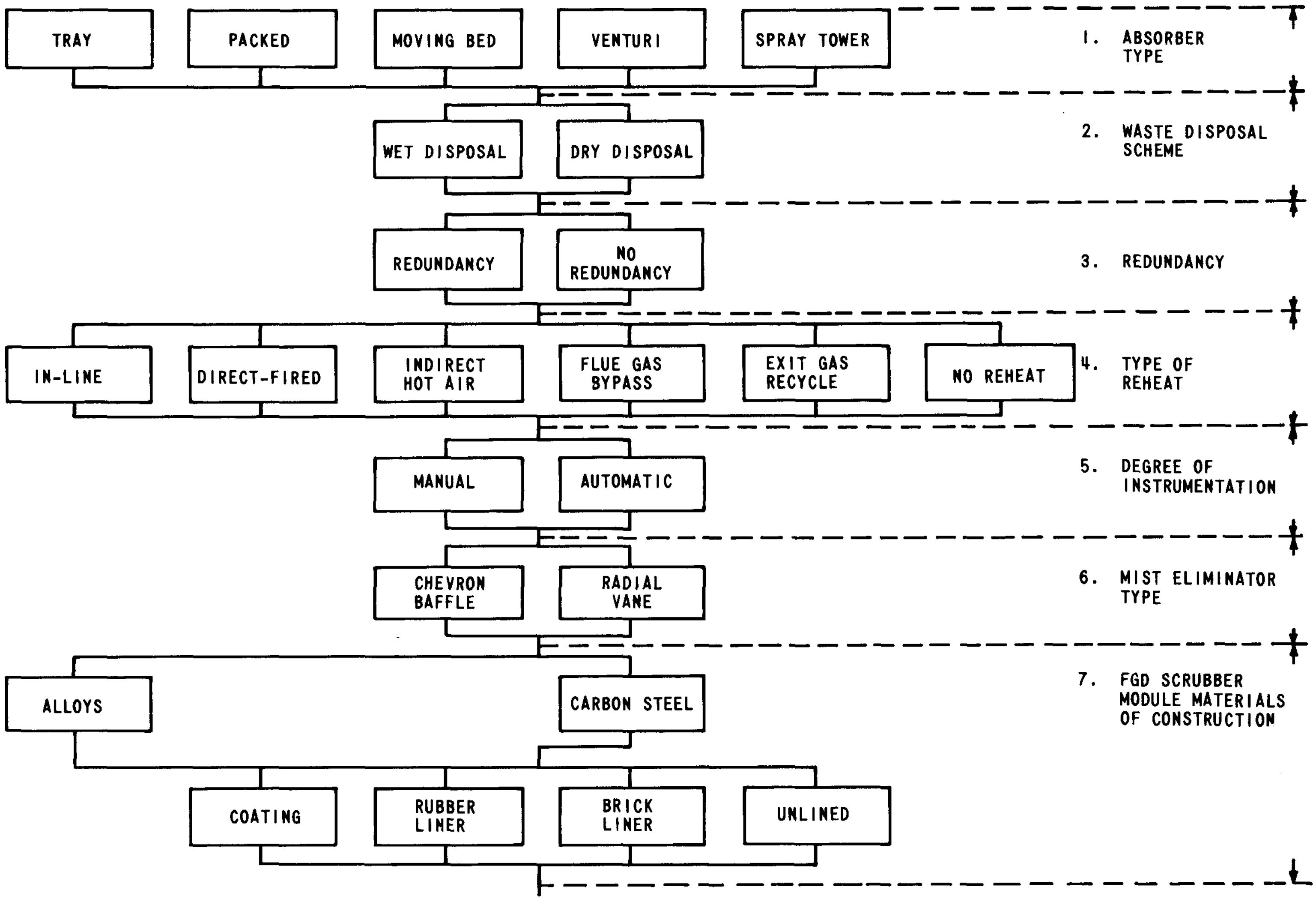
Prior to developing the purchase specification for a wet lime FGD system, a number of basic design decisions must be made. Figure 4-4 shows schematically the alternatives and some of the more important decision variables which are considered in developing a practical lime FGD system.

The alternatives shown in Figure 4-4 are an oversimplification of the overall decision-making process. There are a number of decisions to be made, and there is feedback from one decision to another. Nevertheless, these are the critical design decisions, and the order in which they are presented is the order in which they will be considered in this section.

Figure 4-5 presents the wet lime FGD scrubber alternatives selected for the hypothetical station considered in this case study. The following subsections provide additional information regarding these selections.

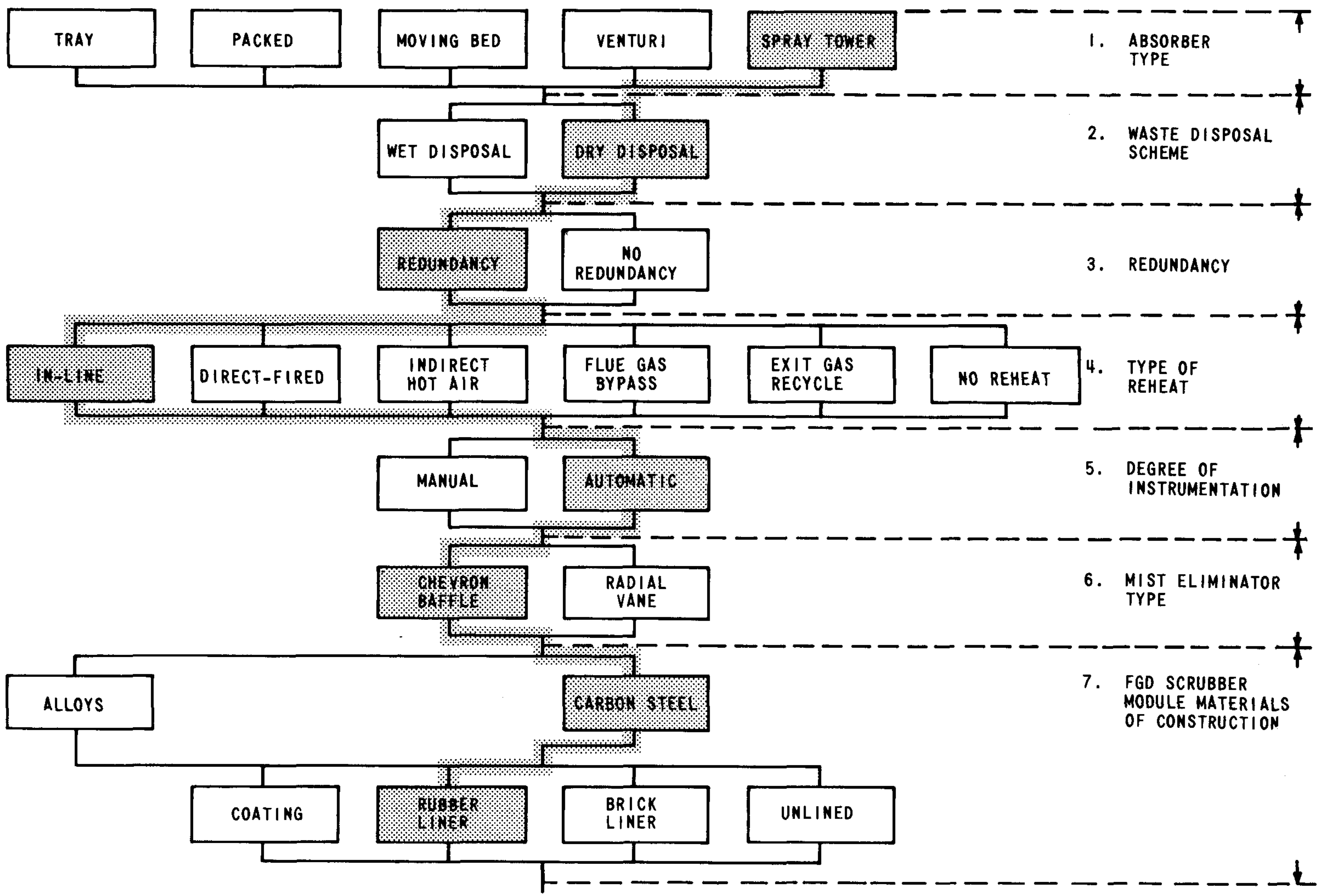
TABLE 4-3. FGD SCRUBBER SYSTEM WATER BALANCE

	Water Quantities			
	Rated Capacity (Higher Sulfur Coal)		66 Per Cent Rated Capacity (Nominal Coal)	
	kg/s	(lb/hr)	kg/s	(lb/hr)
Input				
Moisture entering with flue gas	33.0	(262,000)	28.9	(229,000)
Water in lime slurry	18.3	(145,000)	11.2	(89,000)
Return and makeup water	103.7	(823,000)	67.9	(539,000)
Total	155.0	(1,230,000)	108.0	(857,000)
Output				
Evaporation to flue gas	70.2	(557,000)	55.8	(443,000)
Water in scrubber sludge	84.8	(673,000)	52.2	(414,000)
Total	155.0	(1,230,000)	108.0	(857,000)



Case Study
Figure 4-4

WET LIME FGD SCRUBBER ALTERNATIVES



WET LIME FGD SCRUBBER ALTERNATIVES

FIGURE 4-5

4.7.1 Absorber Type (1)

As stated in Section 3.4.3, a wet spray tower type scrubber using lime additive is the most advantageous FGD system for the hypothetical conditions considered. As stated in the "Lime FGD System Data Book" (Section 4.6.2.5, page 4.6-5), spray type absorbers generally have low pressure drop and high liquid flow rate, and are the least expensive type of absorber in terms of capital cost. The extensive operating experience with this system has produced significant design modifications and has greatly improved the present generation of systems.

4.7.2 Waste Disposal Scheme (2)

As previously explained in Section 4.2 dry sludge disposal in a stabilized landfill is assumed. Section 5.0 will establish that this method of sludge disposal is the most advantageous for this case study.

4.7.3 Redundancy (3)

The New Source Performance Standards require a spare flue gas scrubber module for all coal-fired power generating stations larger than 125 MW electrical output capacity. In addition to the module redundancy required, the degree of component redundancy is an engineering decision influenced primarily by capital expenditure and local regulatory constraints on the FGD system operation. The number of component spares (components such as pumps, piping, and lime preparation equipment) that may be needed depends on the number of operating components, the reliability of each component, and the impact on overall operation if the component is not on line.

The following subsections present the degree of redundancy considered for the hypothetical station in this case study.

4.7.3.1 Scrubber Modules. At the time the FGD equipment design criteria for this case study was developed, the largest individual scrubber modules with demonstrated successful operating experience were designed for flue gas flow rates equal to about one-third of the expected flow rate from the 500 MW plant considered in this case study. Therefore, for this case study it is assumed that the lime FGD scrubber system will consist of four modules, with each module designed to treat one-third of the design flue gas flow. More than four modules may be provided if required by the equipment supplier's design to comply with the specifications. Regardless of the number of modules provided, one will be a spare.

4.7.3.2 Pumps. Each pumping system will be provided with a standby pump completely piped to the system. Each pumping system will include two full capacity pumps, except three half-capacity pumps will be provided for larger capacity systems where a spare full capacity pump would not be economical.

4.7.3.3 Piping. All piping, valves, and pumps in slurry service will include:

provisions for automatic clear water flushing complete with clear water piping,

or

an installed parallel piping system.

All slurry lines shall be sized to maintain a minimum velocity adequate to prevent solids from settling in the lines during minimum flow rates.

4.7.3.4 Lime Preparation Equipment. The following redundancy will be required for the additive preparation system.

(1) One installed spare slaker will be provided.

(2) One warehouse spare tank agitator will be provided for each lime slurry tank.

4.7.4 Type of Reheat (4)

Flue gas reheat will be required to minimize corrosion caused by condensation, to minimize a visible plume, and to attain the effective plume rise. As recommended in the Lime FGD Systems Data Book, (Section 4.11.12, page 4.11-29), an in-line reheat system that uses finned tubes and hot water has been selected. Additional information relating to flue gas reheat is provided in EPRI's Stack Gas Reheat For Wet Gas Desulfurization Systems, EPRI FP-361, February 1977.

4.7.5 Degree of Instrumentation (5)

A complete semi-automatic control system with manual initiation and shutdown capability has been selected (Reference: Lime/Limestone Scrubber Operation and Control Study, EPRI FP-627, October 1978). The control system will monitor specific operations and performance from a control panel for the overall scrubber system. The following subsections discuss the primary operations and performance to be monitored.

4.7.5.1 Scrubber.

(1) The control philosophy will be that of a modular system in that individual scrubber modules will be placed in service and out of service at the scrubber control panel. When removing a module from service, automatic flushing of the modules slurry lines with clear water will be accomplished.

(2) The rate of lime slurry feed to the individual modules and slurry bleed-off from the recirculation tanks will be controlled to maintain the solids concentration and the pH at adjustable preset values.

(3) Annunciators will be provided on the scrubber control panel to monitor abnormal operation of the system.

4.7.5.2 Miscellaneous Control Functions.

(1) Makeup and recycle water pressure controls will be provided as required. Other local subloop controls will be provided.

(2) All pumps, motor operated valves, and other devices required to be placed in service or taken out of service during start-up, shutdown, or operation of the scrubber system will be controlled and monitored from the scrubber control panel. Local manual control for maintenance will be provided.

(3) Local instrumentation will be provided where required for maintenance and periodic inspection.

4.7.6 Mist Eliminator Type (6)

Mist eliminators will be required on each scrubber module to minimize mist entrainment that would promote corrosion and scaling of downstream equipment. In accordance with the recommendations of the Lime FGD Systems Data Book (Section 4.7.9, page 4.7-39), a continuous chevron type mist eliminator has been selected for this case study.

4.7.7 Materials of Construction (7)

The choice of materials of construction for the lime FGD system equipment depends on many variables. These variables include the following.

(1) Planned life of the equipment.

(2) Mode of operation of the equipment.

(3) Economic considerations.

(4) Safety considerations.

(5) Past operating experience.

(6) Equipment location and environment.

Based on these considerations, the materials presented in Table 4-4 have been selected for this case study. References from the Lime FGD Systems Data Book that support the selected materials of construction are indicated.

4.8 CASE STUDY SITUATION #1

4.8.1 Situation Objective

The objectives of this case study situation are as follows.

(1) Provide an example of the role of generation engineering in the review process of the lime FGD equipment design criteria document.

(2) Illustrate the manner in which the Lime FGD Systems Data Book can be used to evaluate the consulting engineer's recommendations.

4.8.2 Situation Description

As shown in Step 3 of the project coordination sequence of Figure 1-1, the equipment design criteria document is evaluated by generation engineering prior to issue as a completed document. During the review and comment process, utility management posed a number of questions regarding the consulting engineer's recommendations.

TABLE 4-4. LIME FGD SYSTEM EQUIPMENT MATERIALS OF CONSTRUCTION

Equipment Item	Materials of Construction
Scrubber Module and Reaction Tank	Carbon Steel with neoprene rubber liner[1]
Piping	
-Slurry service	$\geq$ 6.35 cm (2-1/2") ϕ - Rubber lined carbon steel, $\leq$ 5.08 cm (2") ϕ - Fiberglass reinforced plastic (FRP) (ABCO-A150)
-Corrosive service (other than slurry piping)	ASTM A167 Type 316L stainless steel
-Non corrosive service	ASTM A106 GrA
Mist Eliminator	
Demister components	FRP[2]
Support material	Carbon steel with neoprene rubber liner
Reheat Equipment	Carbon steel[3]
Pumps	
-Casing	Cast iron with rubber liner[4]
-Impellers	Cast iron with rubber liner[4]
-Shaft	Carbon steel
-Shaft sleeves	316 stainless steel
Thickener Tank	Carbon steel sidewalls lined with FRP (polyester) with concrete bottom[5]
Lime Slurry Tanks	Carbon steel[6]

The following references from the Lime FGD Systems Data Book EPRI FP-1030, May 1979, support the selected materials of construction.

Reference Number	Section of Manual	Page Number
1	4.6.3.4	4.6-16
2	4.7.4.5	4.7-19
3	4.11.12	4.11-29
4	4.2.2.8	4.2-12
5	4.9.4	4.9-29
6	4.5.4.2	4.5-23

As an example, a question posed by utility management concerned the method of flue gas reheat recommended by the consulting engineer. Three alternative methods of providing flue gas reheat were evaluated in the FGD equipment design criteria document. These alternate methods included:

(1) Plan A--Hot Water In-Line Reheat.

(2) Plan B--Direct Hot Air Injection.

(3) Plan C--Indirect Hot Air Reheat.

Plan A is shown diagrammatically on Figure 4-6. Hot water from the deaerator is circulated through coils located in the gas stream at the outlet of the scrubber. The water after leaving the coil is returned to the deaerator where it is reheated with low pressure extraction steam from the turbine.

In Plan B hot secondary air from the air heater is used to reheat the flue gas as shown on Figure 4-7. The hot air is injected and mixed with the flue gas leaving the scrubber to provide the reheating required.

Plan C, as shown diagrammatically on Figure 4-8, also injects and mixes hot air with the flue gas leaving the scrubber. The air is heated by using a steam coil supplied with cold reheat steam. At full load on the unit, the cold reheat steam temperature will be about 316 C (600 F) and air temperatures of about 232 C (450 F) are expected. The air will be taken from the main fan room where the air will have been heated to about 27 C (80 F) by the air preheat coils. Therefore, the air preheat coils must be increased accordingly. A low head fan is used to provide the required pressure to inject the air into the gas stream. The steam coil is located in the air stream downstream of the fan and a mixing device is located in the gas stream.

Each of the alternate flue gas reheat plans will increase the temperature of the flue gas leaving the scrubber to approximately 71 C (160 F) to 77 C (170 F) or about 22 C (40 F) above the flue gas dew point. The advantages and disadvantages of the three plans considered are presented in Table 4-5.

Plan A using hot water in-line reheat has the lowest comparative capital cost and operating cost of the plans considered as shown in Table 4-6. The consulting engineer has recommended that Plan A with the addition of soot blowers to clean the coil and proper tube material selection to minimize the corrosion potential is the most advantageous flue gas reheat alternative.

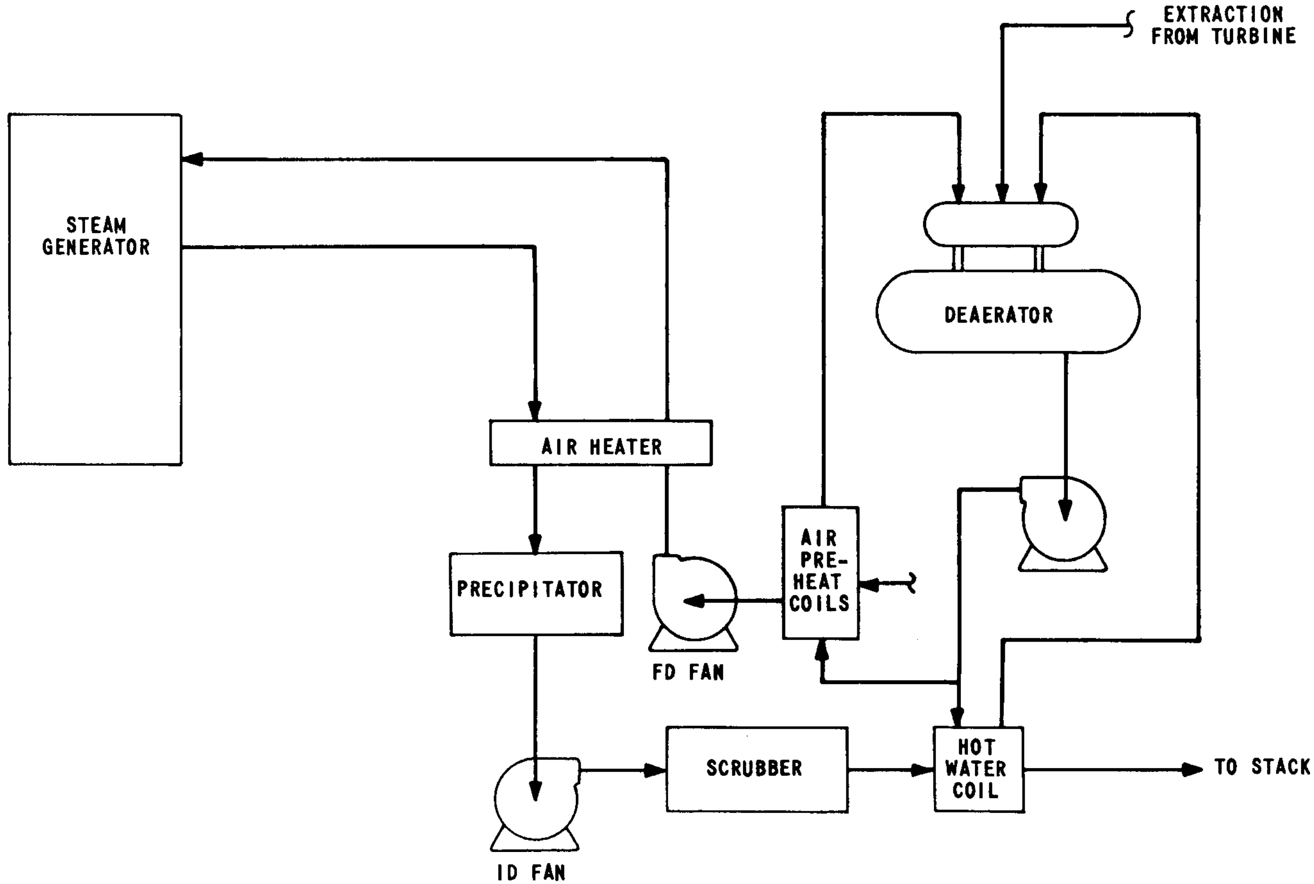
4.8.3 Typical Questions from Utility Management

(1) Question

Would bypass reheat be a feasible alternative for this application?

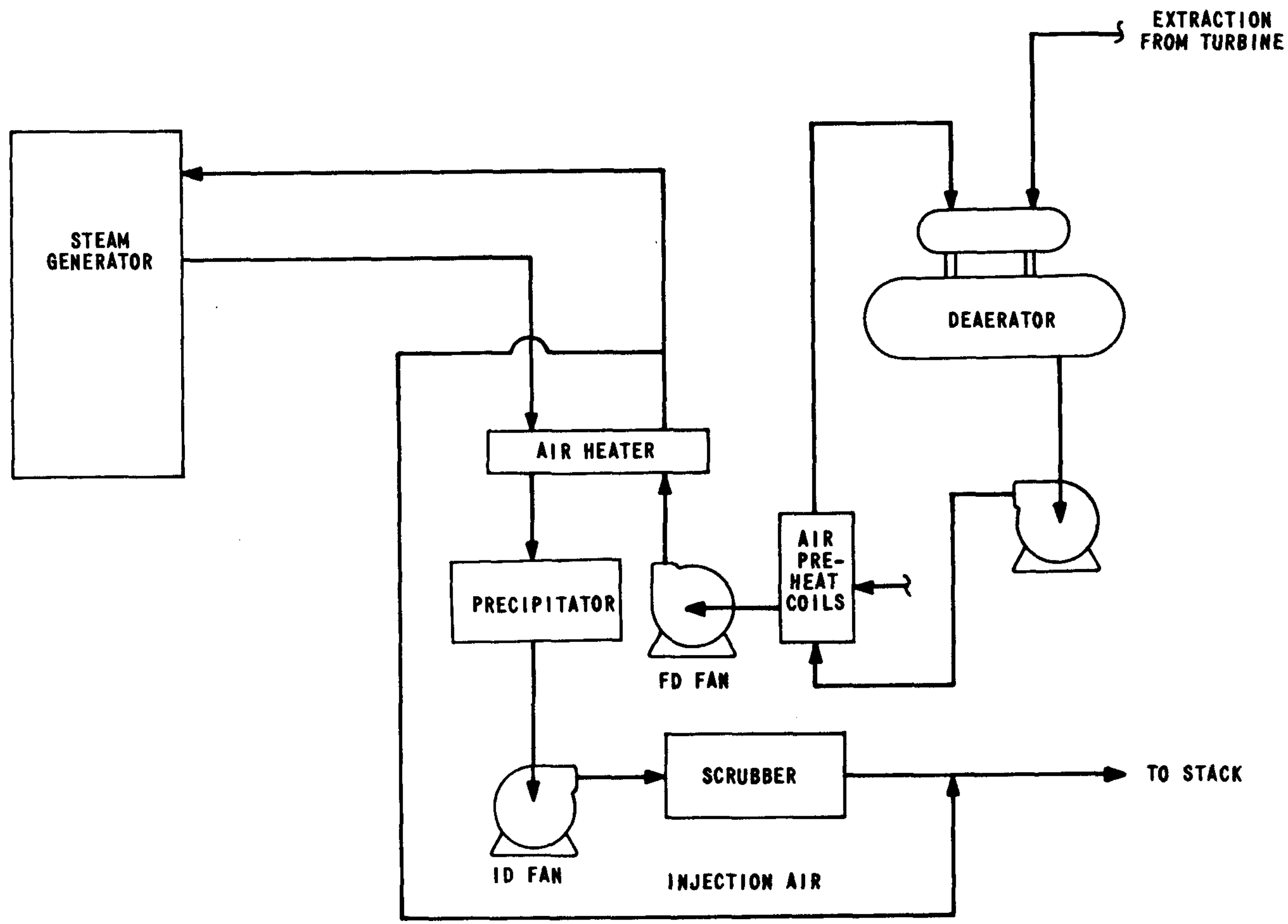
Response

No, regulatory requirement for 90 per cent SO_2 removal efficiency effectively rules out the bypass reheat option (Lime FGD Systems Data Book, Section 4.11.3.4, page 4.11-10).



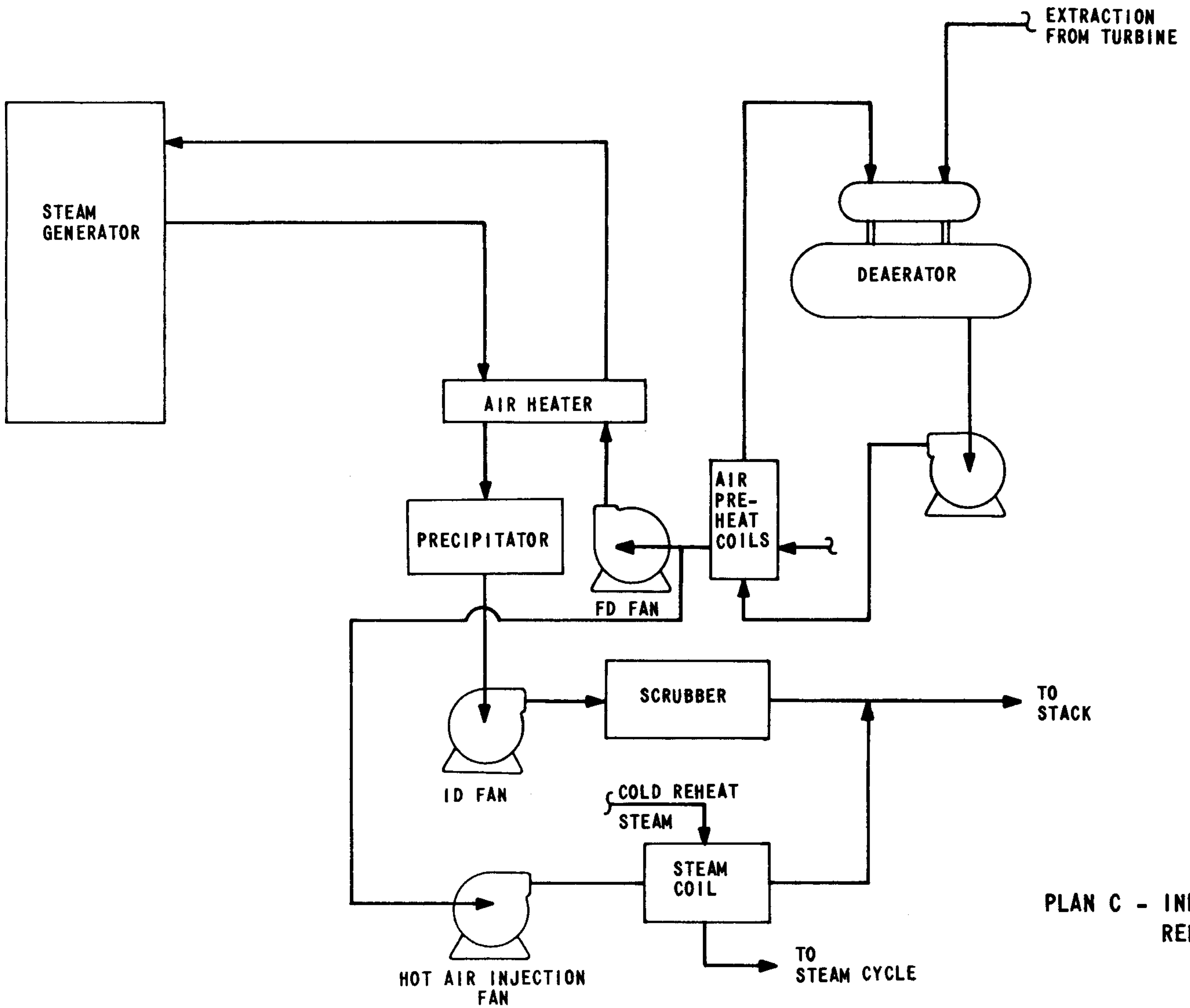
PLAN A - HOT WATER IN-LINE REHEAT

FIGURE 4-6



PLAN B - DIRECT HOT AIR INJECTION

FIGURE 4-7



PLAN C - INDIRECT HOT AIR
REHEAT

FIGURE 4-8

TABLE 4-5. FLUE GAS REHEAT METHODS ADVANTAGES AND DISADVANTAGES

Flue Gas Reheat Method	Advantages	Disadvantages
Plan A--Hot Water In-Line Reheat	(1) Simple in design and installation. (2) Low capital cost and operating cost.	(1) Coil is subject to pluggage. (2) Coil is subject to corrosion due to the wet atmosphere at the flue gas inlet.
Plan B--Direct Hot Air Injection	(1) Eliminates the use of heat exchangers. (2) Addition of relatively dry air slightly lowers the dew point of the flue gas.	(1) Higher capacity forced draft fans required. (2) Larger ducts and stack required to maintain design velocities. (3) Device for mixing the hot air and gas must be located in the wet flue gas stream. (4) Increased ductwork cost.
Plan C--Indirect Hot Air Reheat	(1) Steam coil is located in the air stream and is not subject to pluggage or corrosion. (2) Addition of relatively dry air slightly lowers the dew point of the flue gas.	(1) Additional fan is required for hot air blowing. (2) Larger ducts and stack required to maintain design velocities. (3) Device for mixing the hot air and gas must be located in the wet flue gas stream. (4) Higher energy consumption.

TABLE 4-6. COMPARATIVE CAPITAL AND ANNUAL COSTS OF FLUE GAS REHEAT METHODS

	Plan A - Hot Water In-line Reheat $1,000	Plan B - Direct Hot Air Injection $1,000	Plan C - Indirect Hot Air Injection $1,000
Heating Coil System	630	130	990
Gas Ductwork	BASE	60	120
Hot Air Ductwork	BASE	990	870
Forced Draft Fans and Motors	BASE	110	10
Stack	BASE	100	150
Hot Air Injection Fans and Motors	BASE	BASE	170
TOTAL COMPARATIVE CAPITAL COST	630	1,390	2,310
Indirect Costs @ 25 per cent	160	350	580
TOTAL COMPARATIVE CAPITAL INVESTMENT	790	1,740	2,890
Annual Fixed Charges @ 15 per cent	120	260	430
Comparative Annual Operating Cost	350	700	790
TOTAL COMPARATIVE ANNUAL COST	470	960	1,220
DIFFERENTIAL ANNUAL COST	BASE	490	750

(2) Question

The consulting engineer has recommended reheating the flue gas leaving the scrubber to about 22 C (40 F) above the flue gas dew point. Will this be adequate to attain the effective plume rise and minimize ground-level SO_2 concentrations?

Response

Yes, as explained in the Lime FGD System Data Book (Section 4.11.6, page 4.11-20 and shown on Figure 4.11-10, page 4.11-21) as the scrubber SO_2 removal efficiency increases, the amount of flue gas reheat has less and less effect on reduction of ground-level SO_2 concentration. At 90 per cent SO_2 removal efficiency, an additional 33 C (60 F) of reheat above the 22 C (40 F) recommended would only reduce the ground-level SO_2 concentration approximately 2 per cent.

(3) Question

The captial cost of the heating coil system for Plan C in Table 4-6 is significantly more expensive than for Plan A. Is this practical considering that both plans reheat the flue gas about 22 C (40 F) above the flue gas dew point?

Response

Yes, it is reasonable that the capital cost of the heating coil for Plan C is considerably higher than for Plan A since the heating load for the coil of Plan C is correspondingly higher. The net heat input for Plan C is equal to the heat required to increase an appropriate volume flow of ambient air from 27 C (80 F) to 232 C (450 F) (Lime FGD Systems Data Book, Section 4.11.5.2, page 4.11-19). This Plan will require about 0.25 kilogram (pound) of heated ambient air per kilogram (pound) of flue gas. Heating this large volume of air (25 per cent of the total flue gas flow leaving the scrubber) approximately 370 F will require a larger heating coil than for Plan A and will also consume significantly more energy.

(4) Question

Are any utilities currently reheating flue gas leaving a scrubber with in-line hot water coils? What has been their experience? Do they offer any recommendations to improve the operational and maintenance requirements of the reheat system?

Response

The FGD System installed at the Hawthorn Station of Kansas City Power and Light includes carbon steel in-line hot water reheat coils. No reheater corrosion problems have been reported. Reheater plugging has been a problem. The problem was solved by removing a section of the reheater to facilitate cleaning and maintenance. Currently, it is normal practice to shutdown the scrubber every three days for cleaning the mist eliminator and the reheater. At this installation soot blowing is a heavy maintenance item. The reheat hot water pump is normally started before placing the scrubber in service (Lime FGD Systems Data Book, Section 4.11.11.1, pp. 4.11-25 and 4.11-26).

The following recommendations have been offered (Lime FGD Systems Data Book, Section 4.11.12, page 4.11-29).

- Soot blowers should be installed.
- An efficient mist eliminator should be installed to decrease the heating load on the reheat system.
- Gas should be heated 14 C (25 F) to 28 C (50 F) to prevent downstream water condensation.

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5.0 PRELIMINARY SLUDGE DISPOSAL SYSTEM STUDY

5.1 OBJECTIVE

The objective of this section is to review available methods of sludge disposal and select the most advantageous system for the hypothetical station described in Section 2.0. Figure 5-1 presents schematically the general decision alternatives considered in the selection and design of a sludge disposal system. This section only addresses the first three steps shown, which are the processing selection, transportation selection, and disposal selection. The sludge disposal equipment design criteria for the selected system which contains the remaining steps will be presented in Section 6.0.

5.2 REQUIREMENTS

(1) The sludge disposal systems will be evaluated based on the assumptions listed in the Case Study Design Basis presented in Section 2.0.

(2) The solid wastes considered will include the following.

- Scrubber solids
- Fly ash
- Bottom ash
- Coal pulverizer rejects

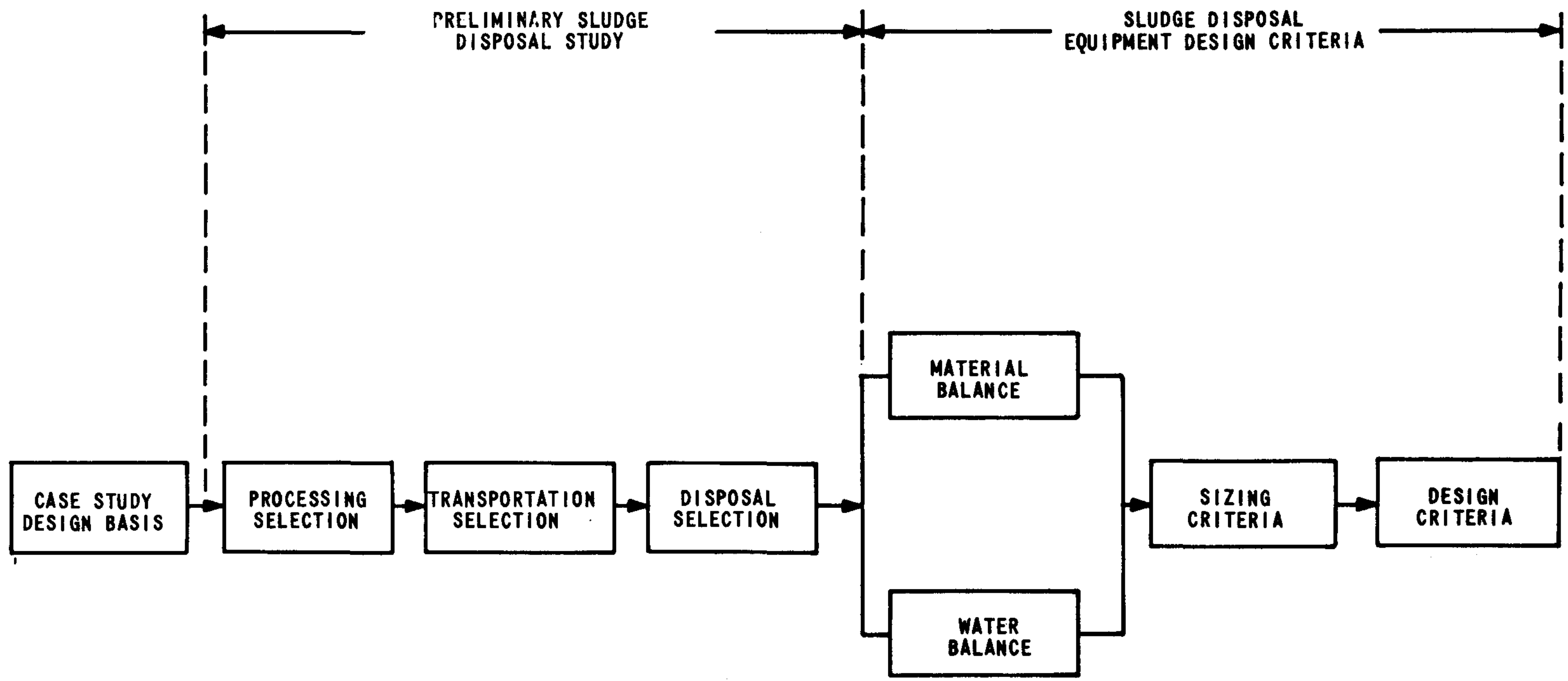
(3) All solid wastes will be placed in a common site for final disposal. However, bottom ash and coal pulverizer rejects will be collected at an interim site to minimize the impact on the plant's makeup water requirements.

(4) Solid waste quantities will be based on the FGD scrubber sludge quantities shown on Table 4-2 in Section 4.0.

5.3 SOLID WASTE QUANTITIES

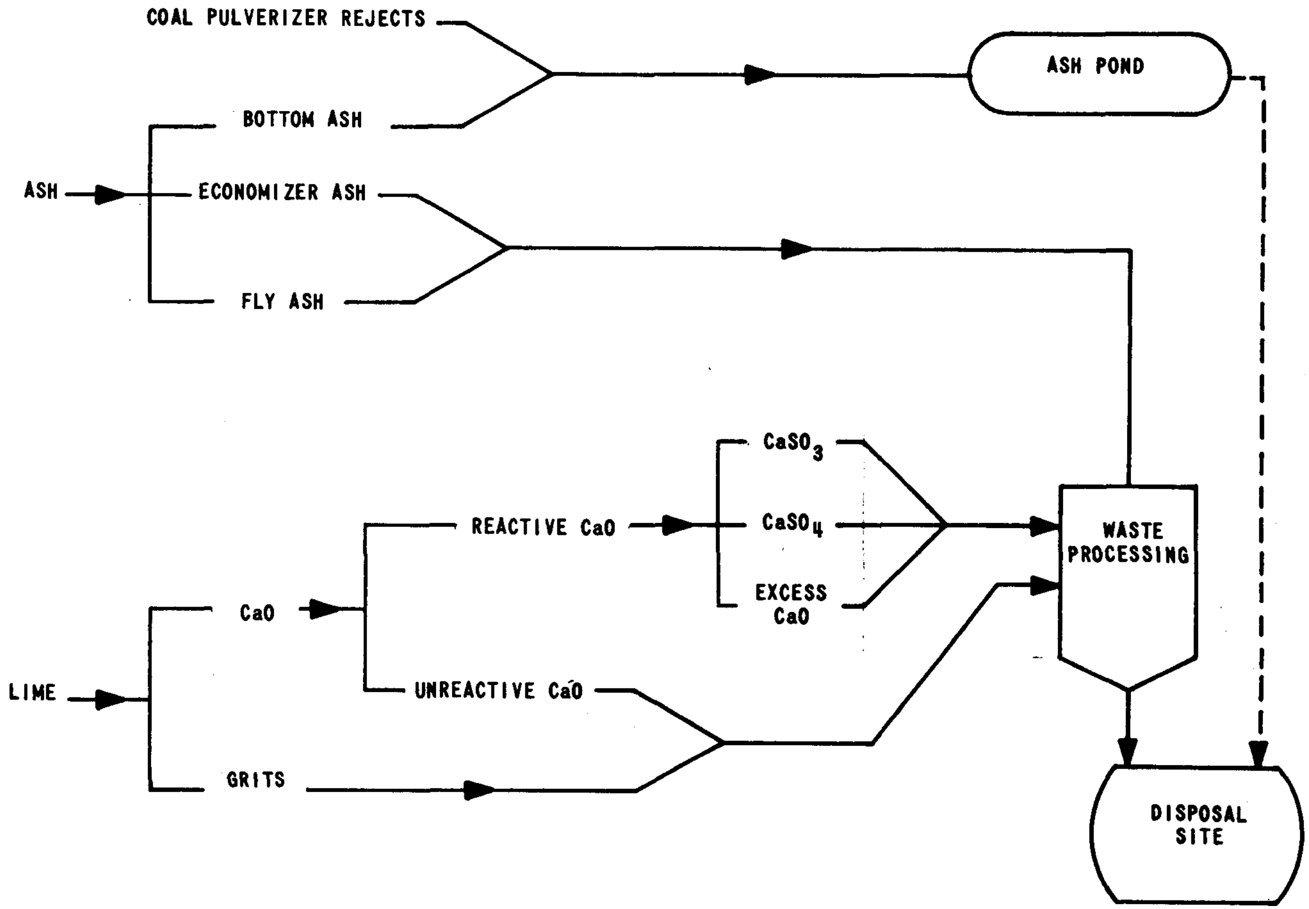
In addition to the mixture of calcium sulfite, calcium sulfate and inert materials from the FGD process, the scrubber slurry blowdown stream may include some volatile components washed from the flue gas. However, the amount of solid wastes produced primarily depends upon the desulfurization reaction products and unreacted additives. The origin and flow of the various components of the solid wastes is shown on Figure 5-2.

The estimated quantities of solid wastes produced hourly by one 500 MW unit at rated capacity are presented in Table 5-1. Also, the annual quantities of solid wastes produced by the unit when operating in accordance with the prescribed load



GENERAL DECISION ALTERNATIVES REQUIRED
TO SELECT AND DESIGN A SLUDGE DISPOSAL SYSTEM

FIGURE 5-1



ORIGIN AND FLOW OF SOLID WASTES

FIGURE 5-2

TABLE 5-1. SOLID WASTE QUANTITIES

	Low Sulfur Coal	High Sulfur Coal	Nominal Coal
Hourly Production* 10^3 kg/hr (tons/hour)			
FGD Sludge Solids**	16.4 (18.1)	33.9 (37.4)	31.6 (34.8)
Fly Ash	24.9 (27.5)	25.8 (28.4)	26.9 (29.7)
Economizer Ash	1.5 (1.7)	1.6 (1.8)	1.7 (1.9)
Bottom Ash	9.3 (10.3)	9.6 (10.6)	10.1 (11.1)
Pulverizer Rejects	1.0 (1.1)	1.0 (1.1)	1.1 (1.2)
Annual Production*** 10^3 kg/yr (tons/year)			
FGD Sludge Solids**	95,300 (105,100)	196,600 (216,700)	182,600 (201,300)
Fly Ash	137,400 (151,400)	141,500 (156,000)	148,000 (163,100)
Economizer Ash	7,300 (8,000)	7,400 (8,200)	7,800 (8,600)
Bottom Ash	36,100 (39,800)	37,300 (41,100)	38,900 (42,900)
Pulverizer Rejects	5,600 (6,200)	5,800 (6,400)	6,100 (6,700)

*Sludge processing system design basis; one 500 MW unit at rated capacity.

**FGD sludge solids include lime slaker grits and unreacted lime.

***Sludge disposal system design basis; one 500 MW unit at 66 per cent annual capacity factor.

model are presented. These values were derived using the procedure detailed in Section 4 of the FGD Sludge Disposal Manual. All values are based on the following.

(1) One 500 MW unit operating at rated capacity and at 66 per cent of rated capacity.

(2) The unit net heat rate is 10,761 kJ (10,200 Btu) per kWh.

(3) The coal properties are presented in Table 2-3 of Section 2.0.

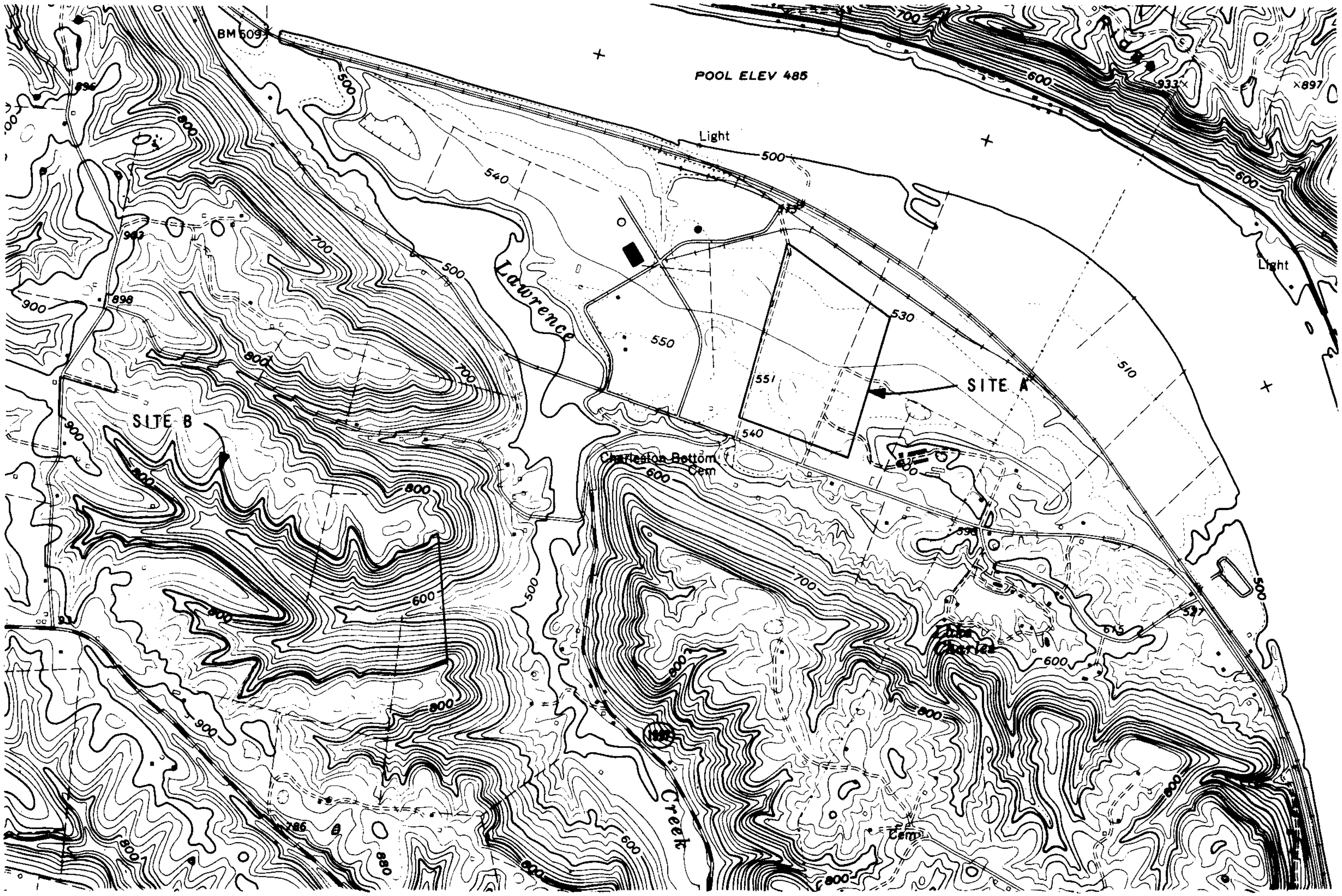
Deviation from the assumed load model; the use of alternative coals with different heating values, sulfur, or ash content; or any commercial sale of the solid wastes will alter the quantity of solids for disposal. Minor solid waste quantity variations can be expected due to fluctuations in performance of the steam generator, scrubber, particulate removal system, and pulverizer equipment. Such fluctuations are the result of variations in maintenance programs and operating procedures.

5.4 DISPOSAL SITE SELECTION

The plant site is located on a major river within 10 miles of a town. With the exception of the plant site, the area is very hilly. Two potential disposal areas have been identified and are outlined on Figure 5-3.

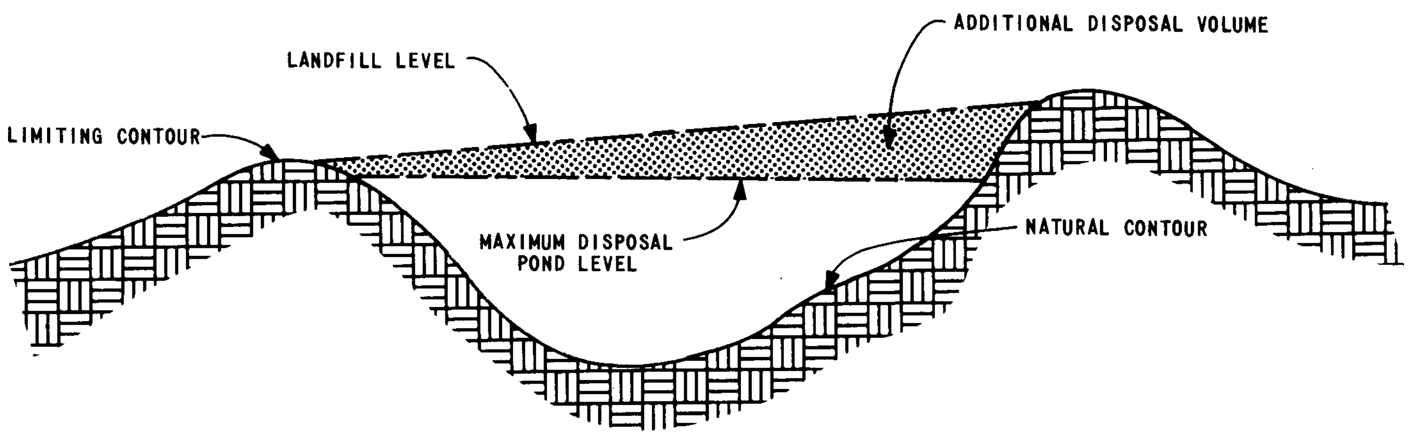
Site A is located within the existing boundaries of the plant. The topsoil consists of approximately 40 metres (130-feet) of clays, gravels, sand, and silt overlying the bedrock. Groundwater is abundant because of the proximity of the site to the river. This site is suitable for either pond or landfill disposal provided there is adequate sealing. There are about 324,000 square metres (80 acres) available for storage and pond depth or landfill stack height of 14 metres (45 feet) is practical. Site A has the advantage of proximity to the plant and the disadvantage of being suitable for other future plant development. The impact on animal and plant life would be very limited since it is within the plant boundaries and will be disturbed to some extent by construction activities. Its use for solid waste disposal could impair future plant expansion even after reclamation.

Site B is located in a valley in the hilly terrain approximately 2,400 metres (1.5 miles) southwest of the plant site. The valley provides drainage for about 1,619,000 square metres (400 acres) but there is little indication of groundwater in the area. Approximately 43,200,000 cubic metres (35,000 acre-feet) are available if the site were landfilled to a maximum elevation of 274 metres (900 feet) MSL. To achieve this capacity, the solid wastes would have to be mounded above the limiting contour as shown in Figure 5-4. Due to the limestone formations near the surrounding ridges, maximum pond elevation would be limited to 250 metres (820 feet) MSL. The resulting impounded volume would be approximately 22,200,000 cubic metres (18,000 acre-feet). The site is forested with species typcial throughout this



DISPOSAL SITE ALTERNATIVES

FIGURE 5-3



SOLID WASTE LANDFILL VOLUME

FIGURE 5-4

locale. The topsoil is generally 15.2-centimetres (6-inches) deep with underlying clays to bedrock. The impact on animal species inhabiting this site will be substantial; however, similar habitat is available in the many nearby valleys.

The disposal volumes available for solid waste disposal at both potential sites are summarized in Table 5-2. The landfill capacities shown for Site B in Table 5-2 include allowances for mounding.

Because of the thixotropic property of sulfite-rich sludges produced in lime scrubbers, the maximum achievable solids density is less in a disposal pond than in a landfill. Even with fly ash added to the sludge for stabilization, the density of the settled sludge-fly ash mixture in a disposal pond will be about 880 kilograms of solids per cubic metre (55 pounds per cubic foot). By dewatering the FGD sludge and then mixing with dry fly ash, a density of 1,300 kilograms of solids per cubic metre (80 pounds per cubic foot) is achievable in a stablized landfill.

Lifetime (30-year) disposal volumes are presented in Table 5-3. The values are given for one 500 MW unit operating in accordance with the specified load model and burning that coal which yields the largest total volume of wastes. Two 500 MW units would require the volumes listed in Table 5-3. Fly ash is assumed to be mixed with the FGD sludge prior to disposal. Bottom ash and pulverizer rejects are assumed to be periodically sluiced to an ash pond and later transported to the disposal pond or landfill. The total lifetime solid waste volume for various processing options are compared on Figure 5-5.

Figure 5-5 shows that regardless of method of disposal, Site A is inadequate for disposing of the estimated lifetime solid waste quantities from one 500 MW unit. Site B, on the other hand, is more than adequate regardless of method of disposal. For this reason, the alternate methods of solid waste disposal will be evaluated based on developing Site B only. Site A will remain available to provide a potential location for the following.

- Interim ash pond for bottom ash and pulverizer rejects.
- Temporary sludge disposal area.
- Future plant expansion.

5.5 SLUDGE DISPOSAL ALTERNATIVES

The methods used to process, transport and dispose of FGD sludge and other solid waste must mesh with land availability, topography, and many other site imposed constraints as well as regulatory requirements. As was the case in the selection of a scrubber, the FGD sludge disposal alternatives are many as shown on Figure 5-6.* Furthermore, decisions made in one area of the sludge disposal system feedback into the other areas.

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*From Figure 1-1 in the FGD Sludge Disposal Manual.

TABLE 5-2. AVAILABLE DISPOSAL VOLUMES

	Volume cubic metres (acre-feet)			
	Pond		Landfill*	
Site A	4,400,000	(3,600)	4,400,000	(3,600)
Site B	22,200,000	(18,000)	43,200,000	(35,000)

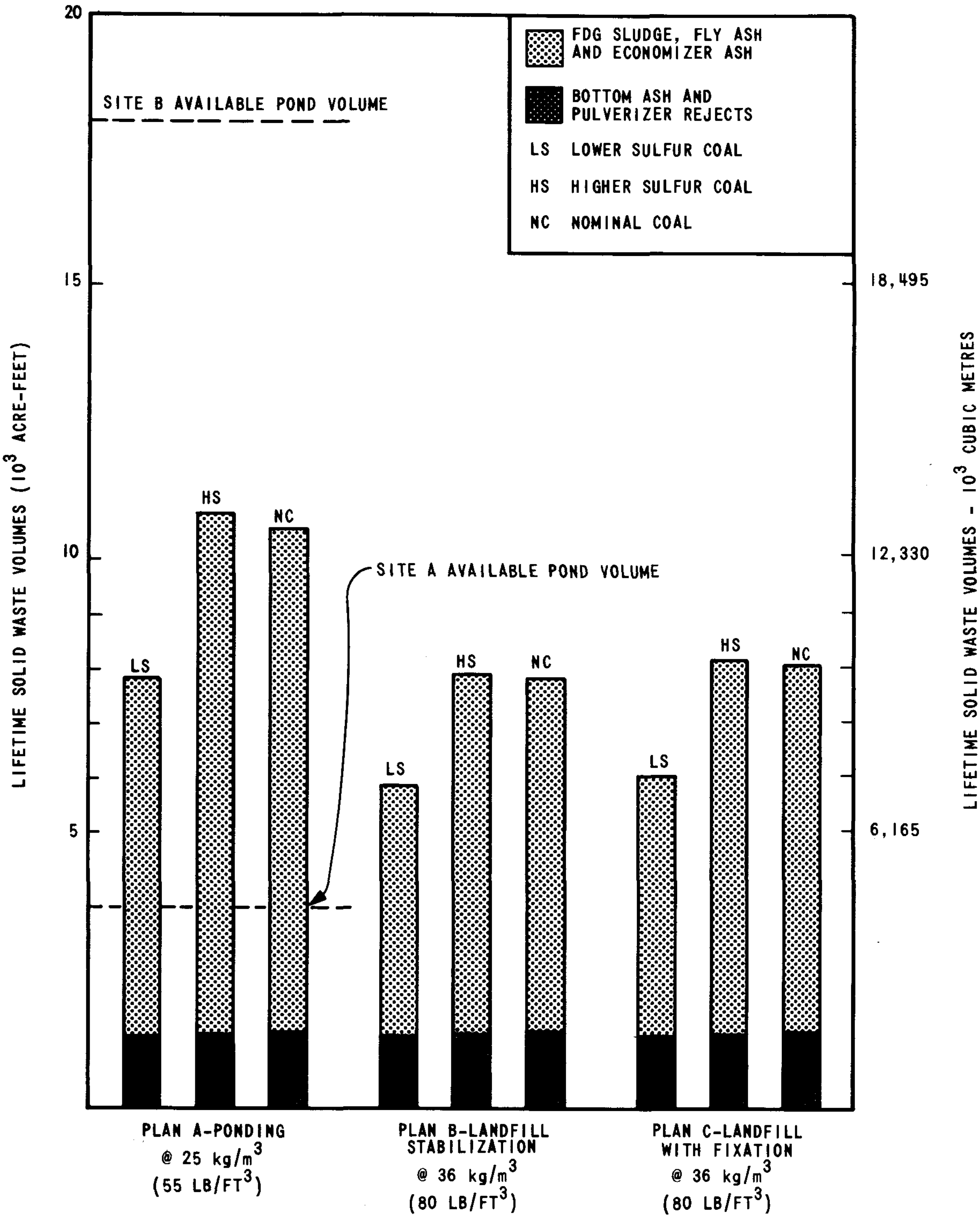
*Includes allowance for mounding above limiting pond contours, if required.

TABLE 5-3. LIFETIME SOLID WASTE VOLUMES FOR ONE 500 MW UNIT

Disposal Option	Lifetime Waste Volume cubic metres (acre-feet)* Lower Sulfur Coal	Higher Sulfur Coal	Nominal Coal
• Pond	9,600,000 (7,800)	13,300,000 (10,800)	13,100,000 (10,600)
• Landfill			
With Stabilization	7,200,000 (5,800)	9,600,000 (7,800)	9,600,000 (7,800)
With Fixation**	7,500,000 (6,050)	10,100,000 (8,200)	10,000,000 (8,100)

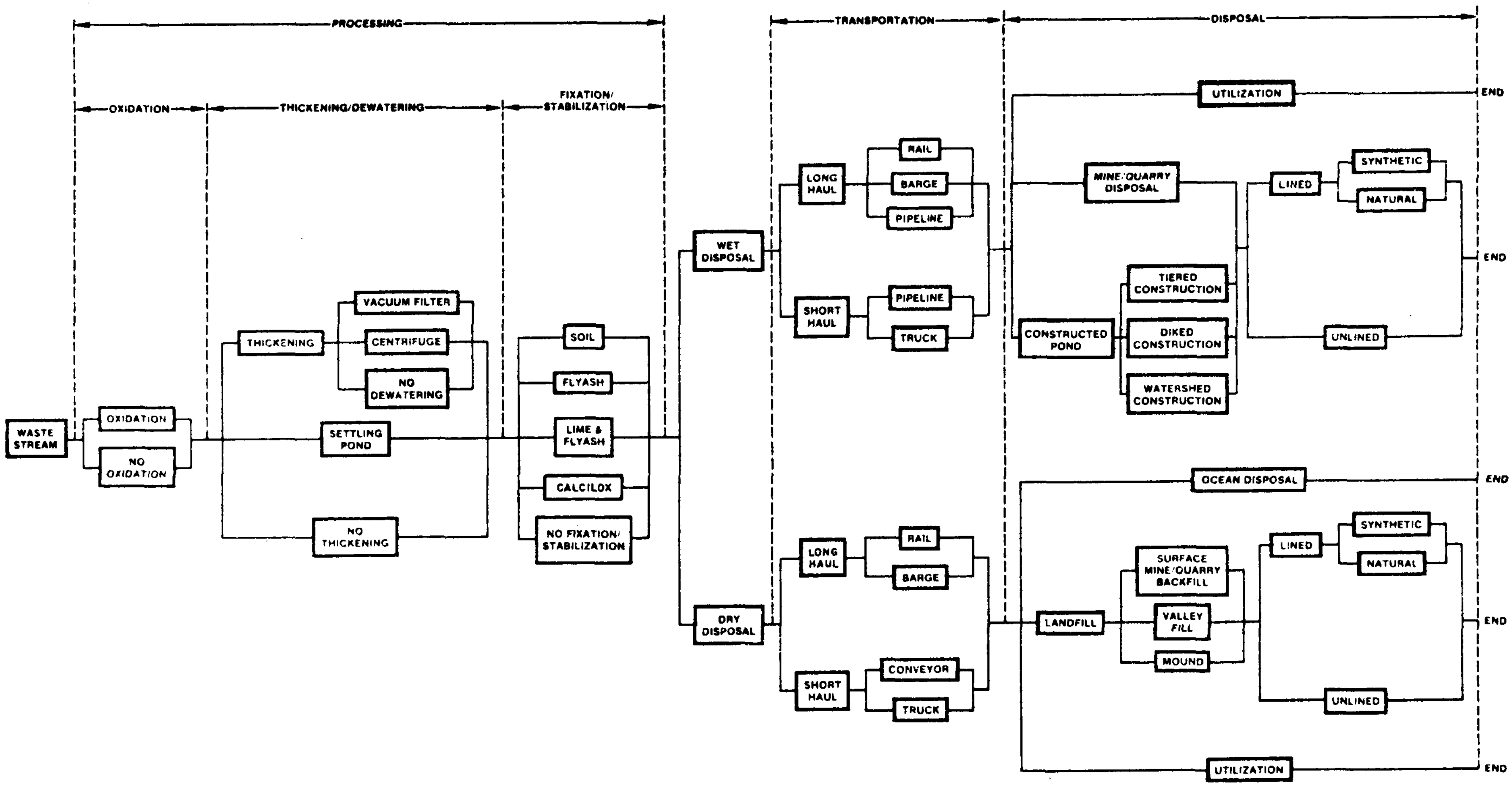
*Based on one 500 MW unit operating at an average annual capacity factor of 66 per cent of rated capacity.

**The fixation process is described in Section 5.6.3.



LIFETIME SOLID WASTE VOLUMES
ONE 500 MW UNIT AT 66 PER CENT
OF RATED CAPACITY

FIGURE 5-5



SLUDGE DISPOSAL ALTERNATIVES

FIGURE 5-6

The selection of a process for sludge disposal must also interface with the selection of the FGD scrubber. The products from a lime scrubber are different than those from a limestone system and with other scrubber systems. The sludge disposal system selection must also account for other material requirements such as fly ash availability for stabilization in landfill disposal.

Once other constraints have been defined; the sludge disposal process, the means of waste transport, and the method of disposal can be selected. FGD sludge processing may be further subdivided into three processing steps: (1) supplemental forced oxidation, (2) thickening and dewatering, and (3) stabilization or fixation. The decision of which processing steps to use and which to bypass depends on the constituents of the FGD sludge and the viability of various disposal methods. The means of transport is then selected to be compatible with both the processing and the disposal methods.

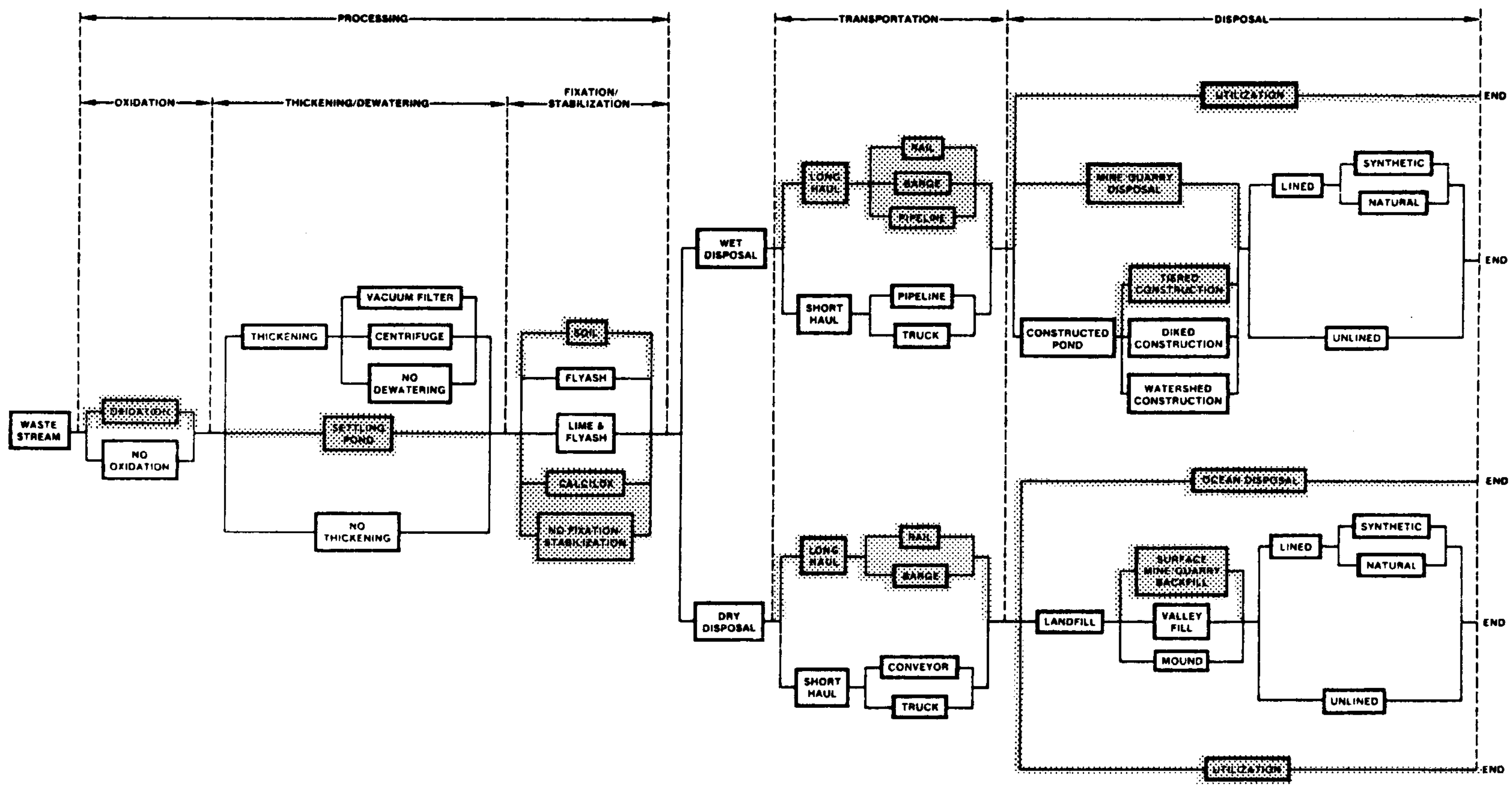
Given the design basis presented in Section 2.0 assumed for this case study, the lime FGD system selected in Section 3.0 and the constraints imposed by site conditions (see Section 6.0 of the FGD Sludge Disposal Manual), the feasible options are selected from the possible alternatives. The feasible options are illustrated on Figure 5-7.

The method of FGD sludge disposal for this case study is limited either to ponding or landfilling since there are no local markets for the FGD sludge (see Section 15 of the FGD Sludge Disposal Manual), and since neither mine nor ocean disposal is available.

Processing options that remain feasible therefore must accommodate both wet and dry disposal. However, the selection of a lime scrubber eliminates forced oxidation of calcium sulfite to calcium sulfate from further consideration since experience has shown it to be relatively ineffective. Thickening and dewatering would be performed for landfill disposal but not for ponding. Settling ponds are not viable based on site conditions and liner requirements. Stabilization by addition of soil and fixation with the CALCILOX process are eliminated from further consideration in this case study because of supply limitation for the required feed materials. And, since there is no current market for fly ash, it will be combined with the FGD sludge for disposal. The transport distances to either site is minimal and therefore only the short haul options are applicable.

5.6 SLUDGE DISPOSAL SYSTEM SELECTION

Since both ponding and landfill are feasible options for sludge disposal, the details of alternate sludge processing systems will be specified and evaluated. The following three alternate systems represent the range of viable options.



FEASIBLE SLUDGE DISPOSAL ALTERNATIVES

FIGURE 5-7

(1) System A--Ponding

(2) System B--Landfill with Stabilization

(3) System C--Landfill with Fixation

5.6.1 System A--Ponding

In the ponding system, the FGD sludge is pumped to an impoundment. The schematic for this system is presented in Figure 5-8. Because of the pumping cost at the distance involved, the FGD sludge is passed through a thickener to reduce the amount of water being transported. Fly ash and economizer ash is mixed with the sludge prior to pumping to the pond.

The settled sludge and fly ash mixture will have a permeability on the order of 1×10^{-5} cm/sec. Due to the potential 120,000 Pascals (40 feet) of hydraulic head with the ponding alternative, a synthetic liner will be provided. The liner will be constructed of hypalon with a thickness of 30 mils.

Bottom ash and pulverizer rejects will be sluiced to an interim ash pond. The ash pond will be dredged once a year with the bottom ash and rejects transported to the sludge pond for long-term disposal.

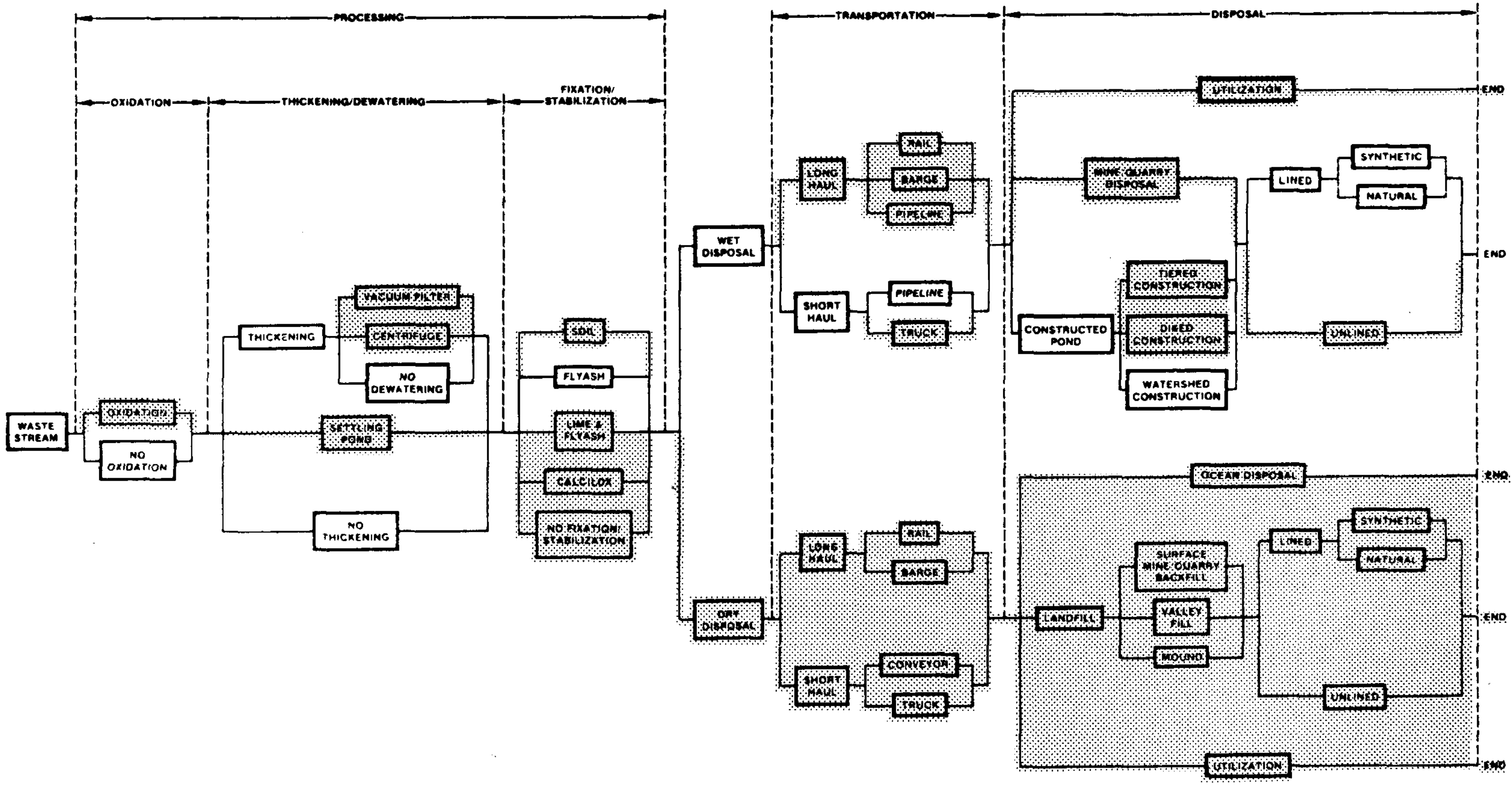
5.6.2 System B--Landfill with Stabilization

In the landfill with stabilization system, the FGD sludge will be processed in two stages (thickening then vacuum filtration) to remove excess water in order to reduce the overall volume of the solid wastes. This dried sludge will then be mixed with dry fly ash and economizer ash to further increase the solids fraction in the sludge. After transport to the disposal site, the sludge-ash mixture will be deposited in a landfill. The schematic for this system is shown in Figure 5-9.

In preparation for dry handling, FGD sludge will be dewatered in a thickener to increase the solids weight fraction of the sludge. The thickener overflow will be returned to the scrubber for reuse. Surge capacity must be provided to accommodate variations in plant output. In addition to routine preventative maintenance and repair of mechanical failures, thickeners may occasionally have to be removed from service to remove any sludge that accumulates in the bottom. For this case study it is assumed that two half-capacity thickeners will be provided in parallel for the 500 MW unit. Each thickener will be approximately 64 metres (210 feet) in diameter.

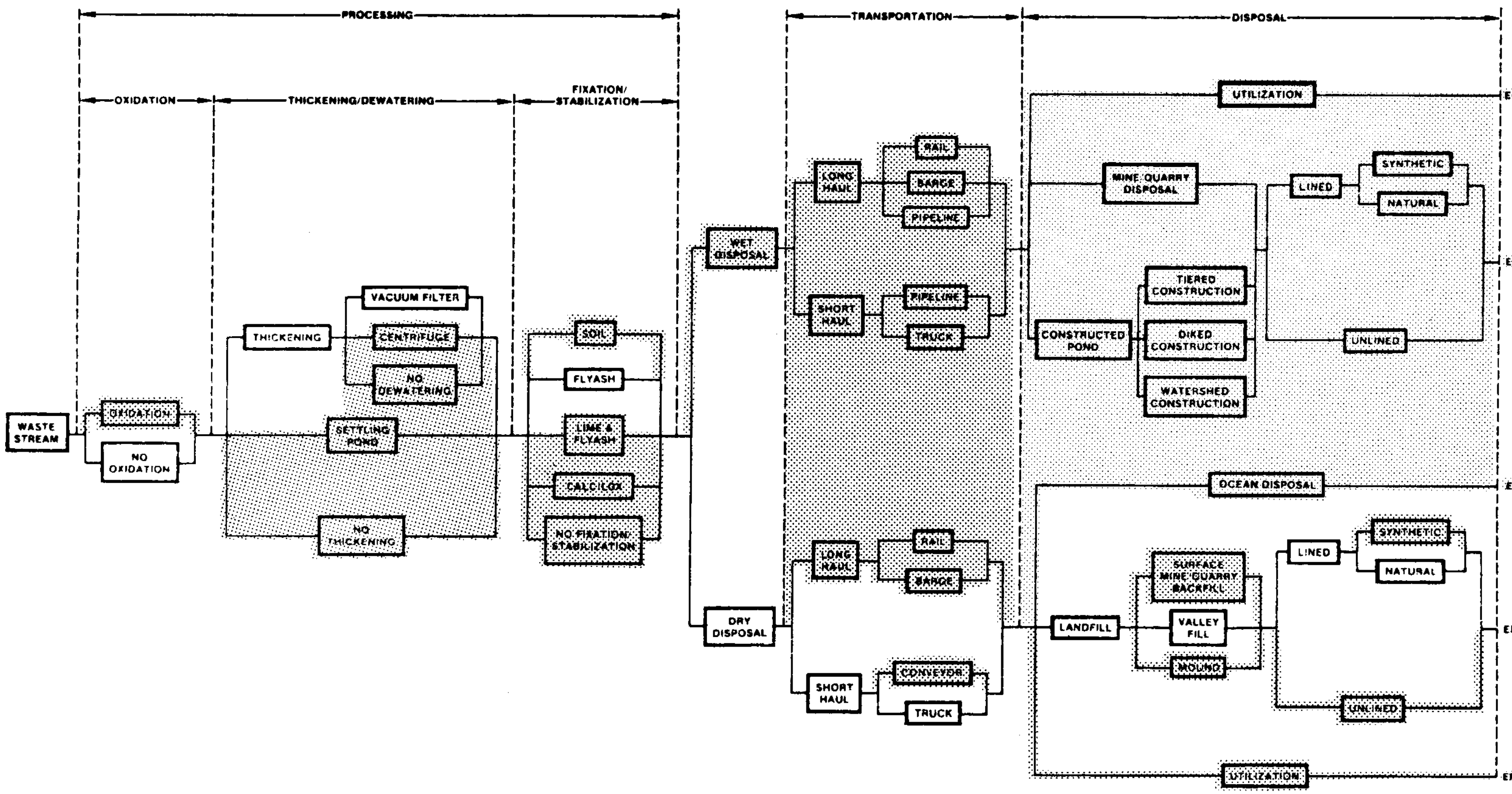
Following discharge from the thickener, the FGD sludge slurry will be piped to a vacuum filter for additional dewatering. The vacuum pump must be protected from filtrate impingement. Low pressure air will be employed to remove the dewatered sludge cake from the filter medium.

Because of its thixotropic property, the dewatered sludge tends to reliquify during subsequent handling in transport to the disposal site. This putty-like



PLAN A - PONDING

FIGURE 5-8



PLAN B - LANDFILL WITH STABILIZATION

FIGURE 5-9

consistency makes the sludge very difficult to handle. Handling characteristics will be enhanced by mechanical mixing with other materials such as dry fly ash to induce physical changes which yield improved structural properties. Dewatered FGD sludge and the stabilization additive (dry fly ash) will be mixed in a muller mixer. The schematic for this plan is given in Figure 5-10.

Stabilization is required to impart desirable characteristics such as moisture content and physical stability. Even though it does not eliminate all environmental concerns associated with sludge disposal, reclamation of the disposal site can be facilitated by stabilization.

The sludge-fly ash mixture will be transported to the disposal site by truck. The change in elevation and the distance between the plant and disposal site preclude the use of a conveyor on an economic basis. Interim storage of dewatered sludge is required to accommodate extended periods when the transport equipment is out of service for maintenance and at night or on weekends when landfill and transport operations are temporarily suspended.

The permeability of untreated sludge is the same as in the ponding case, approximately 1×10^{-5} cm/sec. Therefore, a liner is required for landfilling with stabilization to meet the design basis of 1×10^{-6} cm/sec leakage. Given the site geology of existing clay, the lack of potential hydraulic head with the stabilized landfill alternative, and the high cost of synthetic liners, a 46 centimetre (18-inch) thick natural clay liner will be used.

Bottom ash and pulverizer rejects will be handled in the same manner as in the System A ponding system.

5.6.3 System C--Landfill with Fixation

In the landfill with fixation system, additional improvement of the FGD sludge properties may be achieved by introducing an agent which fixes the contained water and sludge solids by means of a chemical reaction. This reaction produces a dry stable material suitable for landfilling. The agent normally added for FGD sludge fixation is lime. This disposal plan is illustrated on Figure 5-11.

The fly ashes of some western coals contains sufficient calcium oxide (CaO) to achieve fixation without the addition of lime. However, the CaO content in the fly ash from the coal for this plant is not sufficent to produce fixed sludge. Therefore, it will be necessary to add both lime (for FGD sludge fixation) and fly ash (to reduce the moisture content to the desired levels). Studies[1,2] have shown that

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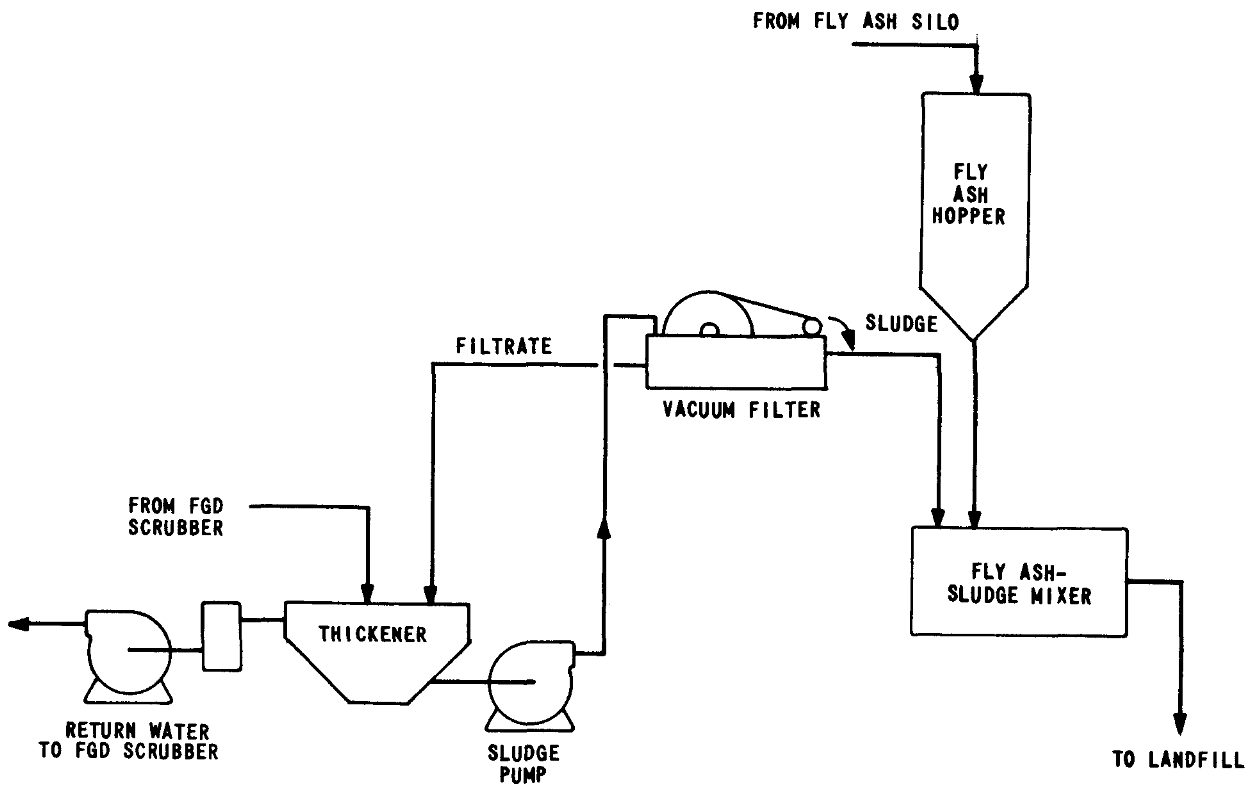
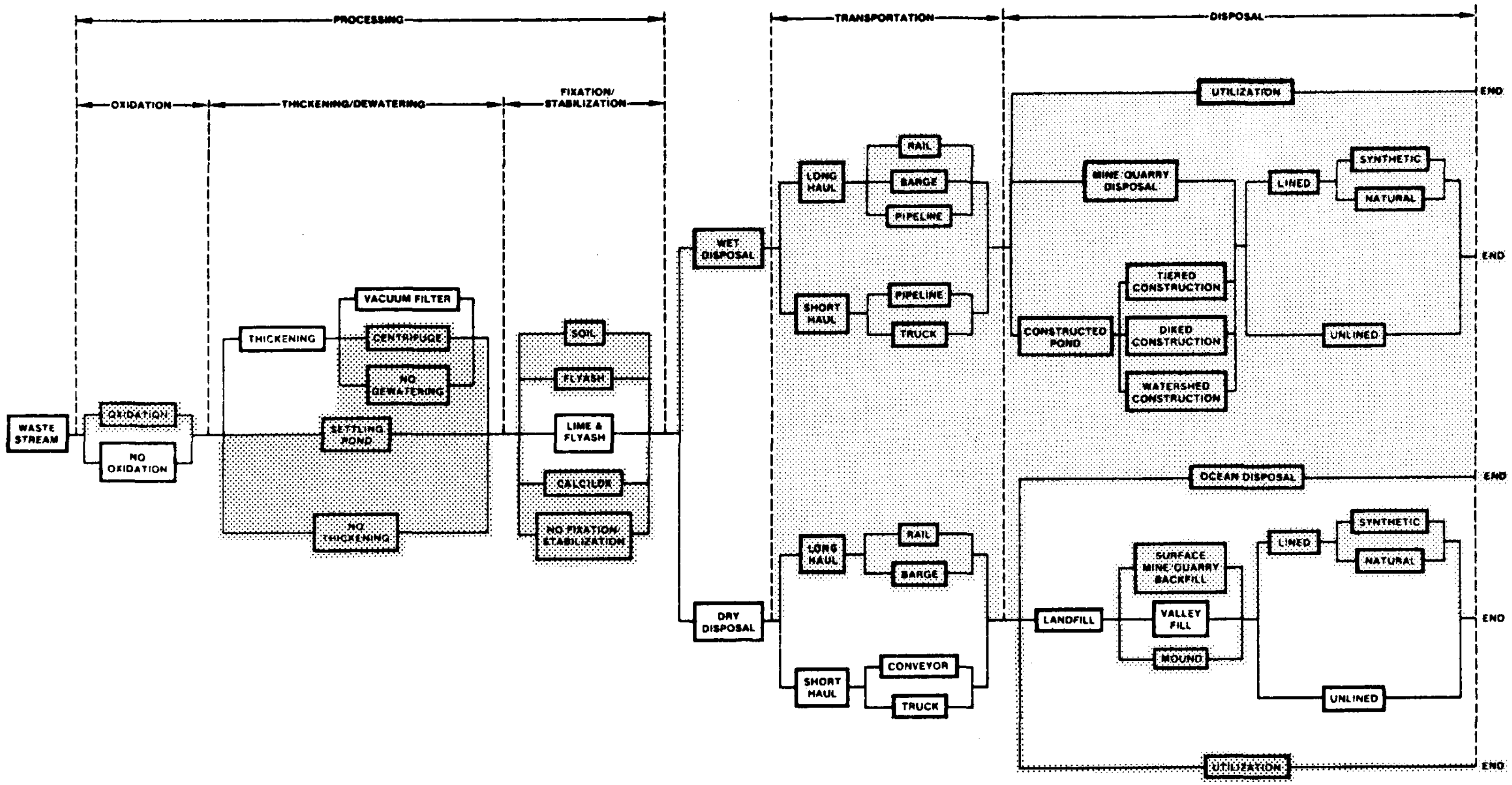
[1]Michael Baker, Inc., "State-of-the Art of FGD Sludge Fixation", EPRI Report FP-671, Palo Alto, California, January, 1978.

[2]R. W. Goodwin, et al., "Options for Treating and Disposing of Scrubber Sludge," Research-Cottrell Technical Bulletin, Bound Brook, New Jersey, April, 1978.



FLY ASH AND FGD SLUDGE DISPOSAL
SYSTEM-LANDFILL WITH STABILIZATION

FIGURE 5-10



PLAN C - LANDFILL WITH FIXATION

FIGURE 5-11

the bearing strength of compacted fixed FGD sludges can exceed 430,900 Pascals (4.5 tons per square foot), and permeability can be reduced to less than 1 x 10^{-6} cm/sec. Therefore, it is assumed that no liner is required.

Lime will be added in the same mixer that is used for the addition of the stabilization additive and at a rate of 4 per cent by weight of the sludge solids. A schematic of the processing system is shown on Figure 5-12. The resulting sludge/fly ash/lime mixture will not reliquify. A compacted density of 1,300 kilograms of dry solids per cubic metre (80 pounds per cubic foot) can be attained. The mixture's permeability of about 1 x 10^{-6} cm/sec, resulting from the fixation process, is sufficient to preclude the need for a liner at the disposal site.

The nature of the chemical reaction that produces fixation is similar to that which occurs in cement. However, the fixation reaction is slower and requires a few days to cure. After processing the wastes will be transported to the disposal site by truck. Loading of the trucks will be accomplished with a front-end loader. The sludge mixture must set for a few days before placement to allow the fixation reaction to proceed. The sludge mixture will be placed in the landfill with dozers and compacted. Maximum strength is attained in 60 to 90 days. Some fixed sludges may tend to reliquify when handled extensively. However, the sludge will resolidify after handling is terminated.

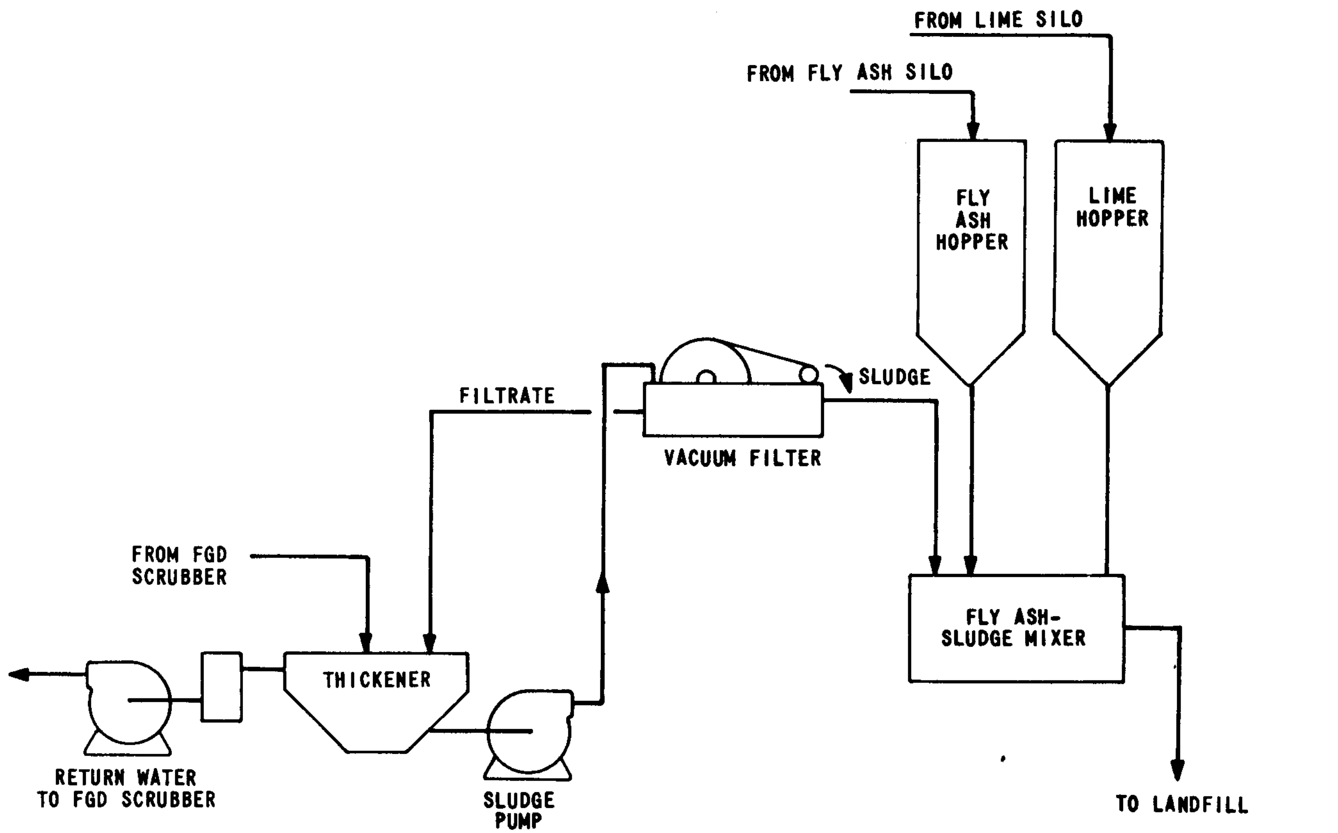
Reclamation of fixed-sludge disposal areas is common. The material strength is sufficient to support one-story buildings and similar structures. Reclaimed disposal areas may also be developed into parks and other recreational facilities. Even though long-term monitoring may be required, perpetual maintenance will not be necessary.

Bottom ash and pulverizer rejects will be handled in the same manner as in the System A ponding plan.

5.6.4 Summary of Alternate Systems

The selection of a sludge disposal system ultimately rests on comparative costs of the alternatives available. Any alternative, in order to be eligible for consideration must satisfy all design basis, meet all regulatory requirements, and be compatible with site conditions or any unique constraints imposed by the utility. A levelized annual cost comparison for the three alternate systems is summarized in Table 5-4. (See Section 4 of the Sludge Manual for additional information on cost estimates.)

System C using landfill with fixation is the most advantageous solid waste management system.



FLY ASH AND FGD SLUDGE DISPOSAL SYSTEM-LANDFILL WITH FIXATION

FIGURE 5-12

TABLE 5-4. ALTERNATE SLUDGE DISPOSAL SYSTEMS--SUMMARY OF COMPARATIVE LEVELIZED ANNUAL COSTS

	System A--Ponding ($1,000)	System B--Landfill With Stabilization ($1,000)	System C--Landfill With Fixation ($1,000)
Total Comparative Capital Costs	36,902	20,488	17,210
Levelized Fixed Charges	5,535	3,073	2,582
Levelized Annual Operating Costs	6,978	8,339	8,437
Total Levelized Annual Costs	12,513	11,412	11,019
- mills/kWh*	4.33	3.95	3.81
- $/1,000 kg ($/ton) solid waste**	32.64 (29.61)	29.76 (27.00)	28.74 (26.07)
Differential Levelized Annual Costs	1,494	393	Base
- mills/kWh	.52	.14	Base
- $/1,000 kg ($/ton) solid waste	3.90 (3.54)	1.02 (.93)	Base

*$2,890,000,000 kWh

**383,400,000 kg/year (422,600 tons/year)

5.7 CASE STUDY SITUATION #2

5.7.1 Situation Objective

The objectives of this case study situation are as follows.

(1) Provide an example of the role of generation engineering in the review process of the lime FGD Sludge Disposal Preliminary Study document.

(2) Illustrate the manner in which the FGD Sludge Disposal Manual can be used to evaluate the consulting engineer's recommendations.

5.7.2 Situation Description

As shown in Step 2 of the project coordination sequence of Figure 1-1, the Sludge Disposal Preliminary Study is evaluated by generation engineering prior to issue as a completed document. During the review and comment process, utility generation engineering questioned the consulting engineer's recommendations regarding the costs of ponding and landfill with stabilization presented in Table 5-4.

5.7.3 Typical Questions

(1) Question

Considering Plan A, the ponding alternative, how can thickening be justified since Figure 14-9 of the FGD Sludge Disposal Manual (page 14-22) shows no thickening to be economically advantageous for distances less than approximately 4,000 metres (2.5 miles)?

Response

Even though the site is located 2,400 metres (1.5 miles) from the plant, it is necessary to convert the head loss due to the more than 90 metres (300 feet) of elevation change into head losses for an equivalent length of straight and level pipe. The utility generation engineer can correct the overland distance to include this elevation change head loss. In addition, the generation engineer can also account for other differences between the parameters used in this study and the assumptions which serve as a basis for Figure 14-9. For this study these differences include a scrubber discharge of 10 per cent solids and a thickener underflow of 30 per cent solids versus 15 per cent and 35 per cent, respectively for the development of Figure 14-9.

By knowing the type and size of pipe to be used, the flow, and the elevation change, the utility generation engineer can calculate an equivalent level distance to the disposal area for his particular situation. For this case study, a total equivalent distance of 6,400 metres (4.0 miles) is determined. Therefore, the appropriate capital investment correction factor is 1.45 without thickening and 1.37 with thickening. Similarly, the annual revenue correction factor is 1.52 and 1.48 without and with thickening, respectively. In other words, thickening the sludge will result in a lower capital investment and lower annual revenue requirement than pumping unthickened sludge.

(2) Question

What are the appropriate capital and annual cost correction factors to use for the Hypalon 0.76 mm (30 mils) pond liner and the 46 centimetres (18-inch) natural clay liner for the landfill with stabilization?

Response

The utility generation engineer must adjust the figures in Section 14 of the Sludge Manual for the particular requirements at the selected site.

Figure 7-15 of the FGD Sludge Disposal Manual shows an estimated cost for a 0.76 mm (30 mil) Hypalon liner of about $4.80 per square metre ($4 per square yard). Entering Figure 14-13 (FGD Sludge Disposal Manual, page 14-26) with a synthetic liner cost of $4.80 per square metre ($4 per square yard), cost correction factors of 1.50 for the capital investment and 1.44 for the annual revenue correction are determined.

Since no liner is assumed for the landfill alternatives in the FGD Sludge Disposal Manual, estimating this correction is not as straight forward. However, since the assumption for the pond case is a 46 centimetre (18-inch) clay liner and since a correction factor is given for no liner, similar correction factors for the landfill case can be approximated.

Of course, the fact that this is a simplified economic evaluation, as defined in Table 14-1, must be kept in mind. Therefore, if the correction factor for no liner in a pond is 0.84, the correction factor for adding a clay liner to the landfill is assumed to be the reciprocal of 0.84 (i.e., 1.19).

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6.0 SLUDGE DISPOSAL EQUIPMENT DESIGN CRITERIA

6.1 OBJECTIVE

The objective of this section is to establish the FGD sludge disposal equipment design criteria. This section will include the material balance, water balance, sizing criteria, and design criteria as shown in Figure 6-1.

6.2 REQUIREMENTS

(1) The amount of water returned to the FGD scrubber will be evaluated based on landfill disposal with fixation and on the scrubber characteristics developed in Section 4.0.

(2) The FGD sludge disposal system will be sized to permit extended periods of operation without interrupting plant generation.

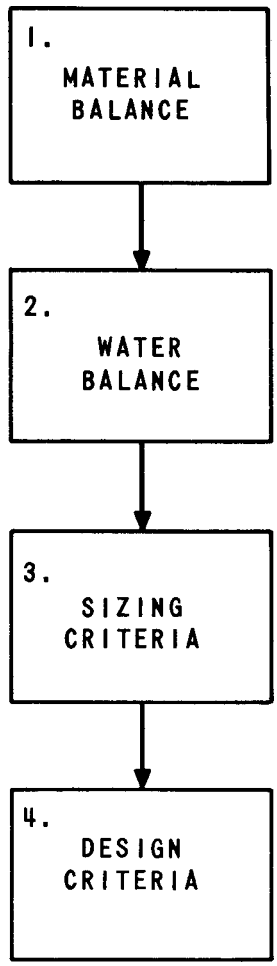
(3) Landfill and waste transport operations will be conducted on a 40-hour work week and will accommodate a sludge production rate based on unit operation at the annual capacity factor of 66 per cent.

6.3 GENERAL SLUDGE DISPOSAL SYSTEM DESCRIPTION

Section 5.0 concluded that landfill with fixation is the most advantageous sludge disposal system for this case study. Figure 6-2 illustrates the basic alternatives for landfill with fixation (Refer to the "FGD Sludge Disposal Manual", Figure 12-3, page 12-15). The scrubber sludge is thickened, dewatered, mixed with fly ash and lime, and transported to a landfill. As stated previously in Section 5.0, for this case study primary dewatering will be by thickening, secondary dewatering will be by vacuum filtering, and transportation will be by truck.

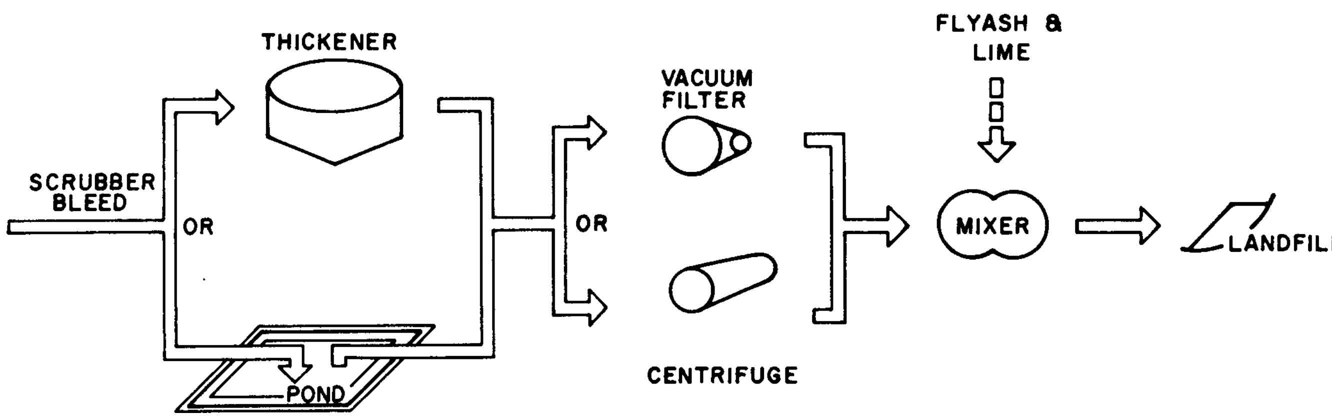
6.4 MATERIAL BALANCE

The primary objective of the sludge disposal system material balance is to establish the lime additive requirements and the quantities of solid wastes to be landfilled. Two separate material balances will be considered. The first will be used for equipment sizing and will be based on burning the higher sulfur coal (3.6 per cent sulfur and 26,749 Joules per gram [11,500 Btu per pound]) at rated plant capacity. The second material balance will be used to determine average annual lime requirements and solid waste disposal quantities. This material balance will be based on burning the nominal coal (3.2 per cent sulfur and 25,586 Joules per gram [11,000 Btu per pound]) at the average annual capacity factor of 66 per cent.



SLUDGE DISPOSAL
EQUIPMENT DESIGN CRITERIA

FIGURE 6-1



ALTERNATIVES FOR LANDFILL
WITH FIXATION

FIGURE 6-2

The basic solid waste material balance is shown in Figure 6-3. Although the sludge disposal system will consist of multiple thickeners, vacuum filters, and mixers, single equipment items are shown to simplify the calculations. The elements of the material balance shown in Figure 6-3 are summarized as follows.

- Input
  - (1) Sludge from the FGD scrubber.
  - (2) Fly ash from the ESP and economizer hoppers.
  - (3) Lime.
- Output
  - (1) Return water to the FGD scrubber.
  - (2) Solid waste to the landfill.

Table 6-1 presents the maximum hourly and average annual input to the sludge disposal system of scrubber solids, fly ash, economizer ash, and lime additive requirements and also the solid waste output quantities. The bottom ash and coal pulverizer rejects will be collected and transported to the landfill separately and are not included in this material balance. These items were, however, considered in the total landfill lifetime waste volumes presented previously in Table 5-3. Table 6-1 shows that a maximum of 63,800 kilograms (70.3 tons) (dry basis) of solid waste per hour will be transported to the landfill from the sludge processing system. Annually, approximately 351,900,000 kilograms (387,900 tons) (dry basis) will be transported.

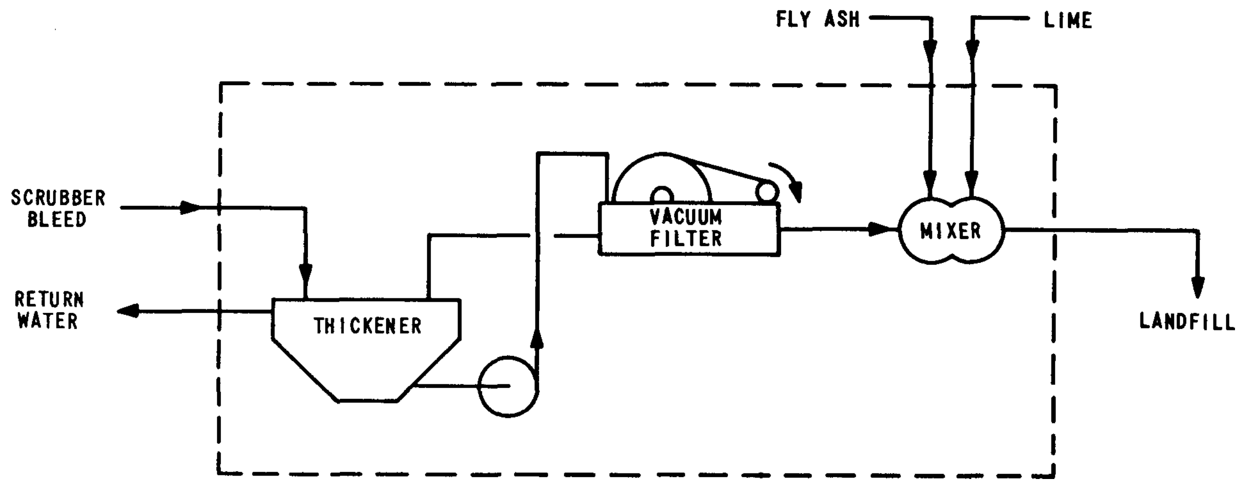
6.5 WATER BALANCE

The objective of the water balance is to estimate the amount of water returned to the FGD scrubber. Subtracting this quantity of return water from the total return and makeup water to the FGD scrubber presented previously in Table 4-3 will provide an estimate of the freshwater makeup requirements.

The basic water balance is shown in Figure 6-4. The elements of the water balance are as follows.

- Input
  - (1) Scrubber sludge at 10 per cent solids by weight.
- Output
  - (1) Moisture leaving with the filter cake at 55 per cent solids by weight.
  - (2) Water returned to the FGD scrubber.

Table 6-2 presents the maximum hourly and average annual water balance for the sludge disposal system. This table shows that an estimated 277,600 kilograms (612,000 pounds) of water per hour (or about 76,000 cubic centimetres per second [1,200 gallons per minute]) will be returned to the scrubber from the sludge disposal



SLUDGE DISPOSAL
SYSTEM MATERIAL BALANCE

FIGURE 6-3

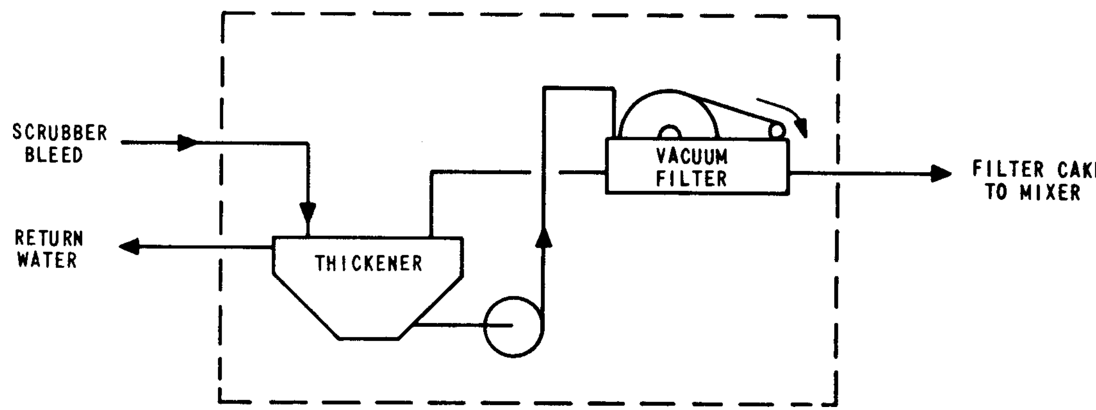
TABLE 6-1. SLUDGE DISPOSAL SYSTEM MATERIAL BALANCE

	Material Quantities*	
	Rated Capacity Burning Higher Sulfur Coal	66 Per Cent Rated Capacity Burning Nominal Coal
	kg/s (tons/hour)	10^3 kg/yr (tons/year)
Input		
Scrubber solids**	9.42 (37.4)	182,600 (201,300)
Fly ash	7.16 (28.4)	148,000 (163,100)
Economizer ash	0.45 (1.8)	7,800 (8,600)
Lime***	0.68 (2.7)	13,500 (14,900)
Output		
Solid waste	17.7 (70.3)	351,900 (387,900)

*All quantities are expressed as equivalent dry weight basis. Scrubber solids, fly ash, and economizer ash quantities are taken directly from Table 5-1.

**Scrubber solids include lime slaker grits and unreacted lime.

***Lime additive requirements are based on 4 per cent of the dry weight of the mixture (Refer to the "FGD Sludge Disposal Manual," page 12-14).



SLUDGE DISPOSAL
SYSTEM WATER BALANCE

FIGURE 6-4

TABLE 6-2. SLUDGE DISPOSAL SYSTEM WATER BALANCE

	Water Quantities	
	Rated Capacity Burning Higher Sulfur Coal	66 Per Cent Rated Capacity Burning Nominal Coal
	kg/s (lb/hr)	kg/s (lb/hr)
Input		
Water in scrubber sludge	84.8 (673,000)	52.2 (414,000)
Output		
Moisture in filter cake	7.7 (61,000)	4.8 (38,000)
Return water	77.1 (612,000)	47.4 (376,000)

system at rated capacity. At 66 per cent of rated capacity, approximately 170,600 kilograms (376,000 pounds) of water per hour (or about 47,000 cubic centimetres per second [750 gallons per minute]) will be returned.

Table 6-3 presents the FGD system fresh water makeup requirements. At rated capacity an estimated 95,700 kilograms (211,000 pounds) per hour (or about 26,000 cubic centimetres per second [420 gallons per minute]) of fresh water makeup will be required. At 66 per cent of rated capacity approximately 73,900 kilograms (163,000 pounds) per hour (or about 19,000 cubic centimetres per second [300 gallons per minute]) of makeup water will be required. This water will be introduced to the FGD scrubber primarily as mist eliminator wash water and pump seal water. As a minimum, at least half of this makeup water will be service water. The remainder will be cooling tower blowdown.

6.6 SIZING CRITERIA

Section 6.4 stated that the sludge disposal equipment will be sized based on material balances performed at the rated capacity when burning the higher sulfur. In addition, the sludge disposal system equipment will be designed for safe and reliable operation under the FGD scrubber operating conditions previously stated in Section 4.4. These three conditions are as follows.

(1) Daily startup following an overnight shutdown of approximately 8 hours duration.

(2) Weekly startup following weekend shutdown of approximately 48 hours duration.

(3) Operating at 25 per cent of rated capacity over extended periods of time.

An additional constraint is that the landfill and truck waste transport operations will be limited to a 40-hour work week.

6.7 DESIGN CRITERIA

Section 4.7 discussed that prior to developing the purchase specification for a wet lime FGD system, a number of basic design decisions must be made. One of those decisions illustrated in Figure 4-4 was the sludge disposal scheme. The objective of this section is to evaluate in detail the alternatives that must be considered once the sludge disposal scheme has been selected. Figure 6-5 shows schematically the alternatives and six of the more important decision variables which are considered in developing a practical landfill with fixation disposal system.

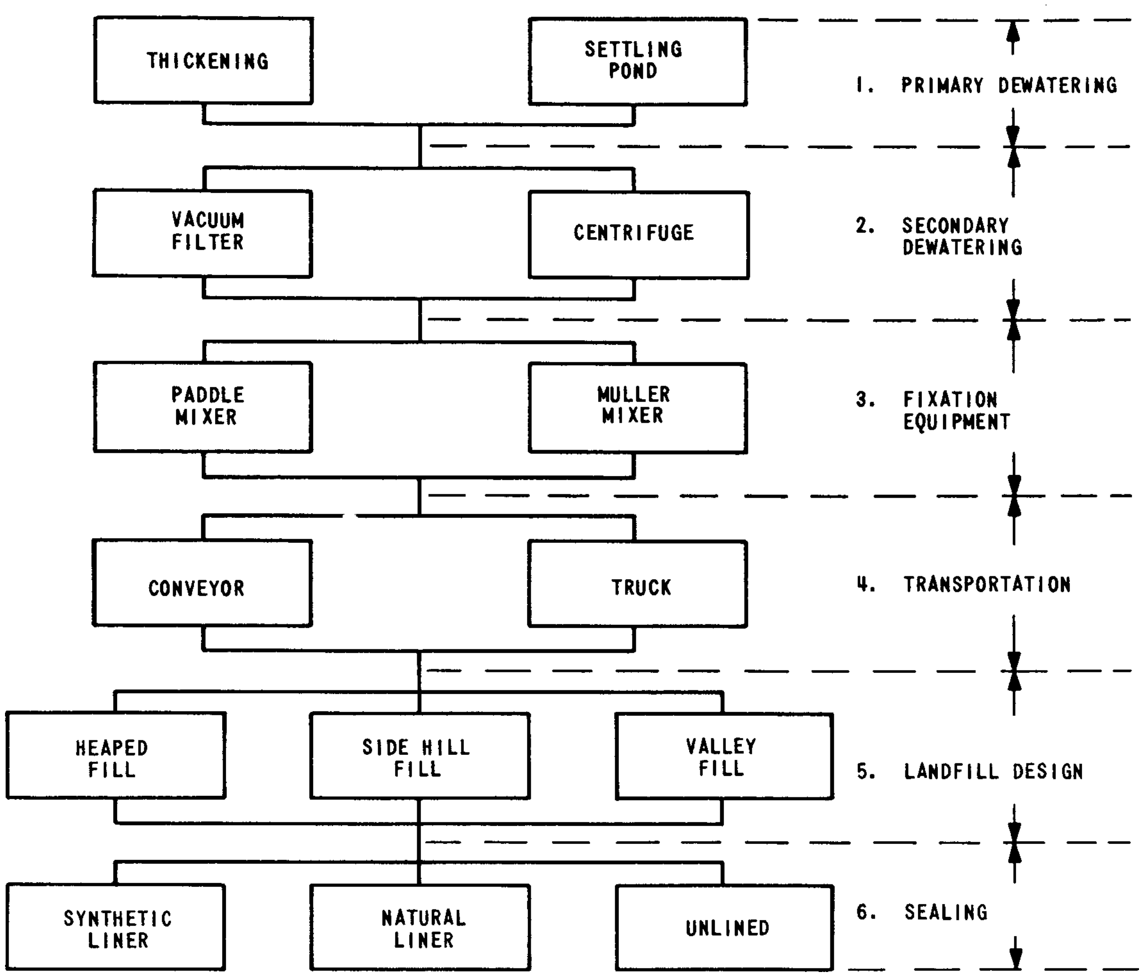
Figure 6-6 presents the six solid waste disposal decisions for the hypothetical station considered in this case study. The following subsections provide additional information regarding these decisions.

TABLE 6-3. ESTIMATED FRESH WATER MAKEUP REQUIREMENTS

	Water Quantities	
	Rated Capacity Burning Higher Sulfur Coal	66 Per Cent Rated Capacity Burning Nominal Coal
Stream Description	kg/s (lb/hr)	kg/s (lb/hr)
Total scrubber return and makeup water requirements*	103.7 (823,000)	67.9 (539,000)
Return water**	77.1 (612,000)	47.4 (376,000)
Differential makeup water requirements	26.6 (211,000)	20.5 (163,000)

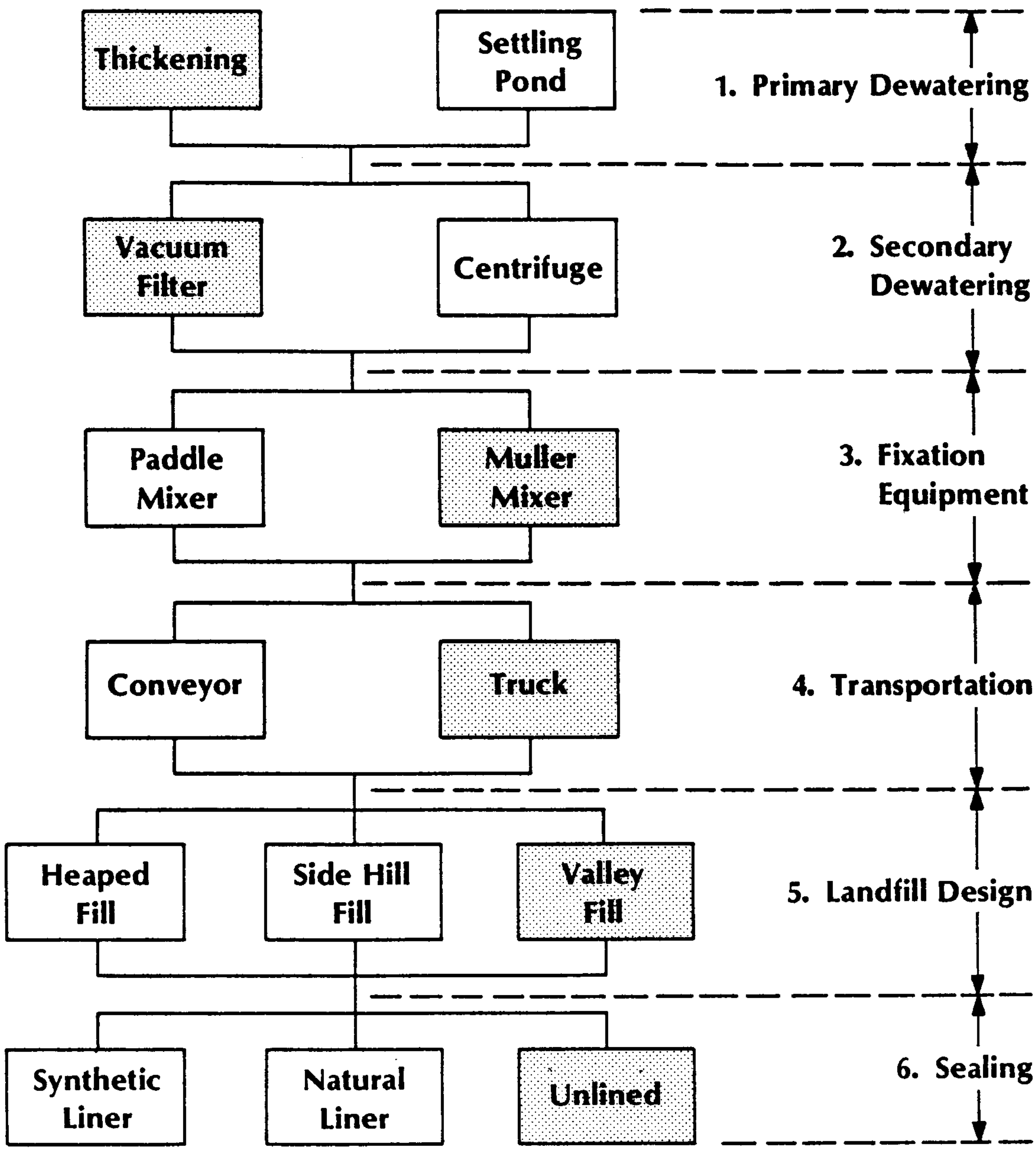
*Refer to Table 4-3

**Refer to Table 6-2



LANDFILL WITH FIXATION ALTERNATIVES

FIGURE 6-5



LANDFILL WITH FIXATION ALTERNATIVES

FIGURE 6-6

6.7.1 Primary Dewatering

As stated in Section 5.6, for this case study it is assumed that two half capacity thickeners will be provided in parallel for the 500 MW unit. Each thickener will be approximately 36 metres (120 feet) in diameter.

A cross sectional view of a gravity thickener is shown in Figure 6-7 ("FGD Sludge Disposal Manual", Figure 11-3, page 11-7). Although possibly more expensive, thickeners were selected rather than settling ponds because of increased ease and flexibility in solids removal, flexibility in location, and smaller space requirements ("FGD Sludge Disposal Manual", Page 11-3).

6.7.2 Secondary Dewatering

Secondary dewatering will be accomplished by vacuum filtration. Three half capacity vacuum filters will be provided. The vacuum filters will be of the rotary drum type. A cutaway view of a rotary drum vacuum filter is shown in Figure 6-8 ("FGD Sludge Disposal Manual", Figure 11-11, page 11-22).

6.7.3 Fixation Equipment

Fixation involves mixing the dewatered FGD scrubber sludge with lime and fly ash to bind the solids together, reduce the permeability, and increase the shear strength of the solid waste. The selection of the type of mixing equipment is somewhat arbitrary at present. There are only two types of mixers in service in FGD sludge processing systems, and experience is extremely limited ("FGD Sludge Disposal Manual", page 12-29). For this case study, three half capacity muller mixers will be provided. A top view of a muller mixer is shown in Figure 6-9 ("FGD Sludge Disposal Manual", Figure 12-6, page 12-32).

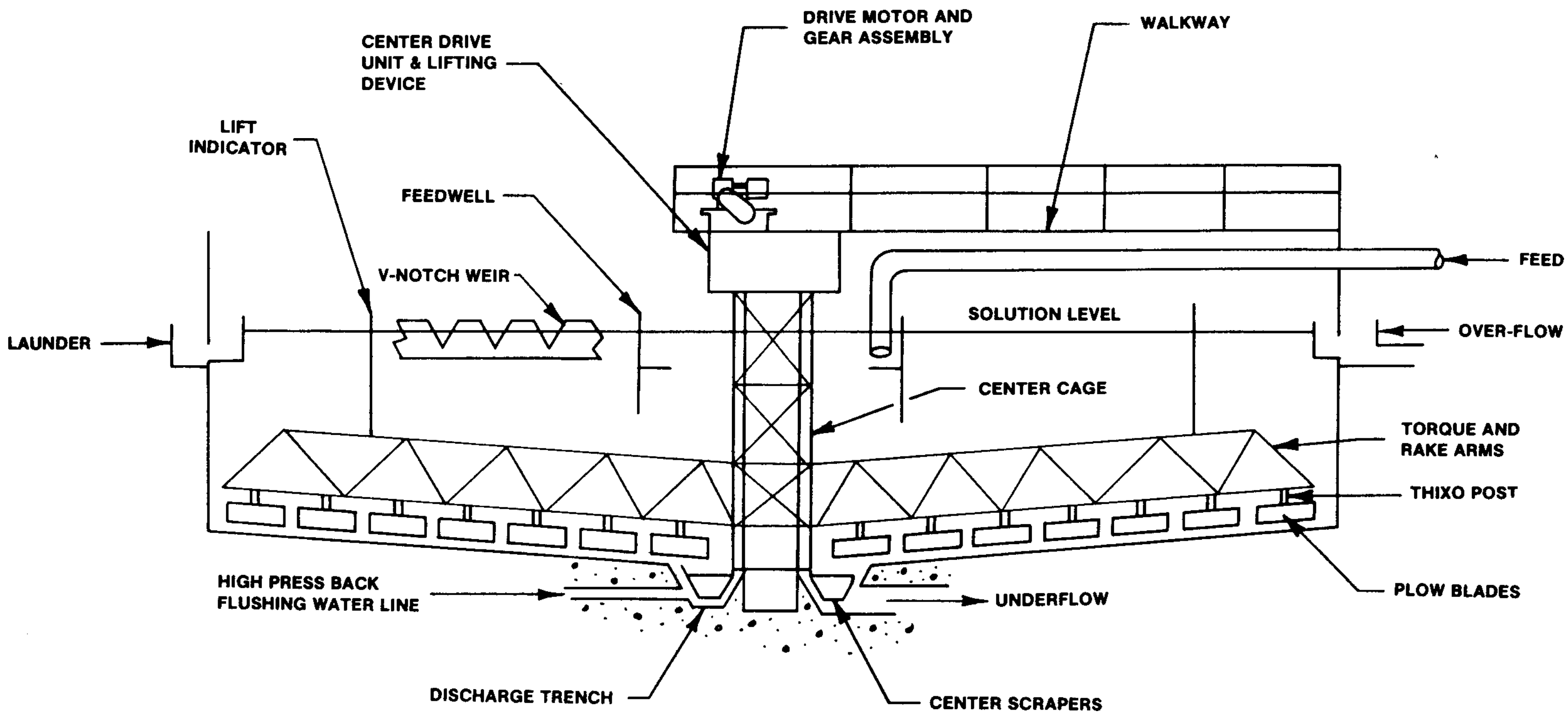
6.7.4 Transportation

The fixed solid waste will be transported to the landfill area by 59,000-kg (65-ton), off-road rear dump trucks. The landfill operations will be limited to 40 hours per week. Therefore, the entire quantity of solid wastes generated from operating at rated plant capacity for seven days (168 hours) must be transported within those 40 hours. Under these conditions approximately forty 59,000-kg (65-ton) truckloads per day will be required to haul the solid waste from the plant.

Assuming that a round trip will take approximately one hour including loading and unloading, a minimum of five trucks will be required. However, six will be required to provide redundancy for unscheduled maintenance. Routine maintenance on the transport equipment will be performed on the swing shift (4 p.m. to midnight). The equipment required for landfill operations is given in Table 6-4.

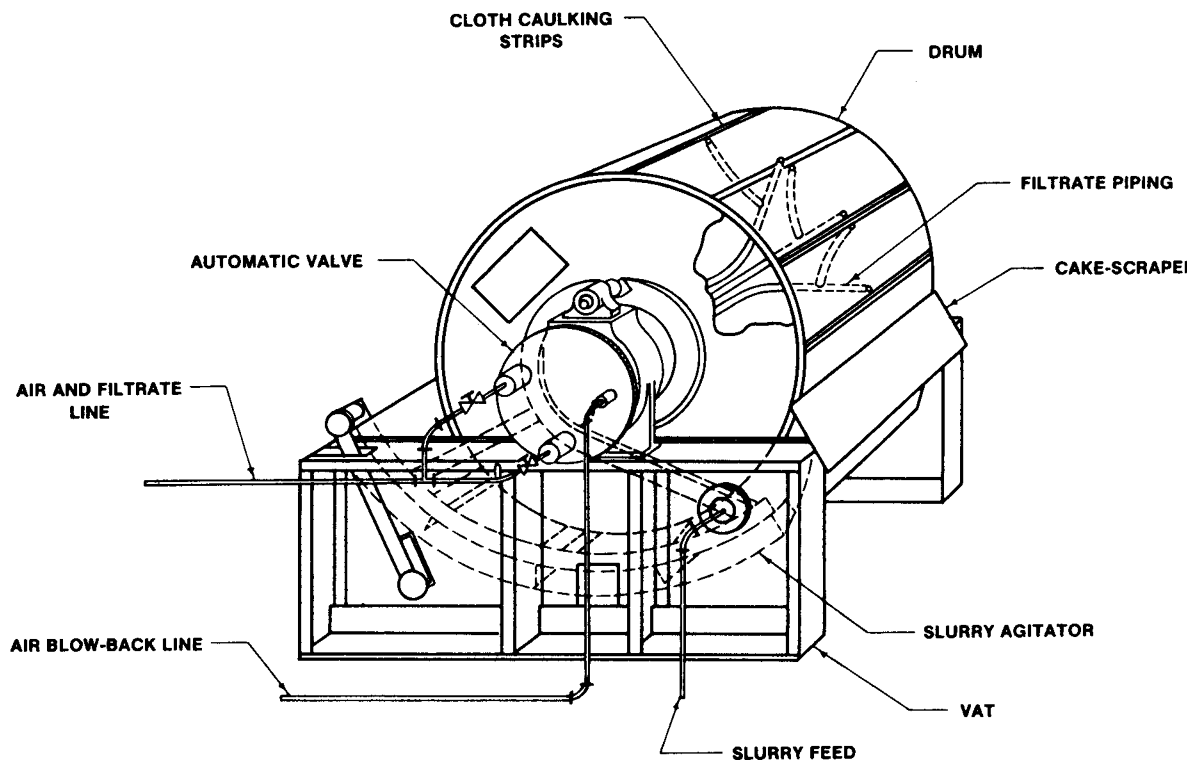
6.7.5 Landfill Design

The landfill will utilize the valley-fill disposal configuration shown in Figure 6-10 ("Lime FGD Sludge Disposal Manual", Figure 8-11, page 8-14). The site



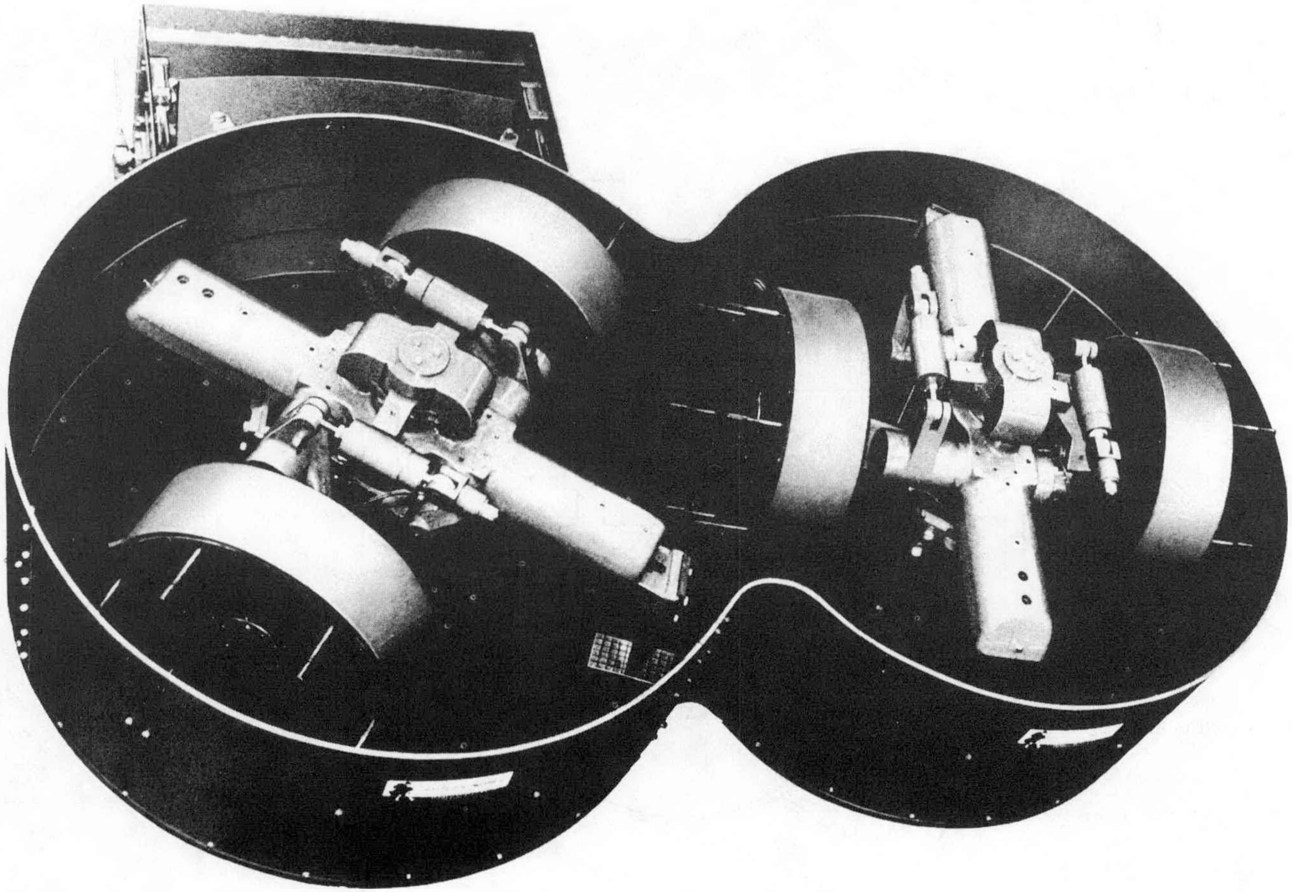
CROSS SECTION OF A CONVENTIONAL
GRAVITY THICKENER

FIGURE 6-7



CUTAWAY VIEW OF A ROTARY DRUM VACUUM FILTER

FIGURE 6-8

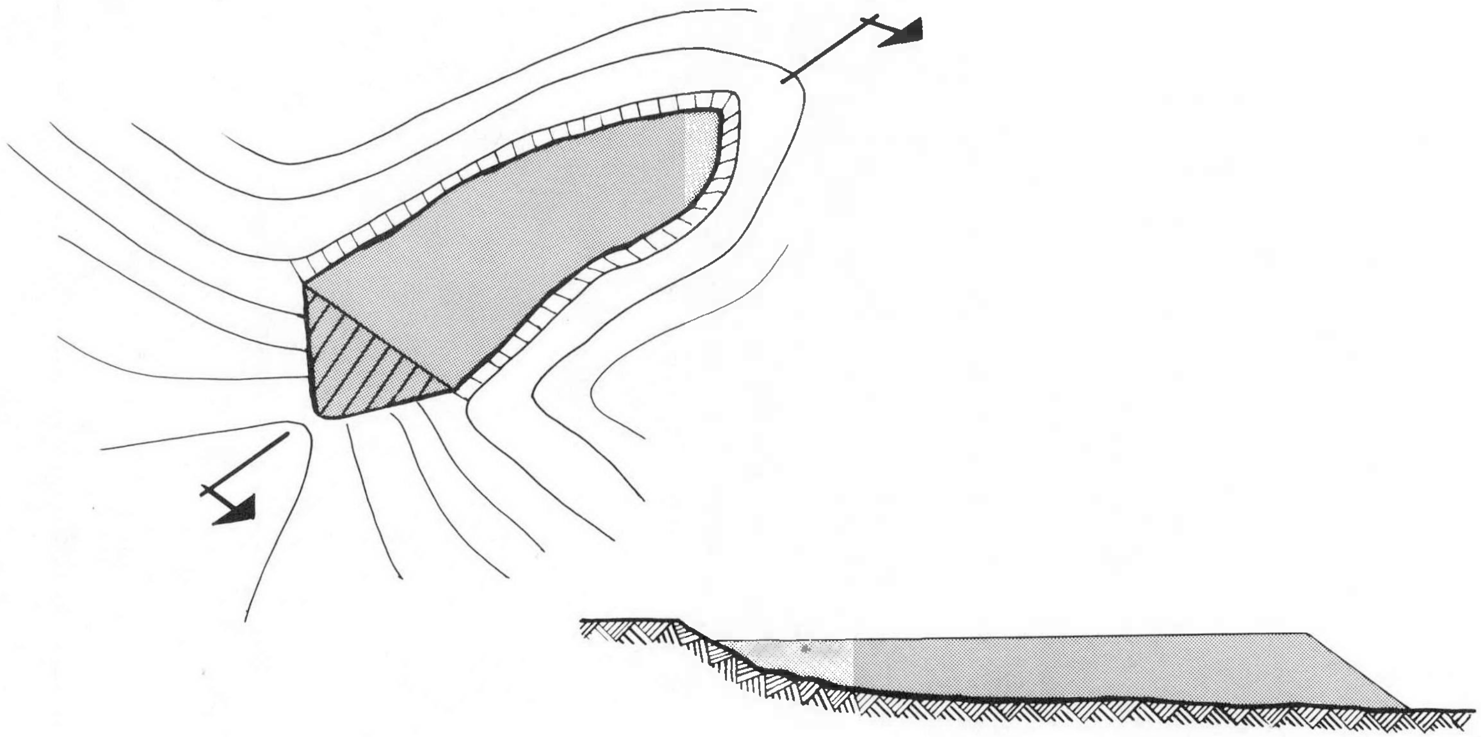


TOP VIEW OF A MULLER MIXER

FIGURE 6-9

TABLE 6-4. EQUIPMENT REQUIRED FOR LANDFILL OPERATIONS

Quantity	Item
6	59,000 kilogram (65 ton) Rear Dump Trucks
3	7.6 cubic metre (10 cubic yard) Front End Loaders
5	275 horsepower Crawler Tractors
4	300 horsepower Compactor Rollers
1	21 cubic metre (28 cubic yard) Scraper
2	250 horsepower Graders
1	19 cubic metre (5,000 gallon) Water Truck



VALLEY FILL DISPOSAL
CONFIGURATION

FIGURE 6-10

identified as Site B in Section 5.4 will be more than adequate for the estimated lifetime solid waste quantities.

Site A will be used for temporary fixed sludge storage. This site will provide surge storage capacity for the sludge/fly ash/lime mixture produced during unmanned shifts of the landfill transportation system. A radial stacker will be used to provide a crescent shaped windrow as shown in Figure 6-11 ("FGD Sludge Disposal Manual", Figure 13-4, page 13-24). Front end loaders will be used to reclaim and load the stacked sludge into the hauler trucks for transportation to the landfill.

6.7.6 Sealing

As stated in Section 5.6.3, the fixation process will result in a mixture with a permeability sufficiently low to preclude the need for a liner at the disposal site. However, a natural clay liner will be installed at the temporary solid waste disposal site since this area may be used for temporary storage of unfixed dewatered sludge in case of mixing equipment upsets.

6.8 CASE STUDY SITUATION #3

6.8.1 Situation Objective

The objectives of this case study situation are as follows.

(1) Provide an example of the role of generation engineering in the review process of the sludge disposal equipment design criteria document.

(2) Illustrate the manner in which the FGD Sludge Disposal Manual can be used to evaluate the consulting engineer's recommendations.

6.8.2 Situation Description

As shown in Step 3 of the project coordination sequence of Figure 1-1, the equipment design criteria document is evaluated by generation engineering prior to issue as a completed document. During the review and comment process, the utility Power Production Department posed a number of questions regarding the consulting engineer's recommendations. It is the responsibility of the generation engineer to respond to these questions.

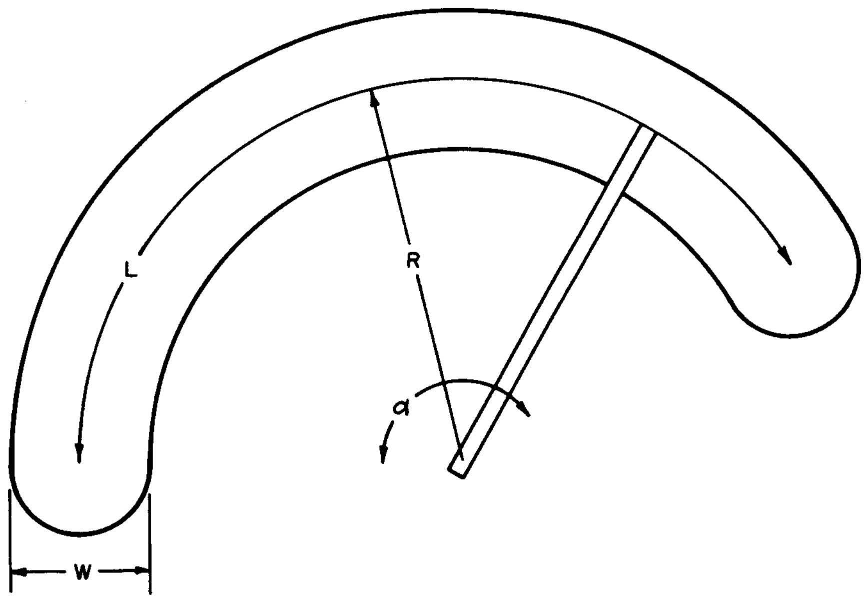
6.8.3 Typical Questions from Power Production Department

Question

In Section 6.7.5 the consulting engineer recommends using a radial stacker for stocking out the fixed sludge. This radial stacker conveyor represents a high capital cost as well as a potentially high maintenance requirement. Would it be practical to use either surface equipment or a single fixed conveyor to stock out the solid waste?

Response

According to the "FGD Sludge Disposal Manual", page 13-27, surface equipment, such as front-end loaders, dozers, and wheeled scrapers can be used to place dry



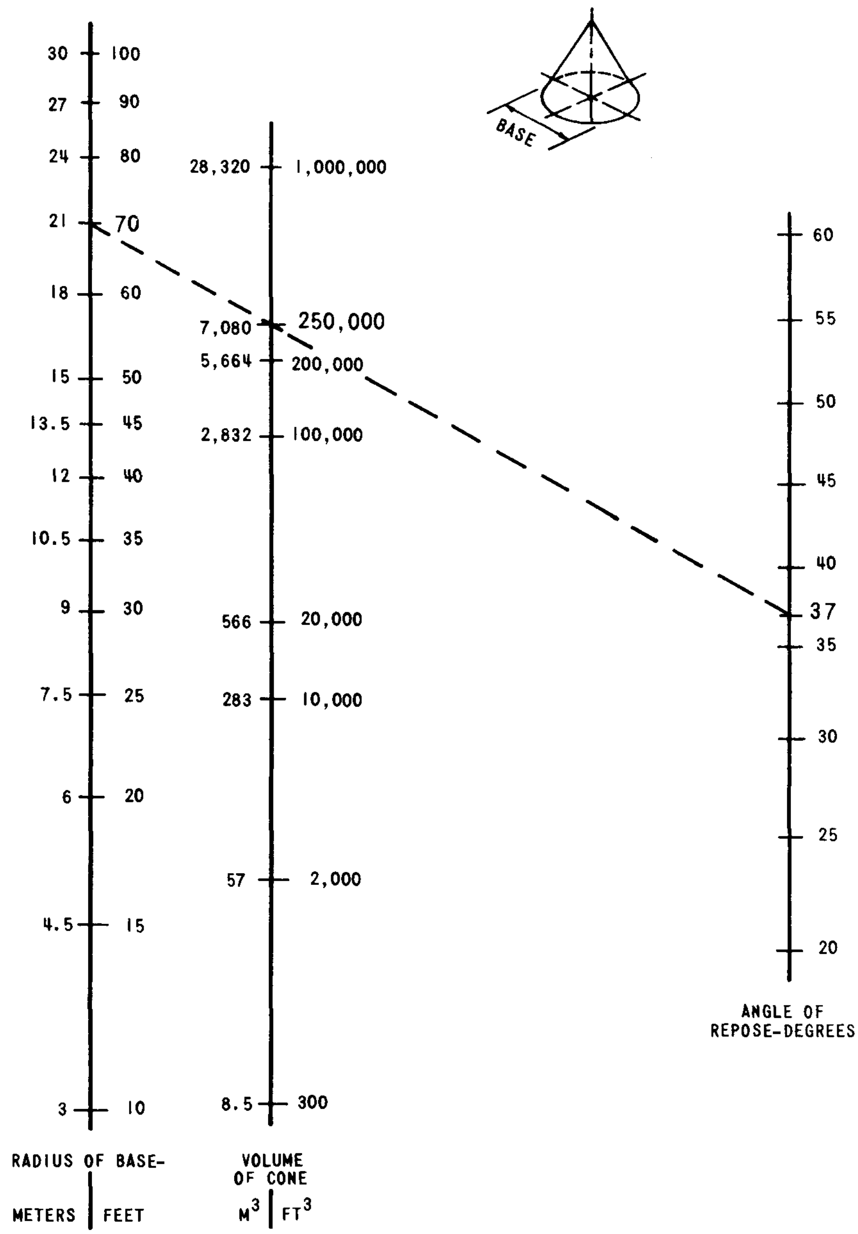
WINDROW FORMED BY A
RADIAL STACKER

FIGURE 6-11

FGD sludge in surge piles. However, the operation of surface equipment on the surge pile can be difficult if the pile surface is loose, soft, or wet. Also, operation of surface equipment may compact the sludge, making it difficult to reclaim. For these reasons, placement by conveyors is preferred.

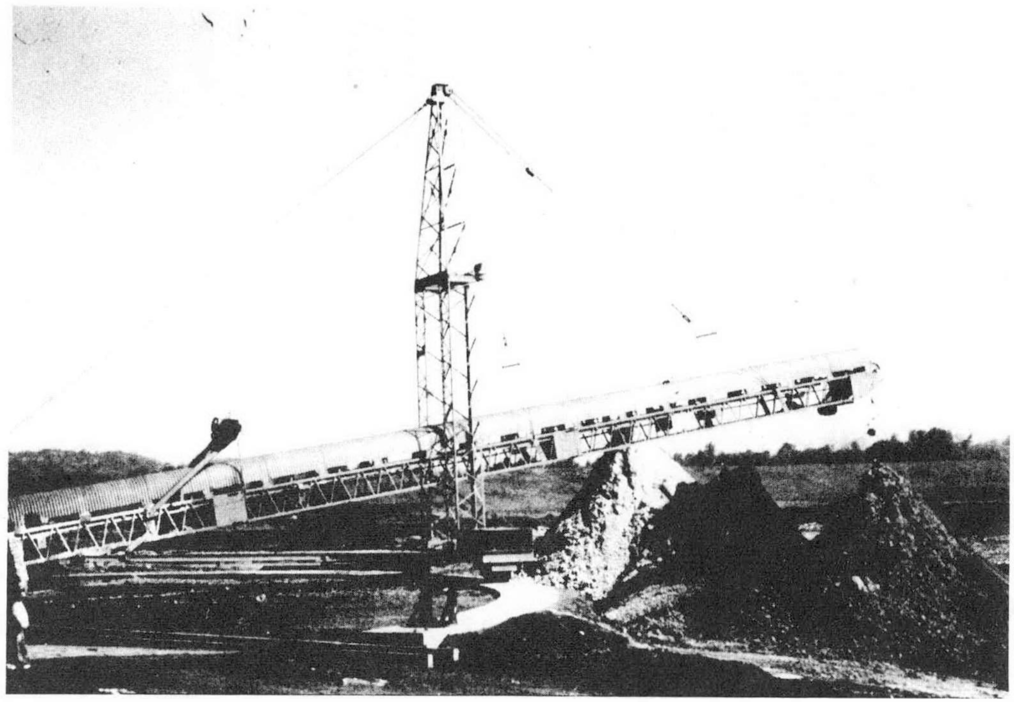
A single stationary conveyor is satisfactory for delivering dry sludge to surge piles of moderate size. However, only a conical pile can be built with a single conveyor. The "FGD Sludge Disposal Manual", Figure 3-13, page 13-23 (See Figure 6-12) presents a nomograph for determining the volume of conical surge piles. Based on five days of sludge production and a sludge density of 1,500 kilograms per cubic metre (95 pounds per cubic foot), the required storage volume is about 7,080 cubic metres (250,000 cubic feet). From the nomograph of Figure 6-12, assuming an angle of repose of 37 degrees, the estimated radius of the base of the conical surge pile is 21 metres (70 feet). Therefore, the dimensions of five days of sludge production would be a cone with a base of approximately 140 feet and a height of about 15 metres (50 feet). A surge pile with these dimensions would be impractical for reclaim by front-end loaders.

Figure 6-13 is a picture of the radial stacker at Columbus and Southern Ohio Electric Company's Conesville Station. The windrow produced by this stacker has a volume of 7,080 cubic metres (9,000 cubic yards or about 250,000 cubic feet). The FGD Sludge Disposal Manual on page 13-27, states that this radial stacker is 31 metres (101 feet) long with an effective radius of 28 metres (92 feet) at maximum height and a turning radius of 160 degrees. Using the estimating technique presented on page 13-22 of the manual, the dimensions of the surge pile can be calculated. The results of these calculations are presented in Figure 6-14. The dimensions shown for the windrow would be adequate for five days storage at rated capacity burning the higher sulfur coal.

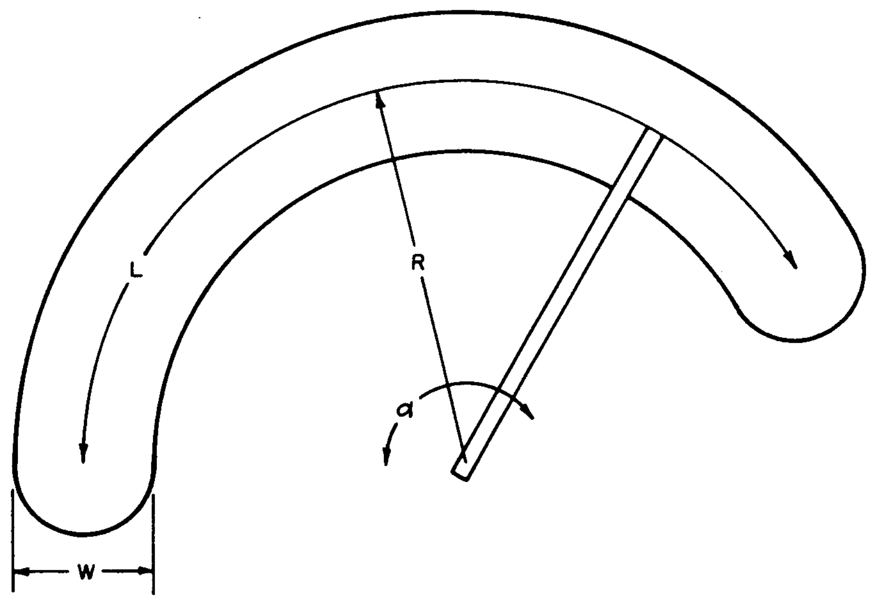


NOMOGRAPH FOR DETERMINING THE
VOLUME OF CONICAL SURGE PILES

FIGURE 6-12



RADIAL STACKER, CONESVILLE STATION,
COLUMBUS & SOUTHERN OHIO ELECTRIC COMPANY
FIGURE 6-13



R = 28 metres (92 Feet)
α = 160 Degrees
L = 79 metres (260 Feet)
W = 21 metres (70 Feet)

ESTIMATED TEMPORARY SOLID WASTE
SURGE PILE DIMENSIONS

FIGURE 6-14

7.0 PURCHASE SPECIFICATIONS

7.1 OBJECTIVE

The objective of this section is to describe the contents of a typical lime FGD system purchase specification and the procedures for issuing the document.

7.2 REQUIREMENTS

(1) The equipment specified will include all of the items listed in Table 7-1 and shown schematically in Figure 7-1.

(2) The equipment listed in Table 7-2 will be provided under separate specifications. These equipment items are routinely specified and purchased by utility staff and will not be considered further in this case study.

7.3 GENERAL PURCHASE SPECIFICATION DESCRIPTION

A purchase specification document typically includes three major sections as follows.

(1) Bidding Requirements.

(2) Contract Requirements.

(3) Specifications.

Figure 7-2 presents the primary components of these three sections and the basic format of the following discussion. The majority of the components of the lime FGD system purchase specification will be very familiar to the utility staff. These same components are commonly included with major equipment purchase specifications. The primary exception is the Equipment Requirements section. This section contains information specific to the design of the lime FGD system. For this reason the Equipment Requirements section will be discussed in greater depth than the other sections of the purchase specification.

7.4 BIDDING REQUIREMENTS

The Bidding Requirements section provides guidance and instructions for the bidders in preparation and submission of their proposals. This section consists of three components as follows.

(1) Instruction to Bidders.

(2) Proposal Requirements.

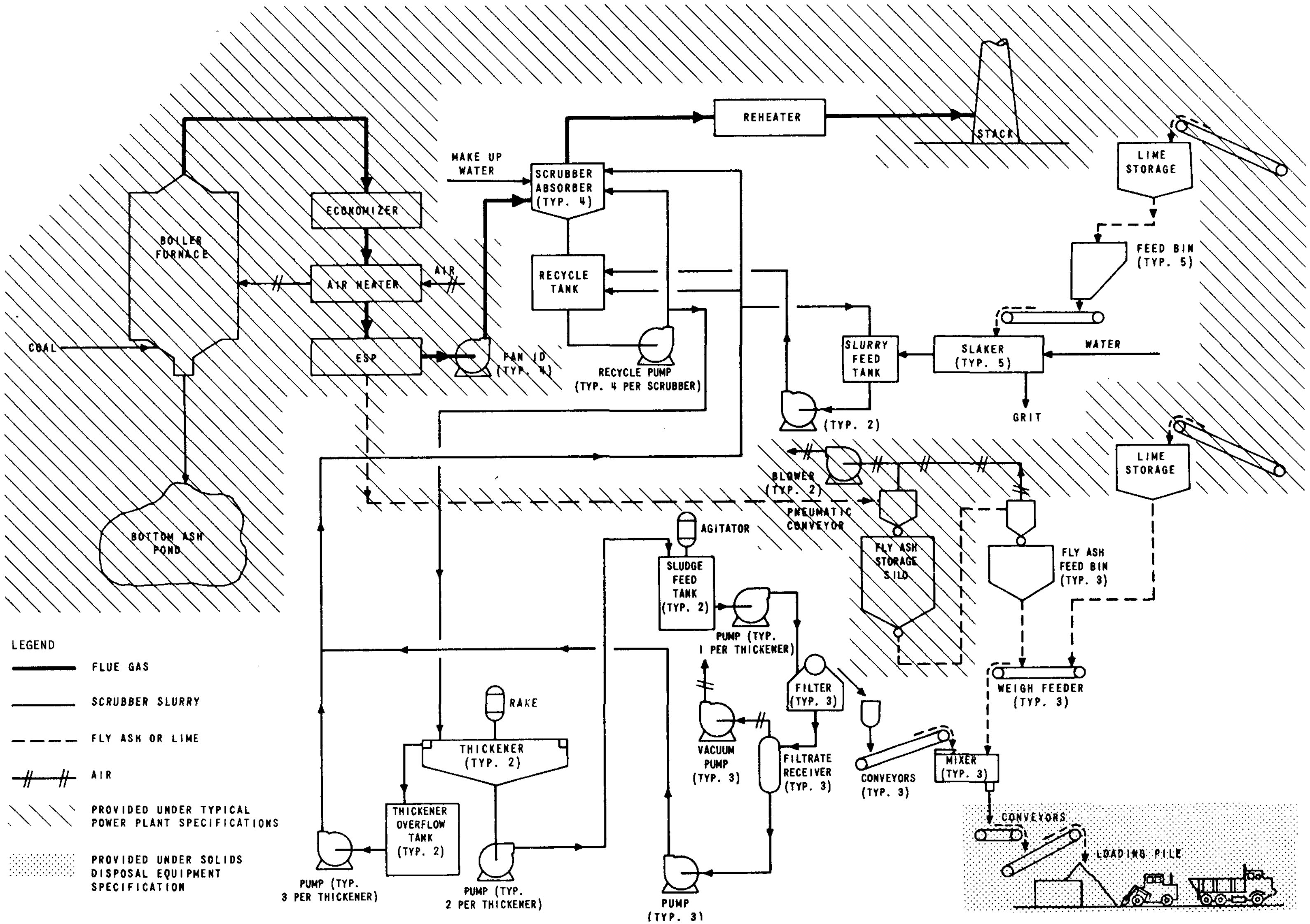
(3) Proposal Data Sheets.

7.4.1 Instruction to Bidders

The Instructions to Bidders provide specific requirements for preparation of proposals. These instructions are general in nature. A few examples of the type of instructions typically included in this section are listed in Table 7-3.

TABLE 7-1. EQUIPMENT ITEMS SPECIFIED IN THE LIME FGD SYSTEM PURCHASE SPECIFICATION

- Scrubber Modules
- Inlet and Outlet Ductwork and Dampers
- Insulation and Lagging
- Additive Preparation System
- Sludge Thickening and Dewatering Equipment
- Solids Conditioning Equipment
- All Required Pumps
- Tanks
- Piping
- System Controls

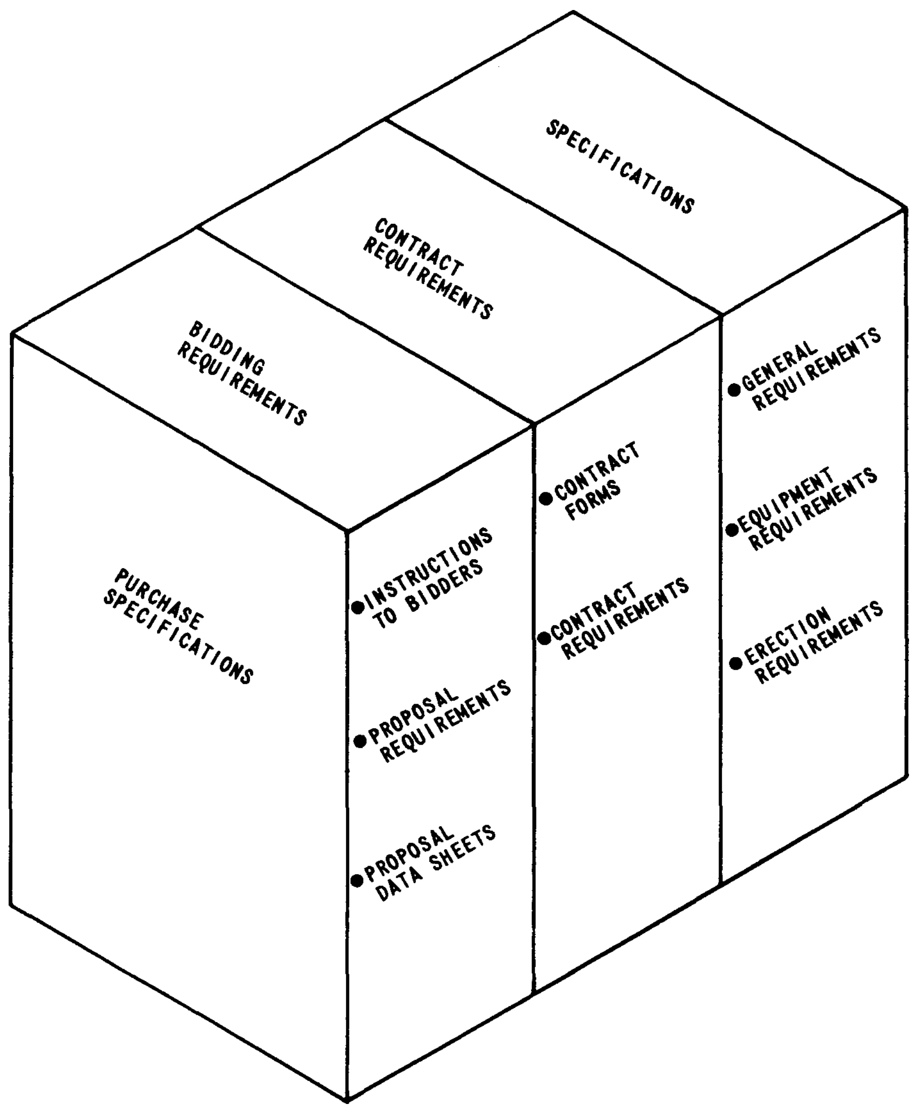


EQUIPMENT ITEMS SPECIFIED IN THE LIME FGD SYSTEM PURCHASE SPECIFICATIONS

FIGURE 7-1

TABLE 7-2. EQUIPMENT ITEMS PROVIDED UNDER SEPARATE SPECIFICATIONS

- Structural Steel
- Foundations
- Enclosures
- Additive Handling Equipment
- Final Solids Disposal Equipment



PRIMARY COMPONENTS OF THE
PURCHASE SPECIFICATION DOCUMENT

FIGURE 7-2

TABLE 7-3. TYPICAL INSTRUCTIONS TO BIDDERS

- To whom, where, and in how many copies to submit the proposal.
- Style and format to be used in the proposal.
- Methods of presenting the bidders' intended deviations from the specifications.

7.4.2 Proposal Requirements

The Proposal Requirements provide a summary of technical information required to be submitted with the bidder's proposal. This information will be used to evaluate the bids. An example of information typically requested in this section is presented in Table 7-4.

7.4.3 Proposal Data Sheets

The Proposal Data Sheets provide forms for the bidders to complete and submit with their proposals. The forms request both pricing and equipment data.

The proposal pricing forms require a breakdown of the lump sum bid into material costs and erection costs. This will permit the application of separate cash flow schedules and/or price adjustment indicies to these costs during the economic evaluation.

The equipment data sheets, once completed by the bidder, will provide technical information concerning specific items of equipment. This information will provide the basis for the technical evaluation of the proposals and for preliminary design considerations once the contract is awarded. Examples of equipment data sheets are presented in Section 5.4 of the "Lime FGD Systems Data Book."

7.5 CONTRACT REQUIREMENTS

The Contract Requirements section consists of two primary components as follows.

(1) Contract Forms.

(2) Contract Regulations.

7.5.1 Contract Forms

The Contract Forms provide the legal contract documents for signing by the successful bidder and the utility. The format and content of the Contract Forms are dictated by the utility's standard requirements.

7.5.2 Contract Regulations

The Contract Regulations provide the commercial terms and conditions, liability, and other special conditions to which the successful bidder must abide. Again, the contents of the regulations are dictated by the utility's standard policy and requirements.

7.6 SPECIFICATIONS

The Specifications section provides the lime FGD system equipment design and performance requirements. This section consists of three components as follows.

(1) General Requirements.

(2) Equipment Requirements.

(3) Erection Requirements.

TABLE 7-4. TYPICAL PROPOSAL REQUIREMENTS

- Performance Curves.
- Drawings.
- Supplementary Information.
  - Scope of Supply
  - Equipment Materials' List
  - Operation and Maintenance Requirements
  - Schedules, etc.

7.6.1 General Requirements

The General Requirements provide generic technical specifications which are common to most or all of the lime FGD system equipment items. Examples of requirements typically included in this section are listed in Table 7-5.

7.6.2 Equipment Requirements

The Equipment Requirements provide specific technical specifications which supplement the General Requirements. The resulting product is a set of comprehensive technical equipment specifications tailored to fit a specific application. The Equipment Requirements section incorporates the design basis, sizing criteria, and design criteria developed in previous sections of this case study. The three basic elements of the Equipment Requirements section are as discussed in Section 5.0 of the "Lime FGD Systems Data Book." These three elements are as follows

(1) Design Basis.

(2) Guarantee Requests.

(3) Equipment and Instrumentation.

An example Equipment Requirements section has been prepared specifically for the lime FGD system considered in this case study. This example section of the purchase specification document located in Appendix A includes the Design Basis and Guarantee Requests. However, the Equipment and Instrumentation section has been abbreviated for this case study. Two specific examples have been selected and are discussed in the Equipment and Instrumentation section of Appendix A. These two examples are as follows.

(1) Absorber Modules.

(2) Controls and Instrumentation.

7.6.3 Erection Requirements

The Erection Requirements specifies the scope of the onsite field erection work to be performed and the construction facilities and services to be provided by the contractor and by the utility. Examples of requirements typically included in this section are listed in Table 7-6.

7.7 BIDDER SELECTION AND ISSUE OF THE PURCHASE SPECIFICATION

The selection of qualified bidders is typically accomplished as follows.

(1) A list of potential bidders is established.

(2) The bidders submit prebid qualifications which include the bidder's related experience and former customers, organization and manpower capability, and financial status.

(3) The consulting engineer or utility contacts the bidder's former customers to verify the bidder's experience and reputation.

(4) Based on evaluation of the prebid qualifications, a list of qualified bidders is established.

TABLE 7-5. TYPICAL GENERAL REQUIREMENTS

- General Description and Scope of the Work.
    - Work included under the specifications
    - Work not included under the specifications
    - Schedule
- General Equipment Specifications.
    - Shipping instructions
    - Instrumentation specifications
    - Electrical equipment specifications, etc.
- Engineering Data.
    - Performance curves and design data
    - Drawings, schematics, and diagrams
    - Instruction manuals, etc.

TABLE 7-6. TYPICAL ERECTION REQUIREMENTS

- Scope of Erection Work.
  - Construction Plant and Temporary Facilities
  - Construction Utilities
  - Schedule
- Equipment Erection.
  - Welding
  - Piping
  - Cleaning, Painting, etc.
- Start-Up.
  - Equipment Check-Out
  - Trial and On-Line Operational Checks
  - Operational Control

For this case study, five qualified bidders have been identified. These bidders will be referred to as Bidders A, B, C, D, and E. Each of these bidders received a copy of the Purchase Specification document and submitted responsive proposals. Evaluation of the proposals will be discussed in Section 8.0.

8.0 BID EVALUATIONS

8.1 OBJECTIVE

The objective of this section is to discuss, by example, the process of evaluating bids that have been received in response to the specification. Actual proposal prices will be adjusted for non-compliance items, balance of plant costs, commercial costs, and operating costs.

8.2 REQUIREMENTS

The equipment to be furnished will include the scrubber modules, inlet and outlet ductwork and dampers, insulation and lagging, the additive preparation system, sludge thickening and dewatering equipment, solids conditioning equipment, all required pumps, tanks, and pipe, and system controls. Structural steel, foundations, enclosures, additive handling equipment, and final solids disposal equipment will be provided under separate contracts.

8.3 SUMMARY OF BIDS

Proposals were received from five suppliers. Bidders A, B, and C bid a lime additive, spray tower system in conformation with the specifications. Bidder D offered a limestone, packed tower system which he guaranteed would meet the SO_2 reduction requirement. Bidder E proposed a dual-alkali system with soda ash as the additive.

Information supplied by each manufacturer on the proposed data sheets is summarized on Table 8-1. This data will be used in the evaluation. The majority of data furnished was used for determining compliance with the specification. Where non-compliance was indicated the supplier was contacted for clarification and a price adjustment obtained or estimated.

Each proposal was compared to the specification and price additions or credits were applied where the systems were deficient or overdesigned. The cost of equipment and materials which were outside of the manufacturer's scope of supply, but necessary for a complete system were estimated and added to the evaluation to put all systems on an equal basis.

Commercial costs were calculated for each proposal based on the manufacturer's terms of payment and the economic criteria contained in the specifications. Operating costs for additive, air, water, electrical demand and energy, and sludge disposal were calculated based on the data supplied by the manufacturer. These operating

TABLE 8-1. SCRUBBER DATA SUMMARY AT MAXIMUM LOAD BURNING HIGHER SULFUR COAL

	Bidder A Lime	Bidder B Lime	Bidder C Lime	Bidder D Limestone	Bidder E Dual Alkali
Gas Factors					
Scrubber ΔP-Through Scrubbing Stage, Pa (in H_2O)	700 (2.8)	470 (1.9)	450 (1.8)	1,600 (6.5)	950 (3.8)
Total all Scrubber Elements, Pa (in H_2O)	1,740 (7.0)	2,190 (8.8)	1,740 (7.0)	2,860 (11.5)	2,110 (8.5)
Superficial Velocity-Through Absorber, m/s (ft/sec)	2.7 (8.7)	3.0 (10.0)	2.7 (8.8)	2.8 (9.3)	2.7 (9.0)
Through Demister, m/s (ft/sec)	2.7 (8.7)	3.0 (10.0)	2.7 (8.8)	2.8 (9.3)	2.7 (9.0)
Water Droplet Carry-over Past Demister, kg/s (lb/hr)	.253 (2,010)	.627 (4,980)	.020 (156)	.315 (2,500)	Unknown
Overall System SO_2 Removal, per cent	90	90	90	90	90
Slurry Recycle System					
Liquid to Gas Rate-Absorber, m^3/s/1,000 m^3/s gpm/1,000 ACFM	11.6 (87)	10.7 (80)	13.4 (100)	14.7 (110)	0.9 (6.5)
Slurry Recycle-Absorber, cc/s (gpm)	8,110,000 (128,568)	7,742,000 (122,720)	8,548,000 (135,492)	9,148,000 (145,000)	635,000 (10,070)
Per Cent Solids in Recycle Slurry	10	10	8.9	10	.01
Absorber Tank Retention Time, Min.	12	3.4	6.3	10	8.1
Additive System					
Lime Additive Required - 90 Per Cent CaO, kg/s (lb/hr)	3.75 (29,790)	3.70 (29,400)	3.71 (29,436)	--	3.42 (27,175)
Limestone Additive, kg/s (lb/hr)	--	--	--	7.31 (58,000)	--
Soda Ash Additive Required, kg/s (lb/hr)	--	--	--	--	.267 (2,116)
Per Cent of Stoichiometric Feed Rate*	1.06	1.05	1.05	1.15	0.97
Per Cent Solids in Additive Slurry	20	15	18.1	20	22
Additive Slurry Flow Rate, cc/s (gpm)	18,800 (298)	26,800 (424)	20,300 (322)	33,100 (525)	14,300 (226)
Soda Ash Additive Slurry Flow Rate, cc/s (gpm)	--	--	--	--	600 (10)
Fresh Water Requirements					
Additive System Fresh Water Requirement, cc/s (gpm)	7,500 (119)	7,400 (118)	10,100 (160)	4,700 (75)	15,800 (251)
Absorber Makeup Fresh Water Requirement, cc/s (gpm)	--	--	21,800 (345**)	--	10,000 (159**)

TABLE 8-1 (Continued).

	Bidder A Lime	Bidder B Lime	Bidder C Lime	Bidder D Limestone	Bidder E Dual Alkali
Vacuum Filter Fresh Water Requirement, cc/s (gpm)	--	--	--	--	11,600 (184)
Demister Wash Fresh Water Requirement, cc/s (gpm)	23,200 (368)	21,500 (340)	300 (4)	11,400 (180)	800 (13)
Pump Seal Fresh Water Requirement, cc/s (gpm)	10,500 (166)	6,100 (96)	3,800 (60)	4,400 (70)	2,600 (41)
Total Fresh Water Requirement, cc/s (gpm)	41,200 (653)	35,000 (554)	35,900 (569)	20,500 (325)	40,900 (648)
Sludge Disposal System					
Blowdown from Absorbers, cc/s (gpm)	64,100 (1,016)	75,500 (1,196)	86,600 (1,372)	93,400 (1,480)	363,000 (5,754)
Per Cent Solids in Absorber Blowdown	10	10	8	10	0.01
Underflow from Thickener, cc/s (gpm)	21,100 (334)	22,000 (348)	20,100 (318)	22,100 (350)	24,000 (380)
Per Cent Solids in Thickener Underflow	30	30	30	35	20
Filter Cake Production, dry kg/s (tons/hr)	7.71 (30.6)	8.01 (31.8)	7.31 (29.0)	9.45 (37.5)	7.36 (29.2)
Per Cent Solids in Filter Cake	53	60	48	64	55

*Stoichometric rate based on SO_2 removed.

**Added to thickener overflow tank.

costs were levelized over the expected plant life and then capitalized for use in the evaluation.

The completed evaluation is shown in Figures 8-1 through 8-6.

8.4 PROPOSAL ADJUSTMENT COSTS

All of the manufacturers took various exceptions to the technical portion of the specification. The proposal adjustment costs are the costs which have been added to each manufacturer's proposal price in order to meet the intent of the specification. Examples of proposal adjustment costs are the cost of spare recirculation pumps, ductwork which was not supplied, changes in materials of construction, and various other pieces of equipment. The proposal adjustment costs summarized in Figure 8-2 were supplied by the manufacturers or were estimated.

Additional discussion of the adjustments made to each manufacturer's proposal is contained in Section 8.8, TECHNICAL EVALUATION.

8.5 BALANCE OF PLANT COSTS

These are costs which, although not a part of the manufacturer's scope of supply, would be incurred in completing the equipment and are therefore necessary for a comparison of prices. These costs are summarized in Figure 8-3 and are described in the following subsections.

8.5.1 Foundations

The amount of concrete foundations and piling necessary was estimated and a cost for material and labor was added in the evaluation of each bidder.

8.5.2 Structural Steel and Enclosures

The amount of structural steel for module and building support, platforms and stairs, and the amount of wall panel and roofing material was estimated and an erected cost was added in the evaluation.

8.5.3 Electrical Power Supply

The amount of electrical wiring, conduit, starters, cable trays, circuit breakers, and other miscellaneous electrical equipment necessary for a complete installation was estimated and an installed cost was added in the evaluation.

8.5.4 Ductwork

Each of the manufacturers included a different amount of ductwork in their scope of supply. In order to compare all of the bids on an equal basis, points on the inlet and outlet of the system were selected as reference points, and additions or deductions from each manufacturer's offering were made from these points.

8.6 COMMERCIAL COSTS

The costs of escalation and interest during construction were calculated and added to the bid evaluation. Each manufacturer's stated terms of payment and price adjustment policies were used in determining the commercial costs. The commercial costs are summarized in Figure 8-4.

BID TABULATION SUMMARY

LIME FGD SYSTEM

PROPOSAL PRICE DATA

NAME AND ADDRESS OF BIDDER	BIDDER A	BIDDER B	BIDDER C	BIDDER D	BIDDER E	
DESCRIPTION	Lime	Lime	Lime	Limestone	Dual-Alkali	
1. Proposal Price Data						
A. Base Price-Materials	13,743,000	14,566,000	9,097,000	16,280,000	9,740,000	
Field Erection	6,456,000	4,358,000	6,270,000	6,975,000	3,703,000	

FIGURE 8-1

BID TABULATION SUMMARY

LIME FGD STUDY

ADJUSTED COSTS

NAME AND ADDRESS OF BIDDER	BIDDER A	BIDDER B	BIDDER C	BIDDER D	BIDDER E	
DESCRIPTION	Lime	Lime	Lime	Limestone	Dual-Alkali	
2. Proposal Adjusted Costs						
Ductwork	525,000	742,000	126,000	380,000	492,000	
Recirculation Pumps and Spray Headers	125,000	530,000	-	920,000	-	
Dampers	92,700	-	145,000	145,000	-	
Scrubber Module	-		90,000	40,000	330,000	
Expansion Joints	28,000	(11,000)	-	24,000	81,000	
Observation Ports	-	-	-	56,000	-	
Electrical Equip.	-	20,000	12,000	-	-	
Insulation & Lagging	195,000	10,000	195,000	195,000	-	
Miscellaneous Tanks	(6,000)	17,000	(44,000)	21,000	(10,000)	
Total Proposal Adjusted Price	959,700	1,308,000	524,000	1,781,000	893,000	
Differential Proposal Adjusted Price	435,700	784,000	Base	1,257,000	369,000	

FIGURE 8-2

BID TABULATION SUMMARY

LIME FGD STUDY

BALANCE OF PLANT COSTS

NAME AND ADDRESS OF BIDDER	BIDDER A	BIDDER B	BIDDER C	BIDDER D	BIDDER E	
DESCRIPTION	Lime	Lime	Lime	Limestone	Dual-Alkali	
3. Differential Balance of Plant						
Foundations	190,000	30,000	160,000	180,000	Base	
Structural Steel and Enclosures	950,000	385,000	470,000	540,000	500,000	
Power Supply	21,000	150,000	55,000	48,000	Base	
Ductwork	Base	55,000	197,000	42,000	62,000	
Total Differential Balance of Plant	1,161,000	620,000	882,000	810,000	562,000	
Differential Balance of Plant	599,000	58,000	320,000	248,000	Base	

FIGURE 8-3

BID TABULATION SUMMARY

LIME FGD STUDY

COMMERCIAL COSTS

NAME AND ADDRESS OF BIDDER	Bidder A	Bidder B	Bidder C	Bidder D	Bidder E	
DESCRIPTION	Lime	Lime	Lime	Limestone	Dual-Alkali	
4. Commercial Costs						
A. Escalation						
Material	956,000	952,000	FIRM	977,000	708,000	
Erection	647,000	229,000	FIRM	418,000	408,000	
B. Interest						
Material	1,312,000	1,211,000	667,000	1,324,000	964,000	
Erection	424,000	263,000	463,000	485,000	240,000	
C. Total Commercial Cost	3,339,000	2,655,000	1,130,000	3,204,000	2,320,000	
D. Differential Commercial Costs	2,209,000	1,525,000	BASE	2,074,000	1,190,000	

FIGURE 8-4

BID TABULATION SUMMARY

LIME FGD STUDY

OPERATING COSTS

NAME AND ADDRESS OF BIDDER	Bidder A	Bidder B	Bidder C	Bidder D	Bidder E	
DESCRIPTION	Lime	Lime	Lime	Limestone	Dual-Alkali	
5. Capitalized Operating Costs						
A. Additive	2,460,000	2,460,000	2,460,000	615,000	12,016,000	
B. Steam	--	--	--	--	370,000	
C. Water	235,000	185,000	27,000	298,000	165,000	
D. Air	BASE	37,000	BASE	118,000	BASE	
E. Power						
Demand	1,538,000	1,010,000	1,619,000	1,277,000	BASE	
Energy	1,010,000	1,564,000	2,159,000	1,145,000	BASE	
F. Sludge Disposal	1,926,000	1,926,000	1,926,000	3,720,000	BASE	
G. Comparative Operating Costs	7,169,000	7,182,000	8,191,000	7,173,000	12,551,000	
H. Differential Operating Costs	BASE	13,000	1,022,000	4,000	5,382,000	

FIGURE 8-5

BID TABULATION SUMMARY

LIME FGD STUDY

TOTAL EVALUATED COSTS

NAME AND ADDRESS OF BIDDER	Bidder A	Bidder B	Bidder C	Bidder D	Bidder E	
DESCRIPTION	Lime	Lime	Lime	Limestone	Dual-Alkali	
6. Total Evaluated Costs						
A. Proposal Price	20,199,000	18,924,000	15,367,000	23,255,000	13,443,000	
B. Differential Adjusted Price	435,700	784,000	BASE	1,257,000	369,000	
C. Differential Balance of Plant	599,000	58,000	320,000	248,000	BASE	
D. Differential Commercial Costs	2,209,000	1,525,000	BASE	2,074,000	1,190,000	
E. Differential Capitalized Oper. Costs	BASE	13,000	1,022,000	4,000	5,386,000	
F. Total Comparative Evaluated Costs	23,442,700	21,304,000	16,709,000	26,838,000	20,388,000	
G. Differential Evaluated Costs	6,733,700	4,595,000	BASE	10,129,000	3,675,000	

FIGURE 8-6

8.6.1 Escalation

The costs due to escalation were calculated based on an annual rate of 6 per cent. The escalation was based on each manufacturer's delivery and erection schedule, when one was given, or on an estimated schedule. The starting and ending dates for price escalation are those given by each manufacturer, unless none were given, in which case the estimated delivery and erection schedule were used. The price used to calculate the escalation includes the base proposal price plus all proposal adjustment costs.

8.6.2 Interest During Construction

The interest during construction was based on the escalated bid price which was calculated using the manufacturer's terms of payment and the 6 per cent escalation rate. The interest is calculated from the date of payment to the date of commercial operation. Simple interest at an annual rate of 7 per cent was used in this evaluation.

8.7 OPERATING COSTS

In order to compare the lime, limestone, and dual-alkali scrubbing systems, the costs of additives, plant services, electric demand and energy, and sludge disposal must be evaluated for each manufacturer's system.

The rate of additive consumption was calculated based on the required sulfur dioxide removal rate at average load. The lime usage rate for all three lime systems was judged to be the same due to the similarities in the process chemistries of the systems.

The soda ash usage rate could not be calculated due to a lack of available information on dual-alkali systems. Therefore, the more conservative estimate of soda ash usage at average load presented in the proposal data sheets was used.

The costs of plant services and electric demand and energy were based on the usages given in the proposals. The electric demand and energy, and fresh water usage rates were discounted to account for the variations in the methods used to calculate those values.

The operating costs are summarized in Figure 8-5.

8.8 TECHNICAL EVALUATION

The technical portion of each manufacturer's offering is discussed below. Detailed discussion of each area of the proposals adjusted in Figure 8-2 is beyond the scope of this case study. However, for the purpose of illustration, the following subsections consider two specific areas of each bidder's proposal which required adjustment to meet the specification.

8.8.1 Bidder A

8.8.1.1 Ductwork. An adjustment cost has been added to the proposal cost for providing 15 metres (50 feet) of outlet duct, and a mixing chamber.

8.8.1.2 Recirculation Pumps. Bidder A will provide two spare pumps for every five in service instead of the original one spare pump. This does not meet the requirement of three 50 per cent capacity pumps, but is considered adequate. An adjustment cost has been added to the proposal cost for supplying these pumps.

8.8.2 Bidder B

8.8.2.1 Additive Preparation Equipment. Bidder B's proposal did not include a spare lime slurry tank agitator. In addition, the slurry tank was inadequately sized. Price adjustments were added to the proposal.

8.8.2.2 Recirculation Pumps. Bidder B did not include any spare recirculation pumps. A cost adjustment for spare pumps has been made.

8.8.3 Bidder C

8.8.3.1 Dampers. Single louver dampers were offered for both the scrubber module inlets and outlets. Double isolation is required and a total of eight additional single louver dampers are needed. An adjustment cost has been added to the proposal cost.

8.8.3.2 Absorber Module Shell. The bidder will provide the neoprene rubber lining specified in lieu of the sprayed-on vinyl coating proposed. An adjustment cost has been added to the proposal cost.

8.8.4 Bidder D

8.8.4.1 Absorber Shell. The base bid included a combination of 317L stainless steel and precrete lined carbon steel for the absorber shell material. The evaluation is based on neoprene rubber lined carbon steel, and therefore an adjustment cost has been added to the proposal cost.

8.8.4.2 Ductwork Arrangement. The ductwork arrangement did not meet the intent of the specification. Bidder D has provided an adjustment cost for a suitable ductwork arrangement.

8.8.5 Bidder E

8.8.5.1 Absorber. Unlined carbon steel was proposed as the material for the absorber shell and is not acceptable. Neoprene rubber lined carbon steel is specified. An adjustment cost has been added to the proposal cost.

8.8.5.2 Expansion Joints. The bidder will provide Garlock Style 8400, Series 400 expansion joints in lieu of Garlock Style 8400, Series 300. An adjustment cost has been added to the proposal cost.

8.8.6 Other Considerations

Prior to the award of the contract, the gas pressure drop through the scrubber modules and the sizing of the booster fan, the ductwork, the bypass, the mixing chambers, and the scrubber modules should be verified.

Prior to the award of the contract, the degree of flexibility in the arrangement of the additive storage and preparation facilities should be discussed to accommodate various methods of transportation from bulk storage to day tanks and slakers.

The maintenance requirements of the various systems has not been included in the comparison of lime, limestone, and dual-alkali systems. Since a dual-alkali scrubber uses a clear solution instead of a slurry for scrubbing, there would be less scaling and abrasion. This would result in a lower maintenance cost for a dual-alkali system, but since it is difficult to accurately judge the value of the maintenance saving, no dollar value has been placed on it in this evaluation.

8.9 COMMERCIAL EVALUATION

Numerous exceptions were taken by each bidder to the commercial terms of the specifications. Only the major exceptions are discussed in this section. All of the exceptions taken by the successful bidder should be clarified and resolved prior to award of the contract.

8.9.1 Performance Guarantee

The major exceptions taken to the specified performance guarantees by each bidder are as follows.

8.9.1.1 Bidder A. During the Reliability Run, the FGD System is required to operate no less than 90 per cent of the hours that it is called on to operate and periodic emission peaks of 30 minutes or less duration shall be considered to be within the guarantee requirement providing that the average of emission levels does not exceed the guarantee levels.

The liability under the emission guarantees is not to exceed the value of the equipment quoted in Bidder A's Technical Proposal. Also, the liability for failing to meet operating costs is limited to five per cent of the contract.

8.9.1.2 Bidder B. Performance Test A is required to be completed within seven days from the date of Bidder B's last notice that the FGD System is ready for testing, but no later than six months after mechanical completion of the FGD System. Performance Test B is required to be completed within seven days from the date of the last notice that the FGD System is ready for testing, but no later than 12 months after satisfactory completion of Performance Test A. Failure to meet these dates, through no fault of the bidder, will result in the performance tests being considered successfully completed.

8.9.1.3 Bidder C. The Reliability Run is required to be completed within one year after completion of Performance Test A. Also, Performance Test B must be conducted approximately 10 months after completion of erection. Failure to meet this schedule through no fault of Bidder C, will result in the tests being considered to be successfully completed. All tests including retesting for non-performance, are at the expense of the Owner.

8.9.1.4 Bidder D. All performance guarantees as required in this specifications have been deleted. The proposed warranty includes only material and workmanship. The effect of the substituted warranty is that Bidder D will provide equipment constructed of good material and in a workmanlike manner, but they will not make any warranty or guarantee regarding the performance of the equipment.

8.9.1.5 Bidder E. Three performance tests are required to be conducted after the completion of the FGD System. Dates of each performance test are recommended by Bidder E who will notify the Owner two weeks in advance. Commencement of each performance test must be prompt. Test results must be delivered to the Owner within 10 days after completion of each test and upon the receipt of the test results, the Owner must inform Bidder E in writing within 10 days concerning the status of the performance test. Should the FGD System fail the performance test, Bidder E will then proceed with the necessary corrective measures, or at their option, provide or pay for the equivalent of two years of operating costs in excess of that specified. All tests are at the expense of the Owner.

8.9.2 Schedule

Several of the bidders took minor exceptions to the specified drawing submittal schedule. None of the exceptions should seriously affect the scheduled completion of the units. These variations should be resolved with the successful bidder before contract award.

8.9.3 Other Commercial Considerations

The following is a listing of the major commercial exceptions taken by the bidders.

8.9.3.1 Bidder A. Bidder A will not be responsible for delays caused by latent site conditions. Their profit and overhead portion for extra work will be calculated as 15 per cent of the direct cost for overhead and 10 per cent of the direct cost for profit rather than the 10 per cent of direct cost for overhead and profit listed in the specification.

8.9.3.2 Bidder B. The proposal from Bidder B is based on statutes and regulations which are currently in effect. Any revisions to these statutes or regulations which affects the proposed equipment will require pricing adjustments. The system is considered to be mechanically complete and will be turned over to the Owner for operation when all work except for painting, insulation, and cleanup is completed.

8.9.3.3 Bidder D. Bidder D has taken a number of exceptions to other commercial sections of the specification. These will require further negotiation prior to contract award.

8.9.3.4 Bidder E. Bidder E will not be liable for consequential or economic damages for their negligence including fines for non-compliance with laws and regulations. Any liquidated damages for non-compliance with the schedule will not exceed $2,000,000.

9.0 EQUIPMENT ERECTION AND STARTUP, PERFORMANCE TESTING, AND OPERATION

Following specification (Section 7.0) of the desired flue gas desulfurization (FGD) system and evaluation of bid proposals (Section 8.0), the important aspects of erecting, testing, and operating the selected FGD system must be accomplished. Although the Lime FGD Systems Data Book and the FGD Sludge Disposal Manual do not directly address these areas which occur after equipment selection, some of the more important considerations are described here in the case study to illustrate how the design objectives and performance of the FGD equipment is demonstrated.

Careful management of the erection effort is required to ensure that the objectives of the FGD specification are met by the installed equipment. Testing of the FGD system is required to demonstrate compliance with applicable flue gas emission regulations as well as to demonstrate that the equipment meets the equipment vendor's performance guarantees for both emissions and operating costs. During subsequent operation of the FGD system, operator training, record keeping, and maintenance are important considerations in the resulting reliability of the system. Particularly during the early operational period of the FGD system, careful observation and monitoring of the system reliability is required to satisfy contractual system performance reliability requirements.

9.1 ERECTION AND STARTUP

The successful FGD system vendor must be informed of the overall power generation unit project schedule and the other interfaces between his work and the work of other contractors on site. A detailed FGD system erection and subsystem shakedown schedule must be developed and followed from the start of construction activities. Well planned startup and shakedown of major FGD subsystems and components can minimize the impact of construction errors or design deficiencies on scheduled overall system startup. The major FGD subsystems include the scrubber additive system, the scrubber liquid loops, and the scrubber sludge thickener and the balance of the sludge disposal system. Representatives of the appropriate equipment suppliers should be present during initial startup of their equipment.

9.1.1 Erection Management

The following is a listing of the major requirements for effective field erection management of a large central station power plant. The FGD system represents one of the major systems constructed and is managed as part of the overall power plant construction activities.

- RESIDENT STAFF. Provide a resident management and field engineering staff which is appropriately sized and staffed to meet the particular needs of the project.
- CONTRACTOR COORDINATION. Management of the physical construction through coordinating, interfacing, and guiding the various construction contractors.
- STARTUP. Management of plant system completion and subsequent startup coordination.
- CONTRACT ADMINISTRATION. Provide complete contract administration of both construction contracts and material supply contracts, which includes, for example administration of contract certification for progress payments, change orders, contract files, and interfacing with the utility.
- INVENTORY AND STORAGE. Provide management of inventory control and storage maintenance of all utility-supplied material and equipment.
- DOCUMENT CONTROL. Provide all document control and clerical services required to support the field management operations. This includes control of all documents, communications records, and the responsibility to control and distribute construction documents to all construction organizations.
- QUALITY ASSURANCE. Provide a Quality Assurance Program to assure that the quality control procedures implemented pursuant to managing the physical construction are effective and that design specifications are met.
- SITE SERVICES. Provide complete management of all site services required to support the construction effort. This includes, for example, security services, sanitary services, health services, fire protection services, road maintenance, potable water supply, cleanup, and other services applicable to the entire construction.
- PROGRESS REPORTS. Provide complete progress and status reporting to utility management.

The construction management team is rather small initially and expands gradually to a maximum occuring some six months before operation and then again declines as the operating date is approached.

9.1.2 Pre-Construction Activities

Written procedures for construction management of the project must be prepared in advance of construction to govern the actions of the project field organization, project documentation, and lines of communication with the utility and the construction contractors. The procedures should include standard forms for use in controlling activities on the project.

The requirements and arrangement of construction facilities must also be established. The construction of physical facilities required for construction management, warehousing, construction power, construction welding, cleanup, and other services are conducted as part of the construction activities.

9.1.3 Activities During Construction

The responsibility of the erection team during construction include the following.

- COORDINATION. Coordination between contractors, resolution of conflicts, assistance in determining priorities for allocation of labor supply, and similar functions.
- FIELD ENGINEERING. Interpretation of plans and specifications and manufacturers' drawings and correction of minor interferences and conflicts.
- RECEIVING. Inspect utility furnished equipment and material received at the project site. Prepare receiving reports and the records of transfer of material and equipment to the contractor having the responsibility to unload, store, and install. Follow-up activities are necessary such as handling loss claims and correction of manufacturing errors.
- SAFETY AND FIRE PROTECTION. Inspect the project site and advise contractors in writing of any observed unsafe conditions and fire hazards, and to followup on the contractors' corrective actions. Final responsibility for safety and fire protection is with the contractor.
- PROGRESS REPORTS. Prepare weekly and monthly progress reports, including such information as the labor force, weather conference memorandums, photographs, and other significant information related to construction progress.
- QUALITY CONTROL. Conduct an appropriate quality control program. This will include monitoring of the contractors' quality control programs as well as inspection of the quality of each contractor's work and monitoring conformance to the plans and specifications.
- CHECKOUT AND TESTING. Provide assistance for pre-operational checking and testing work as required. This will include determination of the extent of systems completion and the coordination of construction work to allow completion in appropriate sequence for startup.
- OSHA. Provide surveillance of contractors' operations with respect to responsibilities for compliance with OSHA.
- SECURITY. Administer the program of security with respect to the physical plant and for the ingress and egress of construction and visiting personnel. Security guards or other security personnel are normally provided on a contract basis.

- INSURANCE. Assist the utility with respect to insurance and the processing of claims.
- AS-BUILT RECORDS. Maintain marked copies of drawings to show reported changes made during construction. The marked copies will be forwarded to the design office for revision of the tracings to conform with actual construction records.

9.2 PERFORMANCE TESTING

A test plan should be written which describes test protocol. This document describes the responsibilities of all participants, the power generation unit and combustion gas cleaning system operational requirements and the test and analysis methods which will be used. An important part of this document will be listing the goals of the test program so that the end use of the data gathered is well established. This will also allow combination of tests to determine system performance and to demonstrate regulatory compliance.

One individual should coordinate the overall testing activities in the field. This individual should coordinate boiler and FGD system operation with the test team work schedule.

All tests should be performed at steady-state boiler load conditions. Load should be stabilized for at least an hour prior to the start of testing. FGD system operations should be maintained at constant conditions during the tests. The FGD system operation should be stabilized for at least one hour prior to testing, for gas stream sampling. For liquid/slurry stream sampling, a much longer stabilization period may be required to reach steady-state conditions. Testing should be interrupted during long term boiler or FGD system upsets. Minor changes which occur do not necessarily require that testing be interrupted since most of the gas stream measurement techniques used are time averaged.

9.2.1 Purpose

Flue gas stream sampling and analysis is performed to demonstrate compliance with the emission standards listed in Table 2-7 and to illustrate that performance guarantees of the type listed in Appendix A are satisfied.

Emission compliance testing consists of measurements for sulfur dioxide (SO_2), particulate, and nitrogen oxides (NO_x). The FGD system is a major factor in the SO_2 emission level, but depending on the overall combustion gas cleaning system design, which may include a separate particulate removal device, it may have only a minor effect on particulate emission levels. The FGD system has no appreciable effect on NO_x emission levels which are normally limited to required levels by boiler design and operating conditions.

The FGD system performance guarantee testing will depend upon the guarantees established by the FGD system specification requirements and as part of the contract negotiations with the successful equipment vendor. This testing will commonly consist of SO_2 removal efficiency measurements, particulate emission rate and/or removal efficiency, scrubber additive usage, and may also include items such as combustion gas stream pressure loss, water usage, and scrubber sludge generation rate.

9.2.2 Sampling and Measurement Techniques

9.2.2.1 Sampling Locations. The purpose of the test will, to some degree, influence the selection of the sampling locations. Regulated emission compliance tests will generally be performed at selected sites in the gas stream following all the pollution control equipment. Performance tests, on the other hand, may include both inlet and outlet gas stream measurements on each piece of equipment. Selection of sampling sites may allow combination of tests, for instance the outlet of the electrostatic precipitator is also the scrubber inlet.

The EPA has provided guidelines for gas stream measurement locations and they are described in standard Method 1 of Appendix A of Title 40 of the Code of Federal Regulations (CFR) Part 60. The guidelines are intended to aid in the selection of a sampling site and to determine the number of traverse points which will yield a representative gas stream sample. The requirements of EPA Method 1 should be considered prior to construction of the power generation unit and associated flue gas cleaning system.

The guidelines suggest that a sampling site be at least 8 stack or duct diameters downstream and 2 diameters upstream from any flow disturbance such as a bend. If these criteria are impractical, an alternate site that is at least 2 stack or duct diameters downstream and 0.5 diameter upstream from flow disturbances may be selected.

When 8 and 2 diameter criterion can be met, the minimum number of sample collection traverse points shall be 12 for stack or duct diameters greater than 0.6 metres (2 feet) and 9 for smaller stack diameters. When the 8 and 2 diameter criterion cannot be met, the minimum number of traverse points is determined by considering the specific configuration of the system being sampled.

9.2.2.2 Regulated Emissions Compliance Testing. The applicable emission standards for the present case study are listed in Table 2-7 for SO_2, NO_x, and particulate. The requirements for continuous monitoring of pollutants emitted from new coal-fired generating stations are also described in Table 2-7.

Continuous source monitors were not originally intended to demonstrate compliance with the new source emission standards. To prove or disprove source compliance, the manual EPA reference sampling and analysis methods listed in Table 9-1

TABLE 9-1. EPA REFERENCE METHODS* FOR SAMPLING AND ANALYZING REGULATED EMISSIONS

Emission Parameter	EPA Manual Reference Method
Sampling Location Selection	Method 1
Sulfur Dioxide (SO_2)	Method 6
Particulate	Method 5
Nitrogen Oxides (NO_x)	Method 7

*Described in Appendix A of Part 60 of Title 40 of the Code of Federal Regulations.

and described in detail in Appendix A, Part 60 of Title 40 of the Code of Federal Regulations must still be performed. Several states, however, are developing enforcement programs utilizing continuous monitoring data. Further developments of this type are expected on the Federal level, as well as from the States.

The Method 6 determination of SO_2 emissions from stationary sources involves extraction of a gas sample from the stack by drawing the gas through a probe by using a pump. The probe is inserted at an appropriately selected sampling site. The probe is made of borosilicate glass, approximately 5 to 6 mm ID, with a heating system to prevent water condensation and equipped with a filter to separate the particulate matter, including sulfuric acid mist (SO_3), from the sulfur dioxide in the gas stream. A bubbler and a series of three impingers are connected in series to the probe and serve to prevent acid mist carryover and remove the SO_2 from the gas stream, respectively. Hydrogen peroxide solution in the impingers removes the SO_2 which is measured by titration with barium-thorin solution. The minimum detectable limit of the method has been determined to be 3.4 mg of SO_2/m^3.

The Method 5 determination of particulate emission from stationary sources involves isokinetically drawing a gas stream sample with a pump from the source through a glass-lined probe and collecting the particulate on a glass fiber filter maintained at temperatures in the range of 120± 14 C (248± 25 F) or higher if the stack temperature is greater than this value. The mass of the particulate is determined gravimetrically after removal of uncombined water (i.e., after drying). The sampling probe is normally lined with borosilicate or quartz glass tubing and is provided with an appropriate heating system. A type "S" pitot tube or similar device is attached to the probe to allow constant monitoring of the stack gas velocity during sampling. An impinger train or an alternate condenser system is connected in series to the probe to measure the amount of water in the gas stream. The impinger system can be modified to permit simultaneous measurement of SO_2 with this sampling system.

The Method 7 determination of nitrogen oxide emissions from stationary sources involves collection of a grab sample in an evacuated flask containing a dilute sulfuric acid-hydrogen peroxide absorbing solution. The nitrogen oxides, except nitrous oxide, are measured spectrophotometrically. This method is applicable to the measurement of nitrogen oxides in the range of 2 to 400 milligrams NO_x as NO_2 per dry standard cubic meter without having to dilute the sample. The sample is drawn through a borosilicate glass tubing by using a pump. The probe is sufficiently heated to prevent water condensation and is equipped with a filter to remove particulate matter.

9.2.2.3 Performance Guarantee Testing. The FGD system SO_2 removal efficiency is determined by measuring SO_2 concentrations at the inlet and outlet of the scrubber system. Similarly, particulate removal efficiency is determined by particulate measurements at both the inlet and outlet of the particulate removal system, which may also be the SO_2 scrubber. In the case of a separate particulate removal system located upstream of the scrubber, it may be necessary and/or required to measure particulate at the outlet of the scrubber since in some instances a small amount of particulate can be generated by the scrubber. Nitrogen oxide emissions are not presently reduced by an emission control device, but emission testing would probably be performed at the stack to confirm boiler guarantees.

Lime stoichiometry (lime usage) and water usage may also be guaranteed at designated emission performance levels for the FGD system and require confirming performance tests. The water usage requirements of the scrubber are determined by measuring selected process stream flow rates and densities and performing the water balance determination described in Section 4.5. Simply, a good water mass balance, from which water usage is determined, must satisfy the requirement that the input of water in the flue gas stream, the lime additive slurry feed, and the makeup water streams plus any accumulation in the scrubber system must equal the water in the output streams consisting of the moisture in the flue gas outlet and the water lost in the scrubber sludge. These streams are shown in Figure 4-3.

Lime stoichiometry is the molar ratio of the amount of lime (CaO and MgO) required to the amount of gaseous sulfur (SO_2 and SO_3) removed by the FGD system or simply, lime added/SO_2 removed. Lime utilization is the reciprocal of the lime stoichiometric ratio. Lime stoichiometry may be determined by measuring the lime feed rate and the SO_2 removal rate or by performing a calcium, magnesium, and sulfur material balance for the scrubber input and output streams described in Section 4.4 and depicted in Figure 4-2. The mass balance approach is more accurate but involves significantly more chemical analysis measurements. Determination of lime stoichiometries by performance testing is probably not more accurate than about ± 10 to 20 per cent when inherent accuracies of flow measurement of liquid/slurry and gaseous streams and chemical sampling and analysis techniques are considered. Calibration of flow measurement instrumentation is important in determining operational performance of the FGD system for parameters such as water usage.

9.3 OPERATION

To achieve required high levels of FGD system reliability, good operator training, operational record keeping, and preventative maintenance programs are necessary.

9.3.1 Operator Training

The operators of the FGD system should be thoroughly trained in the operation of the system. Well trained operators are able to make intelligent decisions about off-normal excursions and changing conditions and initiate anticipatory corrective actions which can minimize operating and maintenance costs and reduce system perturbations. Refresher training sessions can help to keep operators up to date on changing requirements and changes which may optimize system operation. The responsibilities and duties of all maintenance personnel and operators should be well defined. This will minimize problems when malfunctions do occur.

9.3.2 Record Keeping

A detailed FGD system operating log should be maintained. This should identify system malfunctions and modes of operation. From these records, equipment histories, and trouble areas can be identified and potentially reduced or eliminated. Also, early demonstrated system reliability is frequently a guarantee performance parameter for which careful operational records are required.

Operators should also record scrubber operational data, for key flow rates and parameters such as recycle slurry pH, hourly during each shift. This will keep the operator aware of system performance as well as define scrubber operations for training and may suggest system optimization studies.

9.3.3 Preventive Maintenance

There should be a well defined preventive maintenance program for the FGD system. The maintenance can be performed on equipment which is not in service because of low system demand or because spare equipment is available. The maintenance requirements for each piece of equipment should be found in appropriate instruction manuals. A good preventive maintenance program should include good housekeeping programs. Work is easier and completed quicker in a clean area. All spills and overflows should be cleaned quickly. Operator and maintenance personnel responsibilities and duties should also be well defined for housecleaning programs.

Equipment which has been provided with piped-in spares should be rotated in and out of service on an interval which is frequent enough to keep it ready for service. This will also keep lines clear of plugging in dead legs both upstream and downstream of shutoff valves.

APPENDIX A

PURCHASE SPECIFICATIONS
EQUIPMENT REQUIREMENTS SECTION

APPENDIX A
PURCHASE SPECIFICATIONS
EQUIPMENT REQUIREMENTS SECTION

A.1 DESIGN BASIS

A.1.1 GENERAL

This section specifies the operating conditions and design and performance requirements for the flue gas scrubber and associated auxiliary equipment.

The Specifications are based on a four module scrubber with each module designed to treat one-third of the design flue gas flow. More than four modules may be provided if required by the bidder's design to comply with any of the requirements of the Specifications and documents. Regardless of the quantity of modules provided, one shall be a spare.

The flue gas scrubber shall be designed for utility power plant operation. The flue gas scrubber will serve one coal fired steam generator. The steam generator will be equipped with an electrostatic precipitator located to remove particulate matter from the flue gas after it discharges from the rotary regenerative type air preheaters. Induced draft fans will be furnished by the Utility to draw the flue gas from the furnace through the air heaters and electrostatic precipitator and to discharge to the scrubber. The scrubber shall be designed for pressurized operation.

Each scrubber module shall be capable of independent operation. Each module shall be provided with dampers on the flue gas inlet and outlet. A bypass duct and damper shall be provided for unit startup and shutdown.

A.1.2 ARRANGEMENT

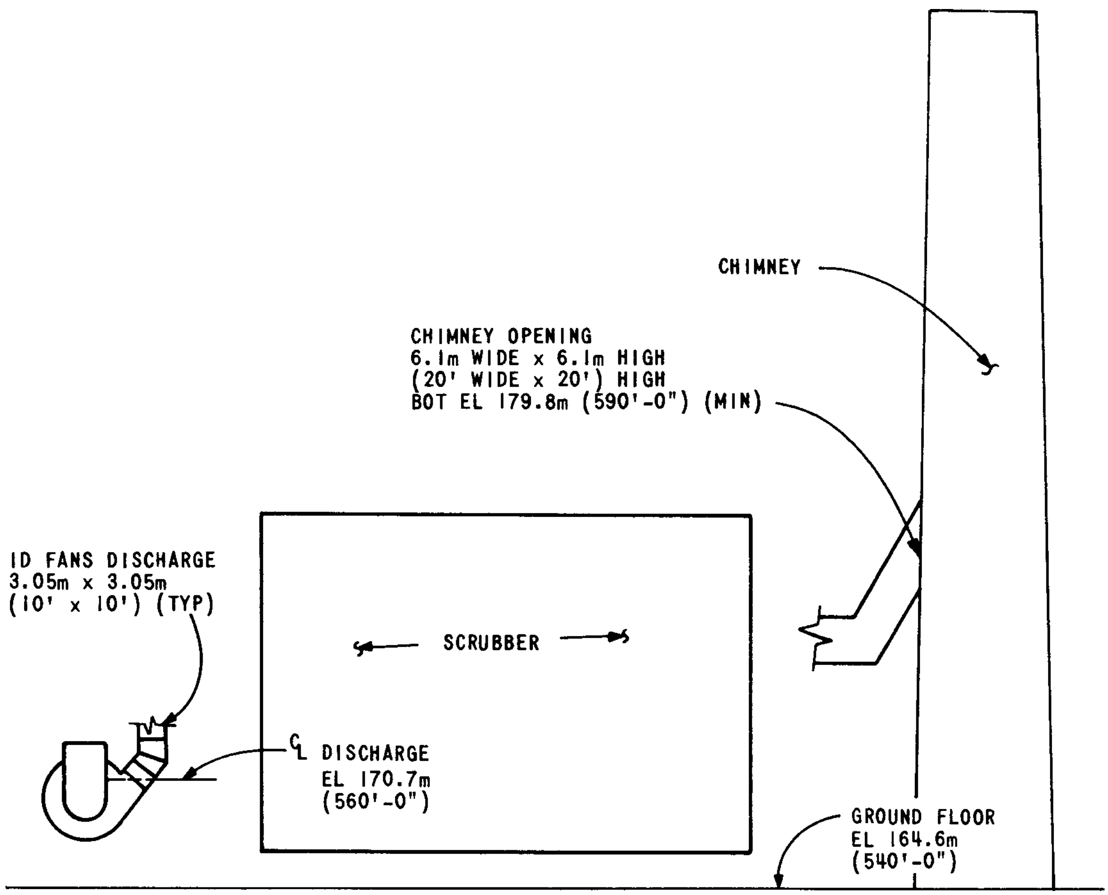
General arrangement area of the flue gas scrubber is indicated on the following arrangement drawings included herein.

- SCRUBBER AREA SIDE ELEVATION (Figure A.1-1)
- SCRUBBER AREA PLAN (Figure A.1-2)
- SCRUBBER DUCTWORK SCHEMATIC (Figure A.1-3)

The space available for location of flue gas scrubber components is indicated on the arrangement drawings.

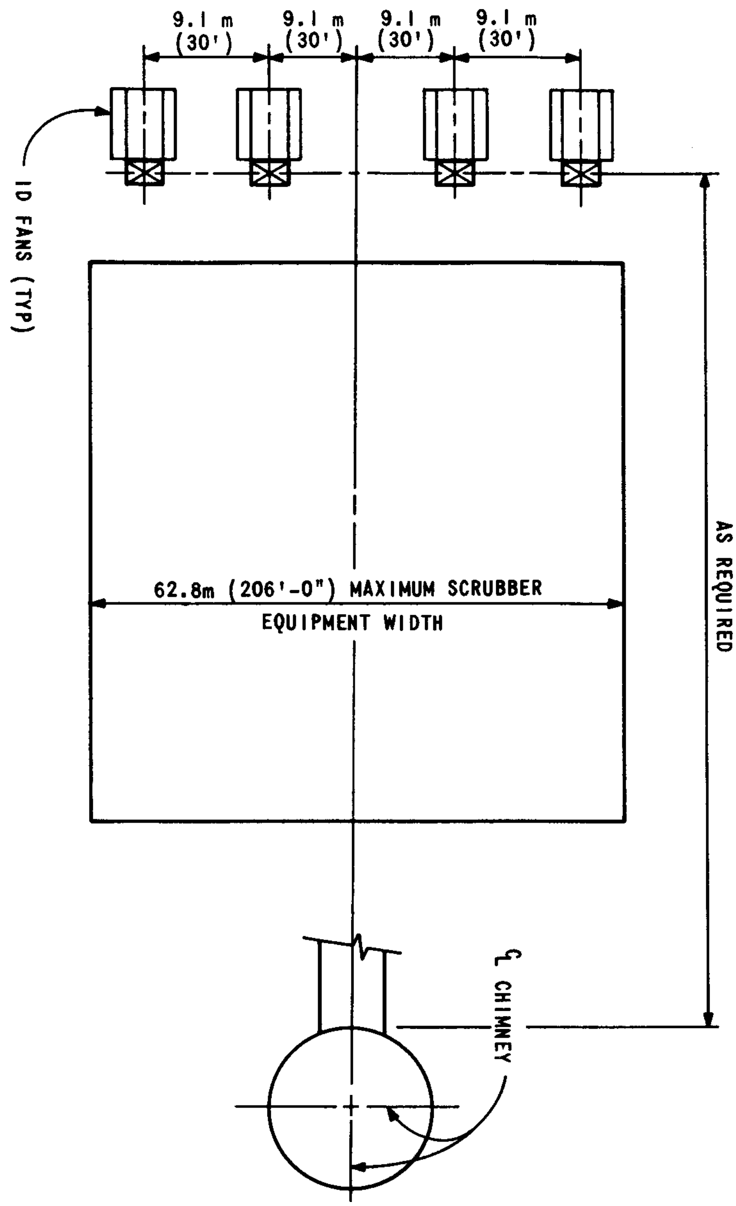
A proposal shall be submitted based on the arrangement area indicated on the listed drawings.

Alternate arrangements or modifications of the arrangement indicated on the drawings will be considered. Complete information shall be submitted for each proposed alternate arrangement or proposed modification to the arrangement indicated on the drawings. Special consideration shall be given to minimizing the extent of scrubber outlet ductwork.



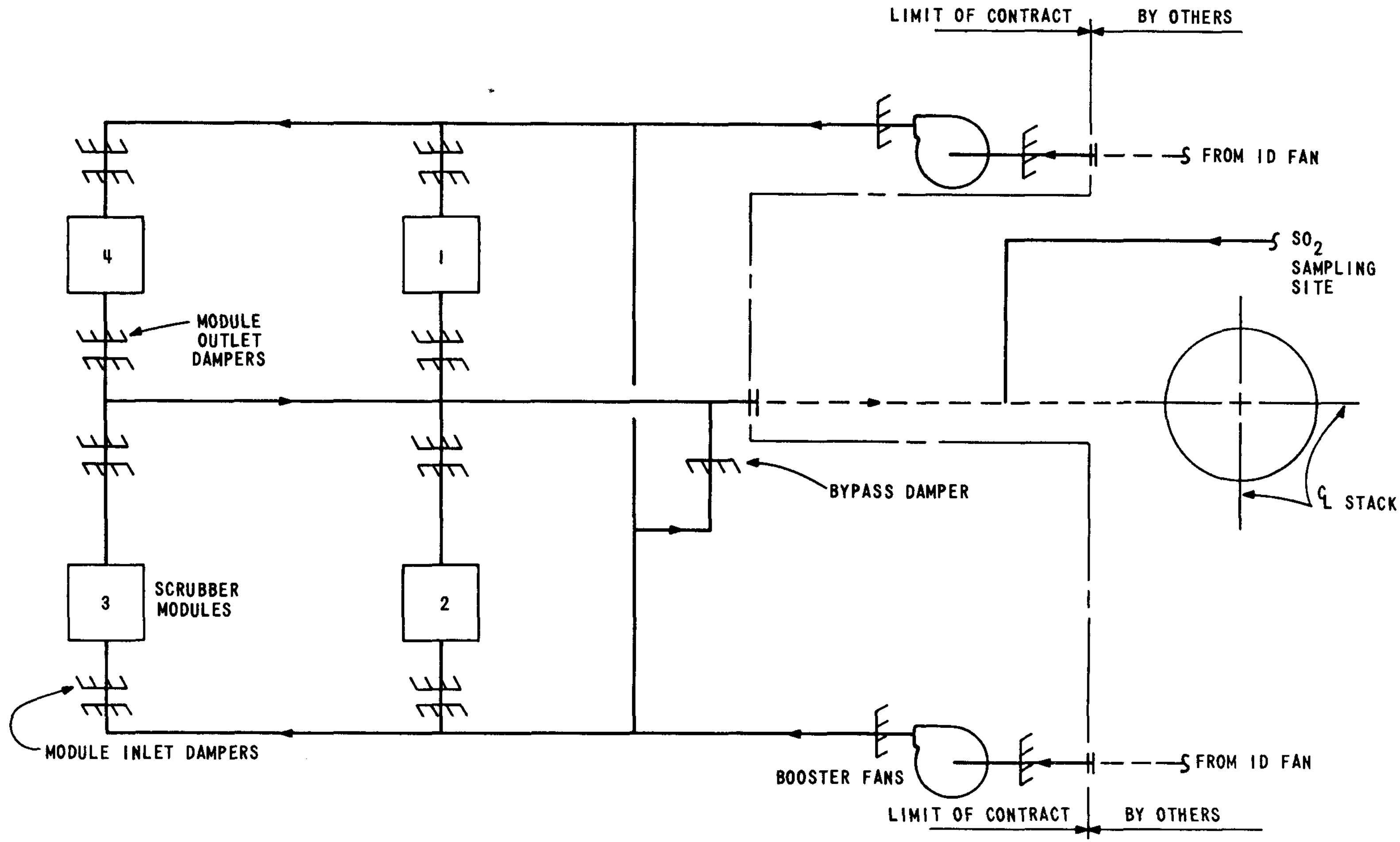
SCRUBBER AREA
SIDE ELEVATION

FIGURE A.1-1



SCRUBBER AREA PLAN

FIGURE A.1-2



SCRUBBER DUCTWORK SCHEMATIC

FIGURE A.1-3

The Utility will provide a building to enclose the scrubber modules, scrubber pumps, slurry pumps, and instrumentation and control equipment. All other equipment will be located outdoors.

Each bidder shall provide arrangement drawings showing his suggested arrangement of the equipment. The final equipment arrangement shall provide adequate space for access, maintenance, stairwells, walkways, elevator, laydown area, access hoistways, monorails, and space for Utility-furnished equipment in the scrubber area.

Control panels, monitoring devices, and control system components, except primary sensing devices and local instruments, shall be located in the scrubber local control room. Complete monitoring capability of the scrubber and slurry disposal systems shall be provided to the Utility's computer system located in the main plant control room. Scrubber controls provided for the main control room shall be as required to control the flue gas flow through the scrubber. The main control room operator will place modules in and out of service. The main and local control rooms will be space conditioned for personnel comfort.

A.1.3 TYPE

The flue gas scrubber shall be countercurrent spray tower or crosscurrent spray chamber; lime slurry, tail end sulfur dioxide removal type specifically designed for operation with a pulverized coal type steam generator.

The scrubber shall be designed to provide adequate liquid holdup, a high degree of liquid turbulence and means for thoroughly mixing the lime slurry with the flue gas.

Each module shall be capable of operating independently and shall include prequench, absorber, demister and flue gas reheat sections, pumps, piping, and controls. Integral or separate reaction tanks shall be provided.

Each scrubber module shall be designed to remove at least 90 per cent of the sulfur dioxide in its inlet flue gas at all load conditions.

The scrubber system shall be completely protected from erosion, corrosion, cementation, or plugging. The Contractor shall provide all special coatings, soot blowers, washers, strainers, screens, grinders, comminutors, or devices as required to provide this protection.

A.1.4 OPERATING CONDITIONS

The flue gas scrubber and auxiliary equipment shall be designed for operation under the following conditions.

A.1.4.1 Steam Generator and Electrostatic Precipitator. The steam generator will be pulverized coal fired, balanced draft, drum type unit with tilting tangential type burners. The steam generator will have a maximum capacity of 1,724,000 kilograms (3,800,000 pounds) of steam per hour. Number 2 fuel oil will be used for ignition and warm-up.

The steam generator will be equipped with an electrostatic precipitator to remove particulate matter from the flue gas. The precipitator will be designed to remove 99.8 per cent of the particulate matter. The expected particulate content in the flue gas at the scrubber inlet is specified under Section A.1.4.4, Flue Gas Conditions.

A.1.4.2 Load Range and Operating Requirements. The flue gas scrubber and auxiliary equipment shall be suitable for operation at all loads from startup to the maximum capacity of the steam generating unit.

In the range from 50 per cent of scrubber rated capacity to maximum capacity of the scrubber, the scrubber system shall be capable of operation with all modules in service.

The scrubber shall be designed for safe and reliable operation under the following steam generator operating conditions in any combination.

Daily startup following an overnight shutdown of approximately 8 hours duration.

Weekly startup following weekend shutdown of approximately 48 hours duration.

Operation at 25 per cent of rated capacity over extended periods of time.

Continuous operation at maximum capacity.

A.1.4.3 Fuel Data. The flue gas scrubber shall be designed and guaranteed to operate as specified with any coal whose properties are stated in the tabulated data.

The values listed as "nominal coal" are included only for the purpose of obtaining proposal data and are not to be used as a sole basis for design or guarantee.

A selection of specific coal analysis reports has been included as an appendix to these specifications to indicate the approximate interrelationship of the various constituents. These data are included for the Contractor's guidance only and are not to be used as a sole basis for design or guarantee.

The properties of the fired coal are as follows.

Ultimate Analysis, Per Cent by Weight	Typical Lower Sulfur	Typical Higher Sulfur	Nominal Coal
Carbon	62.79	63.77	60.04
Hydrogen	4.2	4.2	4.2
Sulfur	1.8	3.6	3.2
Chlorine	0.11	0.03	0.06
Oxygen	7.4	6.1	7.5

Ultimate Analysis, Per Cent by Weight	Typical Lower Sulfur	Typical Higher Sulfur	Nominal Coal
Nitrogen	1.2	1.3	1.0
Moisture	6.5	5.0	8.0
Ash	16.0	16.0	16.0
Heating Value, J/gm (Btu/lb)	27,558 (11,848)	26,749 (11,500)	25,586 (11,000)

It is recognized that the pulverizers will remove a portion of the pyritic sulfur and this has been considered in establishing the specified influent flow rate of sulfur dioxide to the scrubber. Sulfur dioxide removal guarantees shall be based on the influent flow rate of sulfur dioxide specified under Section A.1.4.4, Flue Gas Conditions.

A.1.4.4 Flue Gas Conditions. The flue gas scrubber shall be designed to operate under the following conditions.

	Steam Generator Operating Conditions	
	66 Per Cent Rated Capacity	Maximum Capacity
Steam generator steam flow, kg per second (lb per hour)	301 (2,390,000)	479 (3,800,000)
Fuel heat input, billion Joule per hour (million Btu per hour) to boiler	3,532 (3,348)	5,380 (5,100)
Total flue gas flow, kg per second (lb per hour)	489 (3,878,000)	745 (5,909,000)
Per cent of total flue gas flow to be treated by scrubber	100	100
Flue gas temperature at scrubber system inlet, C (F)		
Nominal	121 (250)	141 (285)
Minimum	113 (235)	132 (270)
Maximum	129 (265)	149 (300)
Flue gas density at specified nominal temperature, kg per cubic metre (lb per cu ft)	0.93 (0.058)	0.87 (0.054)
Expected maximum particulate content in flue gas stream with precipitator operating at 99.8 per cent efficiency, kg per second (lb per hour)	.012 (100)	.019 (150)

	Steam Generator Operating Conditions	
	66 Per Cent Rated Capacity	Maximum Capacity
Sulfur dioxide content of total flue gas stream at inlet to scrubber system, kg per second (lb per hour)	1.29 (10,200) to 2.65 (21,000)	1.95 (15,500) to 4.03 (32,000)
Minimum design sulfur dioxide removal efficiency of each module, per cent	90	90
Guaranteed maximum sulfur dioxide content of effluent gas stream with 100 per cent flow through scrubber, kg per second (lb per hour)	0.25 (2,000)	0.40 (3,200)

The electrostatic precipitator will be designed to remove up to 99.8 per cent of the fly ash from the flue gas; however, the contingency that the precipitator may operate at reduced efficiency for short periods of time shall be considered in design of the scrubber. The scrubber shall be guaranteed to be capable of continuous operation during periods of reduced precipitator efficiency without undue problems caused by erosion, corrosion, or chemical upset within the scrubber system.

Each bidder shall state the limitations, if any, on removal of particulates and sulfur dioxide during startup and at loads below 25 per cent of rated steam generator capacity. The approximate particulate and sulfur dioxide removal at various startup and partial load conditions shall be stated in the proposal data.

The sulfur trioxide removal capability shall be stated in the proposal data.

A.1.4.5 Lime. Pebble lime will be furnished by the Utility. The variation of composition of the lime will be as follows.

Constituent	Per Cent
CaO	85 to 95
MgO	0 to 6
Inerts	0 to 10

The lime is expected to be of 4.45 cm by 0 cm (1-3/4 inch by 0 inch) size.

The scrubber shall be guaranteed for operation with any lime defined by the specified ranges.

A.1.4.6 Makeup Water Supply. Normal makeup water to the scrubber system will be cooling tower blowdown and well water. The analyses of the well water and cooling tower blowdown water are expected to be variable, but the following ranges of constituents are considered typical (all constituents expressed in mg/l as $CaCO_3$ except as otherwise specified).

	Well Water	Cooling Tower Blowdown
Calcium	200	800
Magnesium	55	220
Sodium	30	120
Total alkalinity	225	200
Sulfate	25	800
Chloride	20	80
Silica, as SiO_2	15	60
Orthophosphate, as PO_4	--	2
Total phosphate, as PO_4	--	6
Polyacrylate, as active material	--	1
Total dissolved solids, as such	315	1375
Total suspended solids, as such	<1	7
pH	7.5	7.5-8.0
Conductivity, mmhos	505	2200

A.1.5 EQUIPMENT SIZING

All equipment shall be sized for overload conditions and, where specified herein or recommended by the Contractor, standby equipment shall be provided to ensure reliability.

Each of the four modules shall be capable of safe and reliable operation at 33-1/3 per cent of generating unit maximum capacity while burning the maximum sulfur coal and maintaining the guaranteed sulfur dioxide removal efficiency. If five or six modules are supplied, each shall be capable of safe and reliable operation at 25 per cent or 20 per cent, respectively, of the generating unit maximum capacity while burning the maximum sulfur coal and maintaining the guaranteed sulfur dioxide removal efficiency. All module auxiliaries shall be sized with design margins adequate to ensure this requirement can be met.

The system shall be capable of safe and reliable operation at a total flue gas flow of 745 kilograms per second (5,909,000 pounds per hour) with 100 per cent of flow through the scrubber.

A.1.6 CONSTRUCTION CRITERIA

The flue gas scrubber and auxiliary equipment shall be designed for the following conditions.

Scrubber design pressure, Pa (in. wg)	104,260 to 98,040 (+20 to -5)
Maximum flue gas temperature at scrubber inlet	260 C (500 F) for a duration not to exceed 30 minutes
Makeup water pressure	As required
Seismic loading	Zone 2 as defined by the Uniform Building Code 1976-77
Wind load during erection	36 m/s (80 mph) at 9 m (30 ft) above grade in accordance with ANSI A58.1

Location	Indoor
Grade elevation, metres (feet msl)	173.7 (540)
Barometric pressure, Pa (in. Hg)	99,500 (29.40)
Ambient temperature, C (F)	
Minimum	-21 (-5)
Maximum	35 (95)
Indoor temperature, C (F)	
Minimum	10 (50)
Maximum	46 (115)

A.1.7 PERFORMANCE DATA AND CURVES

Data and curves specified herein shall be submitted.

A.1.7.1 Mass Balance Diagrams. Mass balance diagrams shall be submitted showing flow rates, pressures and temperatures of flue gas, makeup water, additive, slurry, sludge, chemicals, etc., for the complete system furnished under these specifications. Each bidder shall submit elementary mass balance diagrams for operation at 66 per cent of steam generator rated capacity and at maximum capacity of the steam generator. The successful bidder shall submit complete and detailed mass balance diagrams for operation at the above two conditions, and for operation at 25, 50, 75 and 100 per cent of steam generator rated capacity. Mass balance diagrams shall be submitted for operation at the minimum and maximum sulfur dioxide levels specified.

A.1.7.2 Scrubber Performance Curves. Curves as follows shall be submitted.

a. Pressure loss through scrubber versus inlet gas flow in kilograms per second (pounds per hour) for the condition of maximum sulfur dioxide content in the inlet flue gas.

b. Water droplet content in flue gas leaving demister in kilograms per second (pounds per hour) versus load in per cent of rated capacity for the condition of maximum sulfur dioxide content in the flue gas.

c. Superficial gas velocity through scrubbing section and demisters versus load. Curves shall indicate recommended points of changeover to increase or decrease the number of modules in operation.

A.1.7.3 Pump Characteristic Curves. Characteristic curves shall be submitted for each pump furnished under these specifications. The curves shall show head, horsepower, efficiency, and net positive suction head required as ordinates, with capacity as the abscissa.

These characteristic curves shall also be submitted for the maximum and minimum diameter impellers which may be fitted to the pump casing.

A.1.7.4 Fan Performance. Performance curves shall be submitted for all fans furnished. Capacity in cubic metres per second (cubic feet per minute) shall be indicated as abscissae. Brake horsepower, static pressure, and fan efficiency shall be indicated as ordinates.

The fan curves shall be drawn for the fans as supplied and shall not include any velocity pressure recovery beyond the fan outlet, but shall include all damper losses.

A.2 GUARANTEE REQUESTS AND TESTS

A.2.1 GENERAL

The equipment shall operate safely, reliably, and without scaling, plugging, undue maintenance or operator attention. The guarantees shall be such as can be met in everyday operation under all specified operating conditions.

A.2.2 GUARANTEES

The performance of all equipment at 66 per cent rated and maximum steam generator capacity and for any quantity of flue gas to be treated within the limits specified shall be guaranteed to be as specified in Section A.1.4.4, Flue Gas Conditions.

A.2.2.1 Continuous Operation. The adequacy of the system for continuous operation shall be demonstrated by a reliability demonstration run for an uninterrupted period of 60 days.

If the reliability demonstration run is interrupted as a result of malfunction of the scrubber or other plant equipment, the run shall be terminated and another reliability demonstration run period shall commence.

The reliability demonstration run shall begin upon successful completion of the initial performance guarantee tests and within 30 days after permits and licenses to operate have been received.

During the reliability run, the steam generator load will vary between 25 per cent of rated capacity and maximum capacity. Entry into a scrubber module will be permitted, provided the remaining modules are capable of operating at maximum module output, when such entry does not affect scrubber performance or increase emissions above the guarantee point specified in Section A.1.4.4, Flue Gas Conditions. Normal maintenance will be permitted on auxiliaries located outside the modules at any time provided it does not affect scrubber performance or increase emissions above the guarantee point specified in Section A.1.4.4, Flue Gas Conditions. Emissions will be monitored continuously during the reliability run and shall at no time exceed the guaranteed emission except as provided for by the Contractor's statement of limitations for start-up and low load operation in accordance with the requirements of Section A.1.4.2, Load Range and Operating Requirements.

A.2.2.2 Rated Capacity. The rated capacity of each scrubber module shall be demonstrated by continuous operation at rated capacity for 48 hours when the steam generator is firing coal having a composition falling within the specified range.

The adequacy of the overall scrubber system shall be demonstrated by an 8 hour run scrubbing 100 per cent of the flue gas flow with the steam generator operating at maximum capacity.

A.2.2.3 Collection Efficiencies. The overall performance of the sulfur dioxide removal system shall be demonstrated before the start and at the end of the 60 day reliability run with steam generator operation at 66 per cent rated capacity, and maximum capacity for continuous periods of 4 hours, following periods to allow stabilization.

The guaranteed sulfur dioxide removal efficiency of at least 90 per cent for each module, total pressure drop across all scrubber elements, water droplet carry-over after the demisters, makeup water, and additive usage as stated in the Proposal Data and in Section A.1.4.4, Flue Gas Conditions shall be demonstrated during these tests or during separate tests as agreed upon by the Utility and the Contractor. The quantity of particulate leaving the scrubber system shall be guaranteed not to exceed the quantity of particulate entering the scrubber system.

A.2.2.4 Water Consumption. The consumption of makeup water with steam generator operation at 66 per cent rated capacity, and maximum capacity shall be guaranteed not to exceed the amounts stated in the Proposal Data.

A.2.2.5 Additive Consumption. The consumption of additive with steam generator operation at 66 per cent rated capacity, and maximum capacity shall be guaranteed not to exceed the amounts stated in the Proposal Data.

A.2.2.6 Pressure Drop. The total pressure drop across all scrubber elements at 66 per cent rated capacity and maximum capacity shall not exceed the amounts stated in the Proposal Data.

A.2.2.7 Water Droplet Carry-Over. Water droplet carry-over from the secondary demisters with steam generator operation at 66 per cent rated capacity, and maximum capacity shall be guaranteed not to exceed the amounts stated in the Proposal Data.

A.2.2.8 Minimum Load Operation. The scrubber system shall be guaranteed to operate satisfactorily and reliably for extended periods at 25 per cent of rated scrubber capacity. The scrubber shall also be guaranteed to operate satisfactorily and reliably during unit startup during which time the Unit will be at less than 25 per cent load.

A.2.3 TESTS

All tests will be conducted by a qualified independent testing laboratory mutually acceptable to the Contractor and the Utility. The Contractor will be permitted to observe the tests and a copy of the test performance data will be furnished to the Contractor. Such tests shall be binding on the parties of this contract to determine compliance with the guarantees.

The tests will be performed in accordance with the test procedures established by the Environmental Protection Agency for determination of compliance with New Source Performance Standards in effect on the date of the contract.

Each trial shall consist of simultaneous measurements of sulfur dioxide and particulate concentrations in the scrubber inlet and outlet ductwork. Each trial will last at least 8 hours and will include at least one steam generator soot blowing cycle.

If a trial meets all necessary criteria, the calculated efficiency will constitute acceptable data.

The arithmetic mean of the first three acceptable sets of data will be accepted by both the Utility and the Contractor as the true efficiency of the scrubber.

The tests will be conducted at approximately the design conditions specified at 66 per cent of rated steam generator capacity and at maximum capacity.

A preliminary formal performance guarantee test will be conducted as soon as possible after completion of erection of the scrubbers. In addition, approximately one year after successful completion of the preliminary formal performance guarantee test a final formal performance guarantee test will be conducted. These two formal tests will be paid for by the Utility whether successful demonstration of compliance with the guaranteed performance is achieved or not. A formal performance guarantee test shall include determination of collection efficiency, water consumption, additive consumption, water droplet carry-over, and particulate discharge. Should either of the formal performance guarantee tests show that the scrubbers have failed to meet their guarantees, the Contractor shall immediately proceed with modifications of the scrubbers until they meet the guarantees. All costs for the modifications including labor and material and the cost of performing additional formal tests to prove that the scrubbers will meet their guarantees shall be borne by the Contractor.

A.3 EQUIPMENT AND INSTRUMENTATION

A.3.1 GENERAL

This section covers the specific design requirements for the scrubber modules and the controls and instrumentation equipment. These two examples have been selected as being representative of typical line FGD system equipment specifications. Other equipment items will not be considered in this section.

A.3.2 SCRUBBER MODULES

The scrubber modules shall be designed and constructed in accordance with the following criteria.

A.3.2.1 Type. Module type shall be as specified in Section A.1.3.

A.3.2.2 Materials. The scrubber modules, recirculation and reaction tanks shall be constructed of carbon steel with a neoprene rubber liner suitable for long life (30-35 years) in the environment inside the scrubber under all conditions of operation with flue gas, additive and makeup water as specified.

Each bidder shall provide a complete list of scrubber components in contact with the scrubber liquid or wet flue gas and the material used for each. Materials and linings shall be identified by the trade name, ASTM or other specification number, or by chemical composition and physical properties.

A.3.2.3 Construction. The scrubber modules shall be constructed to form a pressuretight envelope from the flue gas inlet to the flue gas outlet.

The scrubber modules shall be constructed of neoprene rubber lined carbon steel. The carbon steel shall be not less than .63 centimetres (1/4 inch thick).

Welded joints shall be used wherever possible.

Any penetrations of the module required for headers, piping connections or accessories shall be sealed to retain the pressuretight integrity of the module.

A complete system of structural reinforcement shall be provided to brace the walls of the module against pressure and vacuum loads, piping forces and moments and all other loads imposed on the module. The bracing and reinforcement shall be adequate to prevent excessive deflection and module shell vibration resulting from any condition which may occur within the scrubber.

If more than one module is associated with a recirculation tank, baffles extending below the low water level of the recirculation tank shall be furnished to prevent flue gas from leaking from one module to another.

All interior baffles, braces and supports shall be designed so they will not trap dirt, sludge, or scale and convenient access shall be provided to permit easy cleaning of all horizontal surfaces.

The modules will be supported on foundations and structural steel supports, where required, which will be furnished by the Utility. Each bidder shall state in his proposal whether the modules are bottom, intermediate, or top supported and shall include a drawing showing the recommended method of support.

The bottom of each module shall be sloped to prevent accumulation of sludge or fly ash, and for ease of cleanout. Each bidder shall state in his proposal any requirements for periodic cleanout and the provisions made for this.

A.3.2.3.1 Expansion Provisions. Provisions shall be made in the design of the modules to absorb differential expansions which may occur under extremes of ambient temperature or during startup. The Proposal shall describe expansion provisions in detail and shall state any special requirements for connections of the Utility's ductwork and piping to the scrubber modules.

A.3.2.3.2 Spray Pipe and Internals. All spray pipes, drains and other scrubber internals shall be constructed of special corrosion-erosion resistant materials.

The spray piping shall be constructed of the following materials.

- Slurry service	$\geq$ 6.35 cm (2-1/2") Φ - Neoprene rubber lined carbon steel
	$\leq$ 5.08 cm (2") Φ - Fiberglass reinforced plastic (FRP) (ABCO A150)
- Corrosive service (other than slurry piping)	ASTM A167 Type 316L stainless steel
- Non corrosive service	ASTM A106 GrA

Spray heads shall be designed for resistance to thermal shock and long life. Low velocities within the spray heads are preferred. Bidders shall state the expected replacement frequency of spray heads.

Drains shall be designed to prevent accumulation of sludge and fly ash leading to plugging. Drain construction which requires periodic cleaning will not be acceptable.

A.3.2.3.3 Access and Observation Openings. All access doors needed for maintenance of the scrubber modules, recirculation and reaction tanks shall be provided. Doors shall be large enough for entry of personnel and equipment including scaffolds if required. Personnel access doors shall be a minimum of 46 by 61 centimetres (18 by 24 inches). Scaffold access doors shall be a minimum of 61 by 132 centimetres (24 by 52 inches). Pressuretight door seals shall be provided and doors and frames shall be structurally reinforced to prevent deflection which could result in leakage past the seals.

All observation openings needed for inspection of scrubber internals during operation shall be provided. Consideration shall be given to the fact that the scrubbers will be pressurized in determining the number of observation openings required. Each observation opening shall be provided with a water jet for cleaning and aspirating air to permit opening with the unit in operation.

Lights of vaportight and watertight construction shall be provided at all locations where observation openings are provided for inspection of internals.

A.3.3 CONTROLS AND INSTRUMENTATION

This section covers the control and instrumentation equipment to be furnished by the Contractor. The controls and instrumentation shall be provided by a control system manufacturer experienced and qualified in power plant scrubber work and shall be acceptable to the Engineer.

Each bidder shall submit elementary logic diagrams, both digital and analog, with a written description of the proposed method of control together with an equipment list describing all control and instrument equipment as part of the proposal data. Completed ISA-S20 standard specification forms shall be submitted for all process measurement and control instruments, primary elements, and control valves as part of the proposal data.

In the event the Contractor proposes to incorporate a computer, a programmable controller and/or multiplexing, a complete description of such equipment shall be furnished with the proposal.

A.3.3.1 Contractor's Scope of Supply. The Contractor shall provide all field and panel mounted devices to monitor and control the scrubber process and place individual modules into or remove them from service. The Contractor shall also provide all field and panel devices required to monitor and control the slurry mixing and disposal system which is designed to mix fly ash, lime, and scrubber solids, and to transport the resultant mixture to landfill. In addition, the Contractor shall provide all field and panel mounted devices required to monitor and control the reagent feed system. Complete monitoring capability of the scrubber, slurry mixing and disposal, and reagent feed systems shall be provided to the Utility's computer system. The inputs furnished by the Contractor shall include running conditions of the drives, positions of valves and dampers, process variables such as levels, temperatures, pressures, flows, density, pH, etc., and selected out of limit or trip annunciations required by the main plant operator. The computer system will be utilized to monitor and record the operation of these systems. Equipment to be provided shall include, but not be limited to, the following.

- Control panel
- Control valves
- Control drives and connecting linkage
- Transmitters
- Local controllers
- Damper drives
- Signal converters
- Flow measurement devices
- Density measurement devices
- pH measurement
- Recorders
- Indicators
- Controller stations
- Annunciators
- Accessory items
    - Limit switches
    - Pressure switches

Temperature switches

Level switches

Solenoid valves

Pressure gages

Thermometers

Temperature detectors

Vibration transducer mountings

Flow indicators

Flow switches

Conductivity cells

Miscellaneous items

Support hardware for installation of control and instrumentation equipment.

Primary instrument piping including process connection shut-off valves from process to instrument.

Control air supply headers, air supply shut-off valves, and air supply regulators as required.

Air supply, penumatic signal and interconnection tubing integral to the equipment.

The system provided to control flue gas flow through the scrubber modules will be furnished by the Utility. This system will be controlled by the main control room operator. The control damper drives provided by the Contractor shall be coordinated with the Utility's boiler analog control system. The Contractor shall provide an optional price deduction for the control damper drives in case the Utility elects to purchase the damper drives under separate specifications.

A.3.3.2 Utility-Furnished Equipment. The Utility will provide flue gas sulfur dioxide analyzers input to the Contractor-furnished lime additive feed three element control loop. The output signal from the analyzers will be 4-20 mA dc.

The Utility will furnish instrument enclosures, as required, for mounting Contractor-furnished field instrumentation which can be mounted remote from the process. This will include, but not be limited to, enclosures for the following instrumentation.

Pressure transmitters

Flow transmitters

Pressure switches

Signal converters

A.3.3.3 Functional Requirements. The system shall include equipment for performing the functions specified. Complete automatic/manual electronic control systems with manual override at all levels of control, supervision, annunciation, monitoring and verification of performance from the scrubber and lime feed control rooms and with monitoring capability from the main control room computer system shall be provided for the specified functions.

Recorders, indicators and other automatic controls shall be provided as required for system design to record and monitor pressures, per cent solids, pH, tank levels, flow rates, temperatures, densities, sulfur dioxide outlet concentration for each indiviual module, total scrubber system sulfur dioxide inlet and outlet concentrations, stack concentrations of NO_x, CO, CO_2, opacity individual module gas flow, total gas flow to the chimney, and other like parameters.

Subloop controls, mist eliminator header pressure and flow, slurry density, recirculation tank and reagent levels and other controls which may require operator supervision shall be provided for the following.

General water and waste water pressure controls as required.

Lime additive feed controls

Other controls not requiring continuous supervision by the operators.

All pumps, motor operated valves, and other devices required to be placed in service or taken out of service individually during startup, shutdown or operation of the scrubber, sludge disposal system, and lime feed system shall be controlled from the scrubber, sludge disposal, and lime feed system control panels furnished under these specifications.

All instrumentation required for monitoring, alarming, and verification of performance in order to assure reliable operation of the scrubber, sludge disposal system, and lime feed system shall be located on their respective control panels.

Local instrumentation shall be provided where required for maintenance and periodic inspection.

Annunciators shall be provided on the scrubber control panel, the sludge disposal control panel, and the lime feed control panel to monitor abnormal operations of the systems. Annunciators shall utilize an alarm sequence of the same type used throughout the plant. All alarm points shall be provided with parallel contacts and one common contact for all windows for use with the Utility-furnished annunciator equipment in the main control room.

A.3.3.3.1 Flue Gas Scrubber. The flue gas scrubber control system shall perform the following functions.

a. Scrubber Module Startup and Shutdown. The main plant control room operator shall place modules in and out of service and control flue gas flow through the individual modules of the scrubber system. The control system for placing a module and its associated equipment in service shall operate in one of two modes: manual or automatic. Selection of either manual or automatic mode shall be by the scrubber control room operator. In the manual mode, the scrubber control room operator, in direct coordination with the main control room operator, will place individual scrubber equipment into or out of service. The scrubber motor-operated valves, pumps, and any other associated equipment shall be opened or closed, started or stopped, from individual switches or push buttons located on the scrubber control panel.

In the automatic mode, a scrubber module and all associated equipment shall be automatically placed in or taken out of service when the module start or stop push button in the main control room is actuated. In both the manual and automatic modes of operation, the main control room operator shall place modules in and out of service. Appropriate indicating lights shall be provided on the main control room control board to inform the operator about the availability of each module for service. These indicating lights shall be coordinated with appropriate interlocks. In both modes of operation, the scrubber inlet and outlet dampers shall be controlled from the main control room and proper interlocks shall be provided to assure that the proper startup and shutdown sequence is followed. Interlocks shall be provided for the Utility's boiler implosion protection system for all dampers located in the flue gas stream. These interlocks shall be utilized to ensure a gas path through the scrubber. Coordination of the scrubber controls with the Utility's boiler analog control system and burner fuel safety and purge system shall be provided.

The indicating lights, control switches, and push buttons required by the main control room operator for placing the scrubber equipment into or out of service shall be provided by the Contractor as specified.

b. Lime Additive Feed. A three element control system shall be furnished to control the rate of lime additive feed to each individual module to maintain its sulfur dioxide removal rate and pH at preset constant values. The three controlling elements shall be module gas flow, inlet gas sulfur dioxide content, and slurry pH.

c. Slurry Bleed Off. Slurry blowdown rate control shall be furnished for each individual module to maintain per cent solids at preset constant values.

d. Mist Eliminator Spray Control. A control system shall be provided to sequence mist eliminator sprays automatically as required to prevent accumulation of deposits.

e. Reheat Temperature. A control system shall be provided to monitor and control the temperature of the flue gas leaving the reheat system provided for each module. This system will be utilized to control the Utility-furnished reheat hot water control valves.

f. Soot Blowers. A control system shall be provided to sequence the reheat system soot blowers automatically to prevent the accumulation of deposits on the reheat coils. A control insert panel shall be provided for the scrubber control panel.

g. Modular System. The control philosophy shall be that of a modular system, in that individual scrubber modules shall be placed in and taken out of service from the main control room control board. When removing a module from service, automatic flushing of the module slurry and sludge lines with clear water shall be accomplished.

A.3.3.3.2 Sludge Disposal System. The sludge disposal control system shall perform the following functions.

a. Fly Ash Storage Silo Fluidizing Air Blowers Control. Each blower shall be controlled from an on-off control switch provided under separate specifications for installation on the sludge disposal control panel. The blowers shall be controlled such that the idle blower starts automatically should the fluidizing air pressure become low.

b. Fly Ash and Lime Feeder Speed Control. The fly ash and lime feed rate into the muller mixers will vary with the speed of the rotary vane feeders. A speed control system complete with a control station to maintain each feeder at the required speed shall be provided. The feeder demand outputs shall be 4-20 mA dc analog signals for interfacing with the feeder variable speed drives. A 4-20 mA dc analog feeder speed input signal for each feeder will be provided by the Utility.

Each of the control stations shall provide indications of actual and demanded feeder speed, setpoint adjustment, automatic/ manual selection, and manual drive positioning. A manual on-off feeder switch and lights will be provided under separate specifications for installation adjacent to each control station.

c. Muller Mixer Control. Three ratio control systems shall be provided for maintaining the consistency of the paste discharge from the three muller mixers by regulating the fly ash and lime feed rate into the mixers. The Contractor shall provide a feed rate measurement device and transmitter for monitoring the feed rate of fly ash and lime into each mixer. The fly ash and lime feeder speed characterized to a feed rate shall be the controlled variable; scrubber slurry flow into the mixer shall be the uncontrolled variable. A timer shall be provided to control the proper sequential starting and stopping of the mixer.

Each of three control stations shall provide indications of ratio selected and valve position, ratio adjustment, automatic/ manual selection, and manual valve positioning. A manual on-off mixer control switch and indicating lights will be provided under separate specifications for installation adjacent to each control station.

A.3.3.4 Control Panels. Two free-standing, rear-entry type control panels, designated as a scrubber control panel and a sludge disposal control panel, shall be furnished. The panels shall contain all logic devices required for the scrubber control system and the sludge disposal system. The panels shall also include visual/audible alarm annunciators, local control and other indicator lights, control devices, graphic displays recorders, and indicators, as specified herein.

In addition, one free-standing, rear-entry type control panel, designated as a lime feed control panel, shall be furnished containing all the logic devices required for the lime feed control system. The panel shall also include a visual/audible alarm annunciator, local control and other indicating lights, control devices and indicators as specified herein.

A.3.3.4.1 Graphic Display Subpanels. Two graphic display subpanels shall be furnished, one on the scrubber control panel and the other on the slurry mixing and disposal control panel.

Graphic display subpanels shall be made of 0.95-cm (3/8-inch) Formica. The graphic equipment symbols, lines, arrows, and nameplates shall be 0.16-cm (1/16-inch) thick engraving stock with a white core and shall be bonded to the base panel with a suitable adhesive.

A.3.3.5 Local Controllers. Local controllers shall be furnished as required. These shall be of a design such that no operator action is required to place the control loop in service.

A.3.3.6 Flow Measurement Devices. Flow measurements of clear fluids shall be made using orifice plates, venturi tubes or rotameters as required by the Contractor's design.

Slurry flow measurements shall be made using magnetic flowmeters.

A.3.3.7 Density Measurement Devices. Density measurement devices shall be furnished as required by the Contractor's design. The density measurement devices shall be gamma source and detection units complete with separately mounted electronic units. The electronic units shall include local indicating lights and relays for use with the Utility's remote alarm system.

A.3.3.8 pH Measurement. Recorders, monitors, and pH cells shall be furnished complete in number and location as required by the Contractor's design. Adequate redundancy for reliable operation and sufficient retransmission capability for control and monitoring shall be provided. The pH cell assemblies shall be designed for operation with a minimum of operator attention and cleaning. The pH cells shall be located in auxiliary measuring vessels which can be isolated. Each cell shall be equipped with ultrasonic cleaning devices.

A.3.3.9 Recorders. Recorders shall have 10.16-centimetres (4-inch) wide charts. Chart speed shall be 2.54 centimetres (one inch) per hour.

The recorders shall have internal illumination, a chart motor switch, a chart tear-off device, identification labels at the front and rear of the case and on the recorder, and legend plates behind the glass on the door.

Each recorder shall be provided with a one year's supply of charts and ink.

A.3.3.10 Indicators. Vertical indicators shall be furnished with internal illumination and an internal or rear zero adjustment.

A.3.3.11 Main Control Room Control Board Scrubber Subpanel. A subpanel shall be provided for the turbine-generator main control room control board for scrubber module startup and shutdown control as specified.