DE-FG22-95PC94256--99

DOE/PC/94256--99-Vol.2

Electric Utility Engineer's FGD Manual Volume II - Major Mechanical Equipment; FGD Proposal Evaluations; Use of FGDPRISM in FGD System Modification, Proposal Evaluation, and Design; FGD System Case Study

Final Report
March 4, 1996

Work Performed Under Contract No.: DE-FG22-95PC94256

For
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PART II
MAJOR MECHANICAL EQUIPMENT

1.0 INTRODUCTION

Part II of this manual provides the electric utility engineer with detailed technical information on some of the major mechanical equipment used in the FGD system. The information in this section can be extremely useful to the engineer involved in preparation or review of a specification for an FGD system for the first time.

1.1 Objectives

The objectives of Part II are the following:

- To provide the electric utility engineer with information on equipment that may be unfamiliar to him, including ball mills, vacuum filters, and mist eliminators; and
- To identify the unique technical considerations imposed by an FGD system on more familiar electric utility equipment such as fans, gas dampers, piping, valves, and pumps.

1.2 Organization and Content

The organization of Part II is illustrated in Figure 1-1. Part II covers 15 FGD system mechanical components:

- Flue gas fans;
- Ductwork and expansion joints;
- Flue gas dampers;
- Slurry pumps;

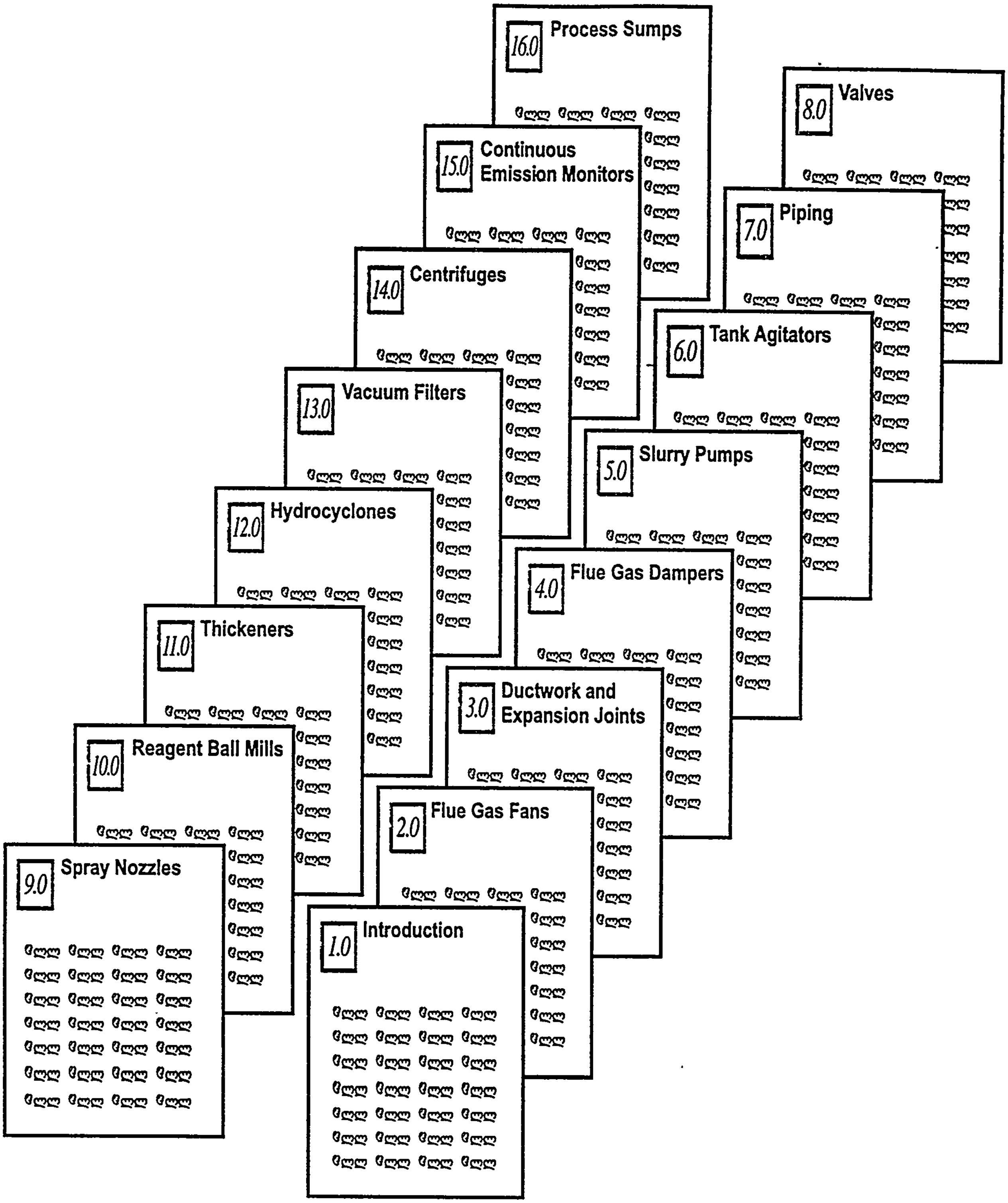

Figure 1-1. Part II Organization

- Tank agitators;
- Piping;
- Valves;
- Spray nozzles;
- Reagent ball mills;
- Thickeners;
- Hydrocyclones;
- Vacuum filters;
- Centrifuges;
- Continuous emission monitors; and
- Process sumps.

For each component covered, Part II presents the state-of-the-art designs considered, the selection considerations, the available materials of construction, and recommendations based on recent experience.

2.0 FLUE GAS FANS

The flue gas fans provide the kinetic energy required to move the flue gas through the ductwork, dampers, absorber modules, stack, and other associated equipment. In design and operation, the flue gas fans associated with an FGD system are nearly identical with typical power plant induced draft (ID) fans. Since detailed descriptions of the design and operation of power plant fans are available from textbooks on power plant design (1,2) and from fan manufacturers, this section of the manual concentrates on the unique fan design conditions imposed by FGD system applications.

2.1 Types Available

Flue gas fans can be categorized by their general type and by their location with respect to the absorber module(s).

Two general types of fans are used in power plants: centrifugal fans and axial fans, illustrated in Figures 2-1 and 2-2, respectively. Centrifugal fans accelerate the flue gas radially to the axis of the fan rotor, in the same manner that a centrifugal pump moves a liquid. Axial fans accelerate the flue gas parallel to the fan rotor, similar to the operation of a ship's propeller. Where new flue gas fans are required for the retrofit of an FGD system, their service is characterized by high flow rate and relatively low pressure rise. Both centrifugal fans and single-stage axial fans are suited to this service. The selection of which of these fan types is better suited to a particular installation depends on a wide variety of site- and utility-specific factors, and is usually the subject of the same type of engineering study applied to selection of the unit's other flue gas fans.

The flue gas fans can be located either ahead of the absorber modules (resulting in operation of the absorber modules above ambient pressure) or following the absorber modules (resulting in operation of the absorber modules below ambient pressure), as shown in Figure 2-3. Fans located upstream of the FGD system handle hot, dry flue gas and are

- Tank agitators;
- Piping;
- Valves;
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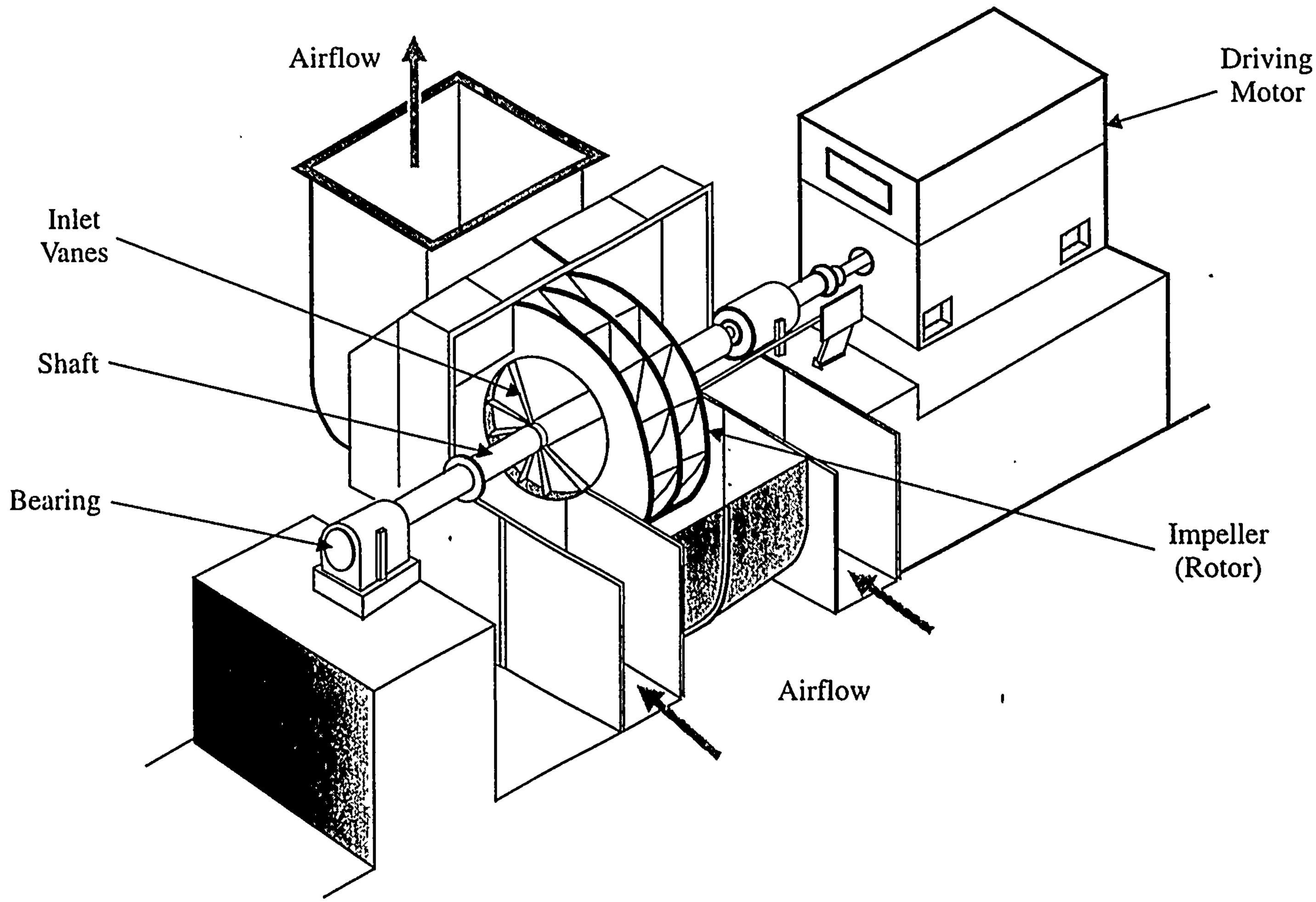


Figure 2-1. Typical Centrifugal Fan

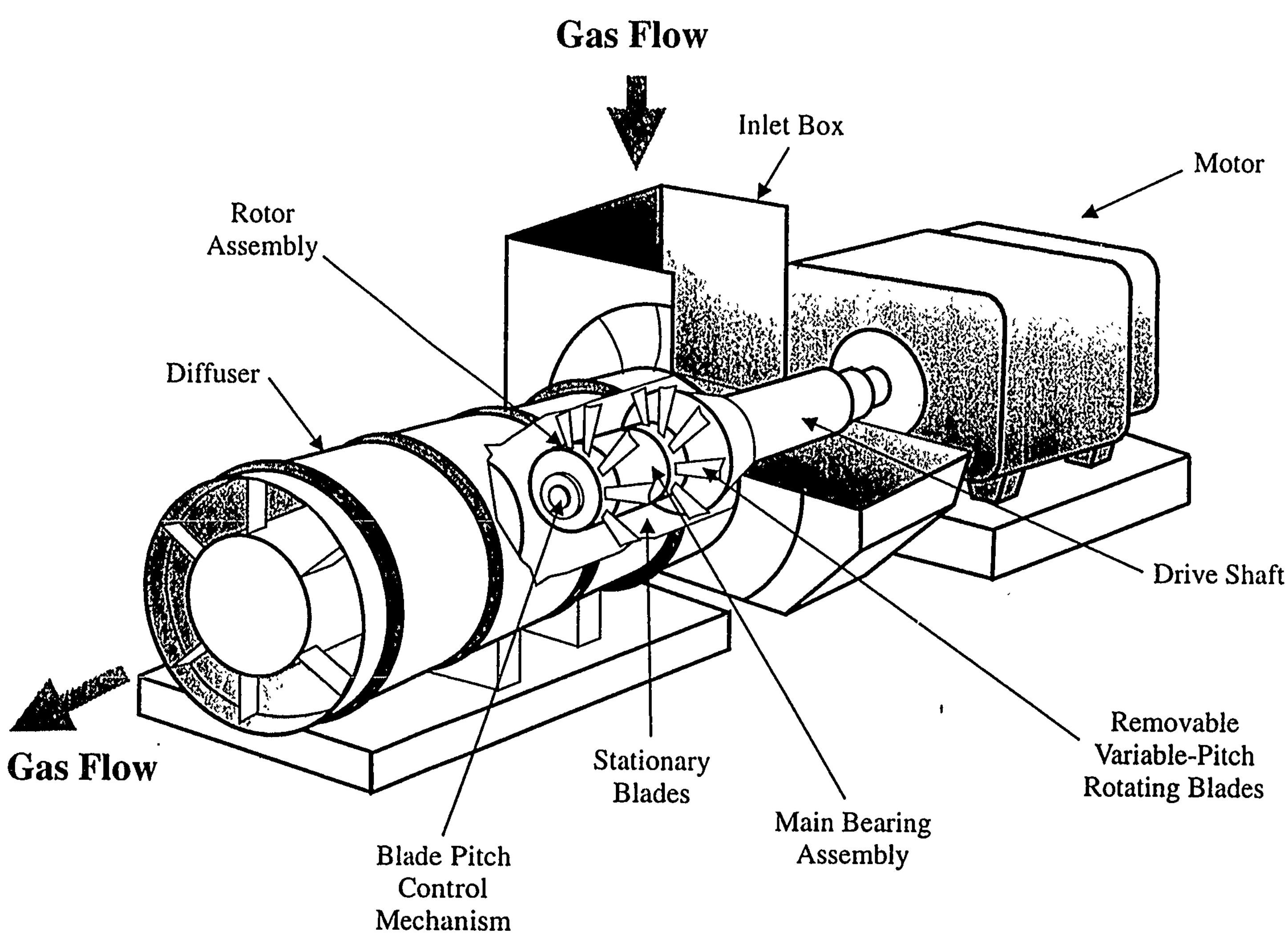
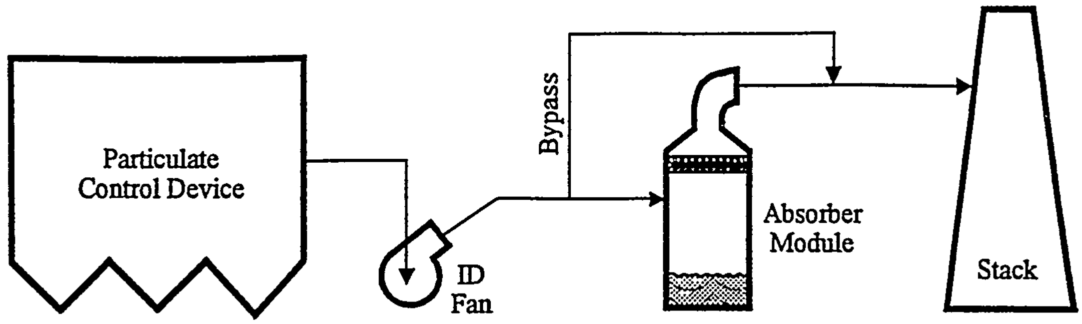
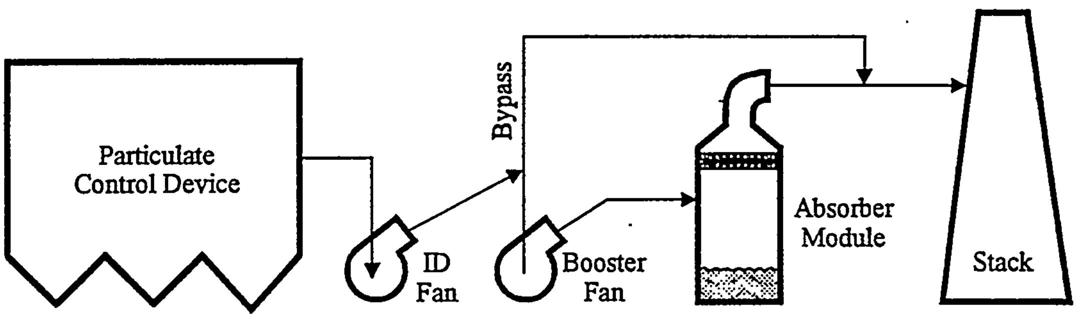


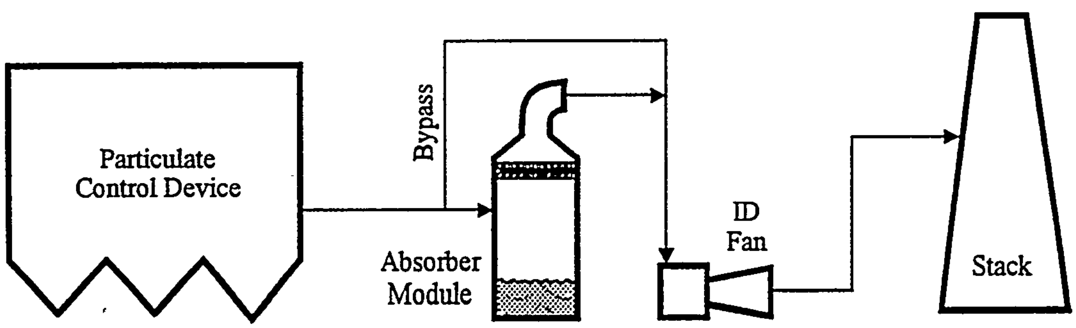
Figure 2-2. Typical Axial Fan



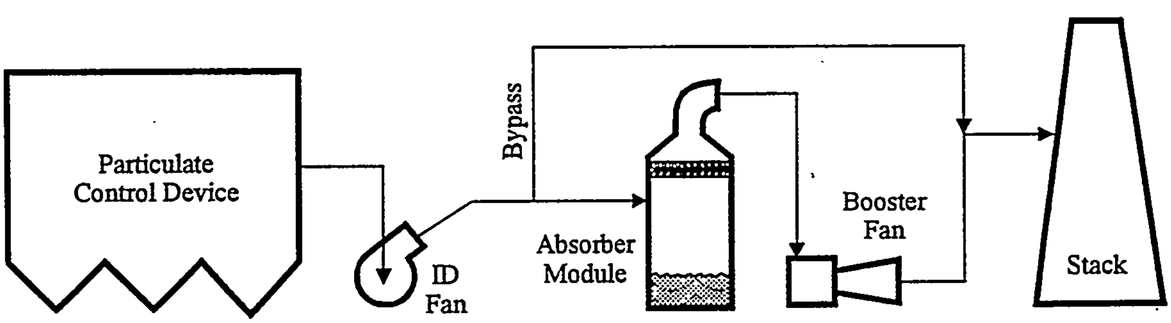
a) Incorporated into Design of Upstream ID Fan



b) Upstream Booster Fan



c) Incorporated into Design of Downstream ID Fan



d) Downstream Booster Fan

Figure 2-3. FGD System Flue Gas Fan Alternatives

termed "dry fans." Fans located downstream of the FGD system handle cooler flue gas that has been saturated with water and are termed "wet fans." When flue gas reheat is applied (see Part I, Section 4.6), the downstream fan may operate in conditions closer to those of a dry fan. In either location, the FGD system's pressure increase requirements can be incorporated into the design requirements of the boiler ID fans (Figures 2-3a and 2-3c) or can be provided by a separate set of booster fans (Figures 2-3b and 2-3d).

A few U.S. FGD systems operate with flue gas fans downstream of the absorber modules. Many of these are systems that combine both particulate and SO_2 removal in the same system. Some of these installations reheat the flue gas prior to the fans, but others operate without reheat. All U.S. installations with downstream fans have used centrifugal fans for this service. Because of problems created by solids buildup, blade erosion, and corrosion, these fans have generally been less reliable than upstream fans. Because U.S. utilities have generally considered the historic problems to outweigh the potential benefits of negative-pressure operation (discussed later in this section), no FGD systems using wet fans have been installed in the United States since the mid-1980s.

European experience with wet fans has been better than that seen in the United States. The European FGD systems were among the first to employ improved, more efficient mist eliminator designs that minimized liquid and solid carryover from the absorber modules. Installations with wet fans primarily used axial fans in a wide variety of flue gas flow orientations, including horizontal, vertical up-flow, and vertical down-flow. Even though U.S. experience with wet fans has been disappointing, the successful application of these fans in Europe may result in their frequent use in the future. Therefore, this section of the manual describes both wet and dry fans.

2.2 Design Considerations

2.2.1 Process Considerations

Process considerations that influence the design or operation of the flue gas fans include fan control and influences on mist eliminator operation.

Fan Control

If the pressure requirements of the FGD system are incorporated into the design of the boiler ID fans, the FGD system presents no new problems in fan control regardless of the type or location of the fans. If, however, the pressure requirements are met by booster fans, fan control becomes more difficult. While a detailed discussion of the control of large boiler draft fans operating in series is beyond the scope of this manual, this is an area that should be given extensive study by knowledgeable fan-control experts. The control system must be able to respond quickly and safely to changes in unit load and the placing of absorber modules in and out of service. While the control of series fans is more complex, this is a very common arrangement for both new and retrofit FGD applications, and the control procedures are well established.

Influences on Mist Eliminator Operation

The efficient operation of the mist eliminators (MEs) is important in all FGD systems, but is of critical importance if flue gas fans are located downstream of the absorber modules. Carryover of slurry solids onto the fan blades can result in fan imbalance, blade wear problems, and increased corrosion. As a result, using downstream fans requires the use of highly efficient, two-stage MEs and very close supervision of the ME wash system.

2.2.2 Mechanical Considerations

The mechanical aspects of the flue gas fans located upstream of the FGD system are the same as those that must be considered for the boiler's ID fans. Additional mechanical factors must be considered when contemplating retrofit booster fans and fans located downstream of the FGD system. The most significant flue gas fan mechanical considerations are the ID fan pressure requirements and installation of a wet fan wash system.

ID Fan Pressure Requirements

The pressure drop across the FGD system (ID fan outlet through stack inlet) is typically in the range of 1.5 to 2.5 kilopascals (kPa) [6 to 10 inches of water, gage (inwg)]. In new installations, this additional pressure requirement can be easily incorporated into the design of the boiler ID fans. Some existing generating units that were originally installed without FGD systems anticipated the future need to add an FGD system, and the original ID fans either have the ability to meet this additional demand or can be modified to do so at relatively low cost. Such modifications might include the replacement of the initial fan rotors with larger diameter rotors (centrifugal fans), installation of a second stage of fan blades (axial fans), and replacement of the fan motors with motors of a larger size.

Where the existing ID fans cannot be modified to provide the pressure requirements of a retrofit FGD system, ID booster fans are required.

Wet Fan Wash System

To control the buildup of deposits on the fans, most fans located downstream of the absorber modules are equipped with on-line wash systems to periodically remove deposits before they have an opportunity to harden. A typical wet fan wash system consists of a fixed grid of wash water supply piping and spray nozzles. The wash system should use fresh makeup water; and often, the same pumps that supply ME wash water also supply fan wash water. Reclaim water should not be used to wash the fans because of the potential for additional solids buildup. The wash frequency depends on the rate at which solids build up on the fan blades and may be adjusted by the operator to suit variable operating conditions.

2.2.3 Other Considerations

Several other factors should be considered in the selection of flue gas fans, most influenced by the location of the fans with respect to the absorber modules. These factors include the following:

- Fan size;
- Structural design;
- On-line absorber module maintenance;
- Positive- versus negative-pressure operation of absorber modules; and
- Cyclic reheater leakage.

Each of these factors is discussed individually below.

Fan Size

The flue gas entering the FGD system absorber modules typically has a temperature in the range of 130 to 150°C (270 to 300°F) and a pressure of 1.5 to 2.5 kPa (6 to 10 inwg). The flue gas leaving the absorber modules is typically 50 to 60°C (125 to 140°F) with a pressure of 0.5 to 1.0 kPa (2 to 4 inwg). It should be noted that higher flue gas pressures entering and leaving the absorber modules are possible, depending on the presence and location of a flue gas reheater, as discussed in Part I, Section 4.6--Flue Gas Reheat. As a result of the reduction in temperature, the volume of flue gas handled by fans located downstream of the absorber modules is significantly smaller (15% or more) than by upstream fans. The smaller gas flow requires a smaller fan. The greater flue gas mass flow rate downstream of the absorber modules, however, consumes more fan power and may require a larger capacity fan motor. Any capital cost advantage derived from the use of smaller fans is offset by increases in the annual electrical power costs and the capital costs of larger fan motors and the fan wash system. Downstream fans also require more corrosion-resistant and expensive materials of construction, as discussed later.

Structural Design

A major design consideration with installation of an FGD system is the potential for increasing negative-pressure excursions in the boiler, ductwork, and particulate control devices (ESP or fabric filter) by 1.5 to 2.5 kPa (6 to 10 inwg) should the air flow to the boiler be disrupted. When the FGD system is installed with the construction of the boiler, these greater negative-pressure excursions can be incorporated into the initial structural design of the boiler and downstream equipment. In retrofit cases, additional structural supports may be necessary to prevent implosion of this equipment under emergency pressure-transient conditions.

If the fans are located upstream of the FGD system, the structural design of the FGD system ductwork and absorber modules must consider the potential for positive-pressure transients should the gas path between the absorber modules and the chimney be obstructed. Potentially, the ductwork and absorber modules could be exposed to the full differential pressure capability of the fans at zero flow.

If the fans are located downstream of the FGD system, the FGD system ductwork and absorber modules could potentially be exposed to a negative-pressure transient equal to the full differential pressure capability of the fans at zero flow if the gas path between the boiler and the fans is lost. The structural design of a vessel to withstand a very high negative-pressure transient is usually more difficult and expensive than the design required to withstand a positive-pressure transient of the same magnitude.

On-Line Maintenance of an FGD Module

In many cases, particularly when a spare absorber module is provided, it may be necessary to enter an isolated absorber module to conduct maintenance while the boiler remains in service. Maintaining "mansafe" breathing conditions inside the module under these conditions is difficult even if guillotine dampers with seal air are used at the module inlet and outlet (see Part II, Section 4.0--Flue Gas Dampers). This problem can be somewhat reduced if the flue gas fans are located downstream of the absorber modules. In that case, any leakage around the dampers would be from the modules into the ductwork.

Positive- Versus Negative-Pressure Operation of Absorber Module

Operation of the absorber modules at negative or positive pressure has no significant effects on the FGD process chemistry. Therefore, the most significant difference between positive- and negative-pressure operation is the exposure of the downstream flue gas fans to wet, corrosive flue gas conditions. The effects of installation of downstream fans on materials of construction are discussed later in this section.

Other effects of positive- or negative-pressure module operation are similar to the same types of effects considered regarding the operation of a pressurized or balanced-draft boiler. In the event that a leak develops in the ductwork or absorber module shell, a positive-pressure absorber (fans located upstream of the absorber modules) will discharge flue gas to the environment. This could become a significant problem, especially if the absorber module is enclosed in a building. Localized corrosion and poor breathing conditions are likely to develop in the vicinity of the leaks. Leaks in the absorber module shell are usually easily identified for repair because the slurry carried by the leaks will be visible as a trail of deposits down the side of the module. Such leaks can be housekeeping problems, however, and may cause corrosion of metal surfaces, equipment and controls. Leaks in the outlet ductwork may allow acidic condensate to damage insulation and lagging (if used), exterior ductwork surfaces, and support steel.

If the absorber module is operated below atmospheric pressure (fans located downstream of the absorber modules), any leaks that develop in the absorber module or ductwork would result in-leakage of ambient air into the FGD system. While this would initially appear to be an advantage over positive-pressure operation, such in-leakage points are more difficult to locate for repair. The in-leakage results in slightly greater flue gas volume to the downstream fans, although a very large leakage rate would be needed to add appreciably to the total gas flow volume. In inhibited-oxidation processes, the oxygen present in the in-leaking air may make suppression of sulfite oxidation more difficult.

Cyclic Reheater Leakage

Some European and Japanese FGD installations use cyclic reheaters to heat the treated flue gas before it enters the chimney (see Part I, Section 4.6--Flue Gas Reheat). Ideally, no untreated flue gas should leak over to the treated gas duct since this would reduce the overall efficiency of the FGD system. However, as discussed in Section 4.6, some leakage does occur when regenerative plate-type reheaters are used. By locating the flue gas fans downstream of the absorber modules and ahead of the reheater, the higher pressure gas would be on the treated side of the cyclic reheater, and leakage would be of treated flue gas to the untreated side.

2.3 Material Selection

The selection of materials of construction is dependent on the location of the fans. Upstream fans are exposed to the same conditions as boiler ID fans, and the same materials can be used. Generally, carbon steel is used for the fan housing and erosion-resistant carbon steel is used for high-wear areas of the fan blades.

Downstream fans must use materials suitable for the very corrosive conditions that may occur. Non-rotating parts such as the fan housings may use rubber-lined carbon steel or corrosion-resistant nickel alloys such as alloy C-276. Corrosion-resistant nickel alloys are also used to fabricate the rotating parts such as fan wheels and blades. Erosion-resistant materials may be used in the high-wear locations such as the leading edges of the fan blades where erosion resistance may be more important than corrosion resistance. Rubber and other linings are not recommended for rotating parts because localized loss of the linings may result in severe imbalance of this equipment and damaging vibrations.

2.4 Recommendations

- If possible, the pressure rise requirements of the FGD system should be incorporated into the boiler ID fans to simplify fan control and minimize capital costs;
- In a retrofit installation, new booster fans are usually more economical than replacement of the existing fans;
- The selections of the fan type (centrifugal or axial) and location (upstream or downstream of the absorber modules) best suited to a specific installation should be the subjects of an engineering study; and
- Downstream fans should be constructed of materials suitable for a wet, corrosive environment and should be equipped with a fan wash system.

2.5 References

1. ASEA Brown Boveri-Combustion Engineering, Inc. Combustion, Fossil Power. Joseph Singer, ed. Windsor, Connecticut, 1991.

2. Babcock & Wilcox. Steam, Its Generation and Use. S.C. Stultz and J.B. Kitto, eds. Barberton, Ohio, 1992.

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Cyclic Reheater Leakage

3.0 DUCTWORK AND EXPANSION JOINTS

The ducts that convey flue gas within the FGD system consist of rigid shells with expansion joints as required to provide necessary flexibility, vibration damping, and accommodation of differential thermal expansion. The flue gas upstream of the first point in the FGD system at which the duct walls become moist is no different than the flue gas produced by power plants without FGD systems. Only the ductwork beginning at the location where the duct walls first become moist is exposed to the operating conditions related to the FGD system.

3.1 Types Available

3.1.1 Ductwork

Virtually all FGD ductwork is fabricated on site and is most frequently defined by its location or role in the FGD system, as shown in Figure 3-1. Beginning at the upstream end of the system the types of ductwork are as follows:

- Absorber inlet plenum--The common duct conveying hot, untreated gas

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- Absorber inlet plenum--The common duct conveying hot, untreated gas from the induced draft (ID) fans, particulate removal device, or other upstream equipment to the absorber module inlet ducts;
- Absorber inlet ducts--The individual ducting conveying the untreated flue gas from the inlet plenum to the inlet of each absorber;
- Absorber outlet ducts--The individual ducts conveying the treated gas from the absorber modules to the outlet plenum;
- Outlet plenum--The common duct conveying the treated flue gas from the absorber outlet ducts to the stack flue; and
- Bypass duct--The duct (or ducts) conveying untreated flue from the inlet plenum either to the outlet plenum or to a separate stack flue.

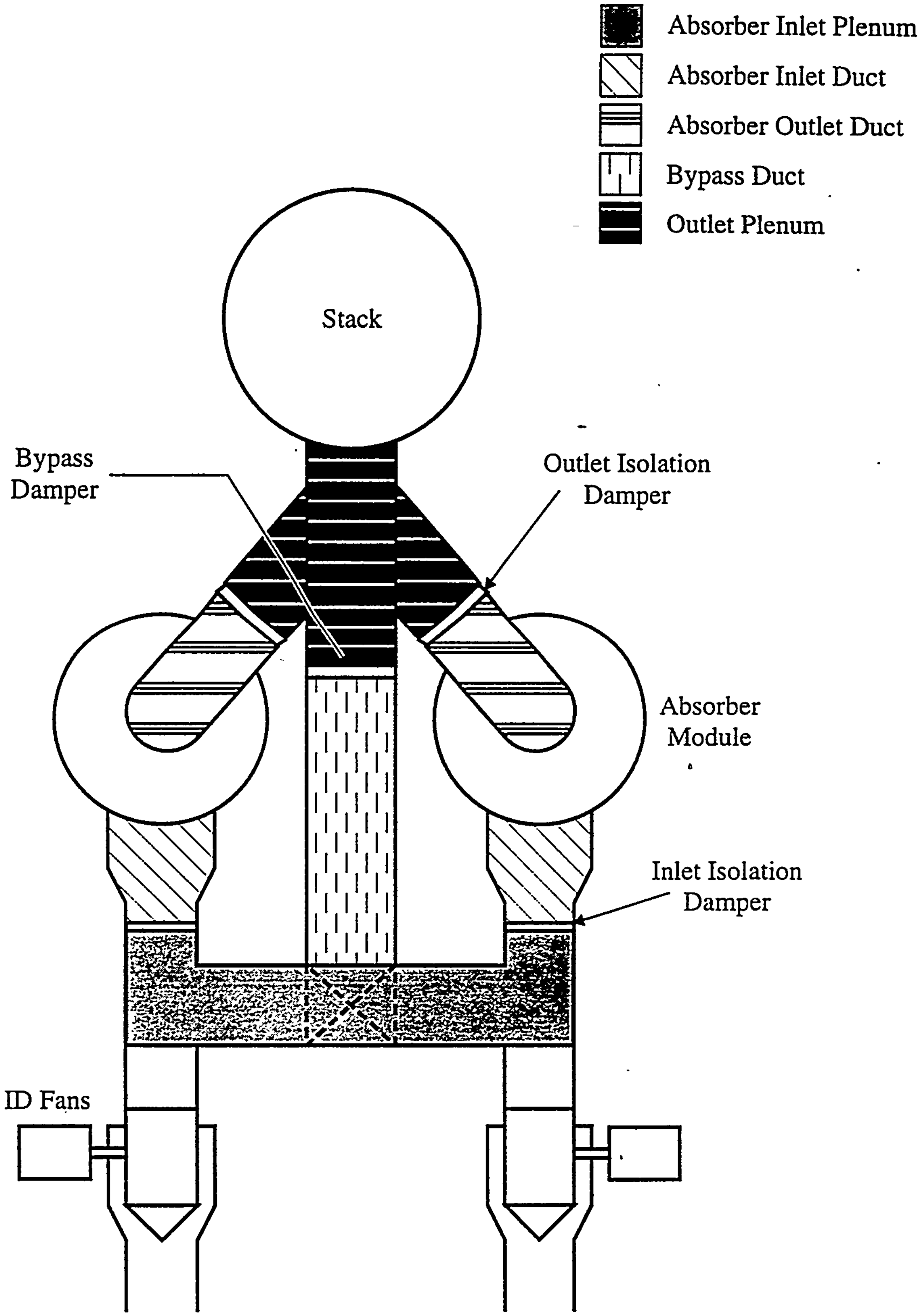


Figure 3-1. FGD System Ductwork Types

The inlet plenum, the portion of the absorber inlet ductwork upstream of the inlet isolation damper, should always operate dry* and, as discussed in the introductory paragraph of this section, is not exposed to flue gas conditions related to operation of the FGD system.

3.1.2 Expansion Joints

Virtually all expansion joints used in FGD ductwork are nonmetallic joints, fabricated from sheet fluoroelastomer reinforced with fiber, wire, or a combination of fiber and wire meshes.

3.2 Design Considerations

3.2.1 Process Considerations

Process considerations include the following:

- Basic operating modes;
- Limiting gas velocities; and
- Mist eliminator efficiency.

Basic Operating Modes

Definition of Modes--The process decisions concerning reheating of the gas and management of bypass gas during startup and shutdown are of vital importance to the design of the FGD system ductwork. Figure 3-2 provides a schematic classification of outlet ductwork operating modes and environments based on process design. The basic operating

* Situations have occurred in which localized reverse flow along the tops of ducts have carried gas streams normally encountered downstream of dampers into upstream areas designed for different environments. While this is not a typically encountered problem, the possibility should be considered.

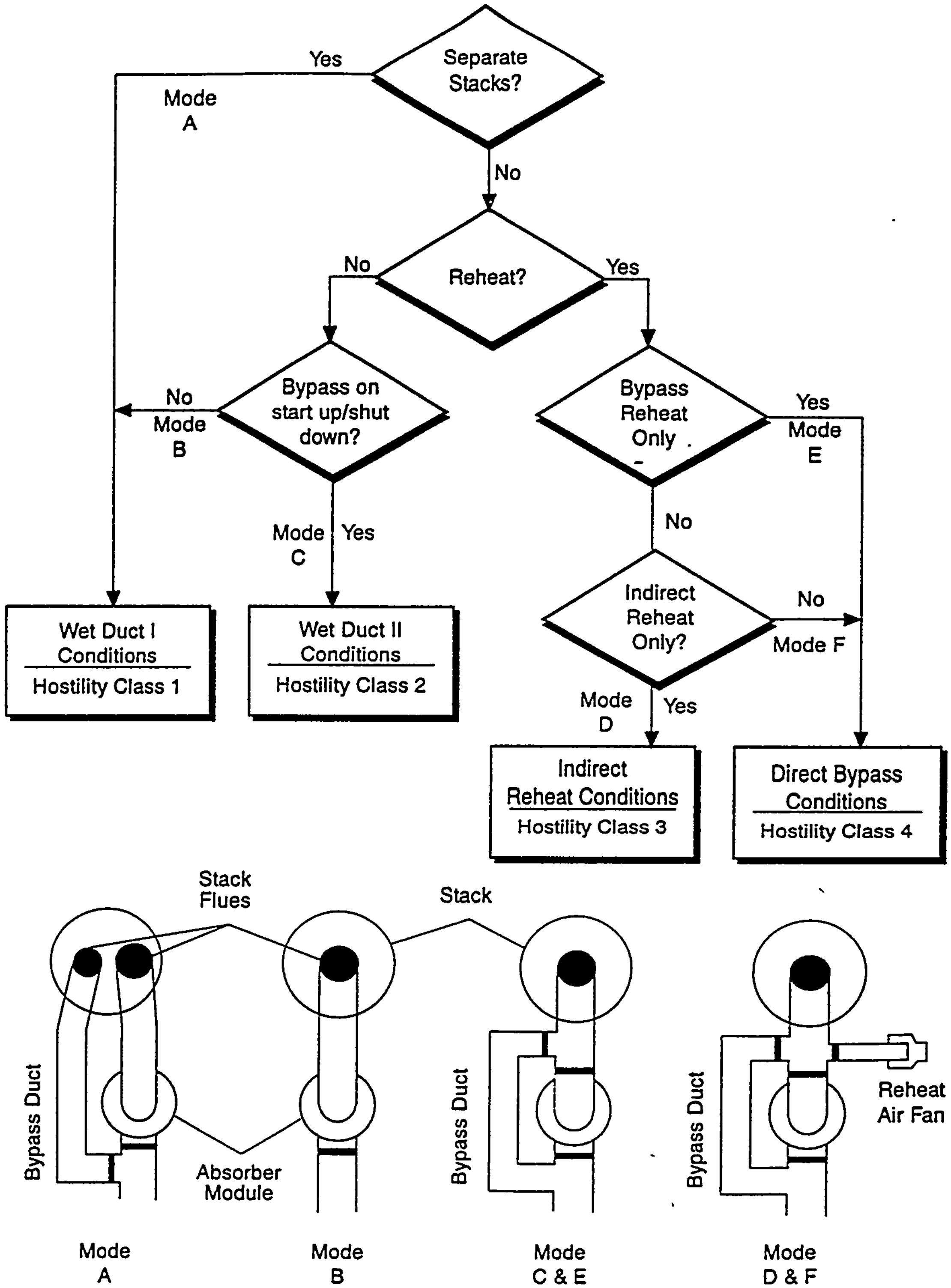


Figure 3-2. Schematic Classification of FGD Outlet Duct Environments

modes are defined in Table 3-1. Mode A is a true wet stack design in which bypass gas is routed to a separate flue and the FGD outlet ductwork is never exposed to hot dry gas. True wet stack conditions also occur if 100% of the flue gas is scrubbed and hot gas is never vented through the outlet duct, Mode B. These operating modes result in the least aggressive operating conditions. Mode C occurs when hot gas is bypassed around the absorbers into the FGD outlet duct only during startup and shutdown, with no bypass during normal operations. This operating mode results in more aggressive conditions than Modes A or B. Mode D illustrates indirect reheat. Hot flue gas is bypassed through the outlet duct during startup and shutdown, but not during normal operations. Reheat is achieved by hot air injections (shown in Figure 3-2) or by some other means. This mode results in still more aggressive conditions. Mode E illustrates direct-bypass reheat, in which some of the hot flue gas is bypassed around the absorbers into the outlet duct during normal operation. This mode generates the most aggressive conditions of all. At least one plant uses a combination of direct-bypass reheat with simultaneous indirect reheat, Mode F. From an aggressivity standpoint, this hybrid situation is direct bypass reheat.

Reheat vs Wet Stack Operation--Reheating the treated gas results in increased buoyancy and draft in the stack flues, reducing induced draft and booster fan power requirements, and allowing operation of the absorbers at negative pressure. At one time it was also thought that reheating the gas would dry it, eliminating droplet rainout near the stacks.

Reheat options are described in Part I, Section 4.6--Flue Gas Reheat. Bypass reheat, in which a portion of the untreated gas bypasses the FGD absorbers and is mixed with the treated gas in the outlet duct, is the simplest form of reheat, but it results in the most severe corrosion problems. Cyclic reheat designs which allow slippage of gas from the hot to cool sides of the process also effectively create direct bypass conditions where the gas mixing occurs.

Table 3-1

Basic Outlet Duct Operating Modes

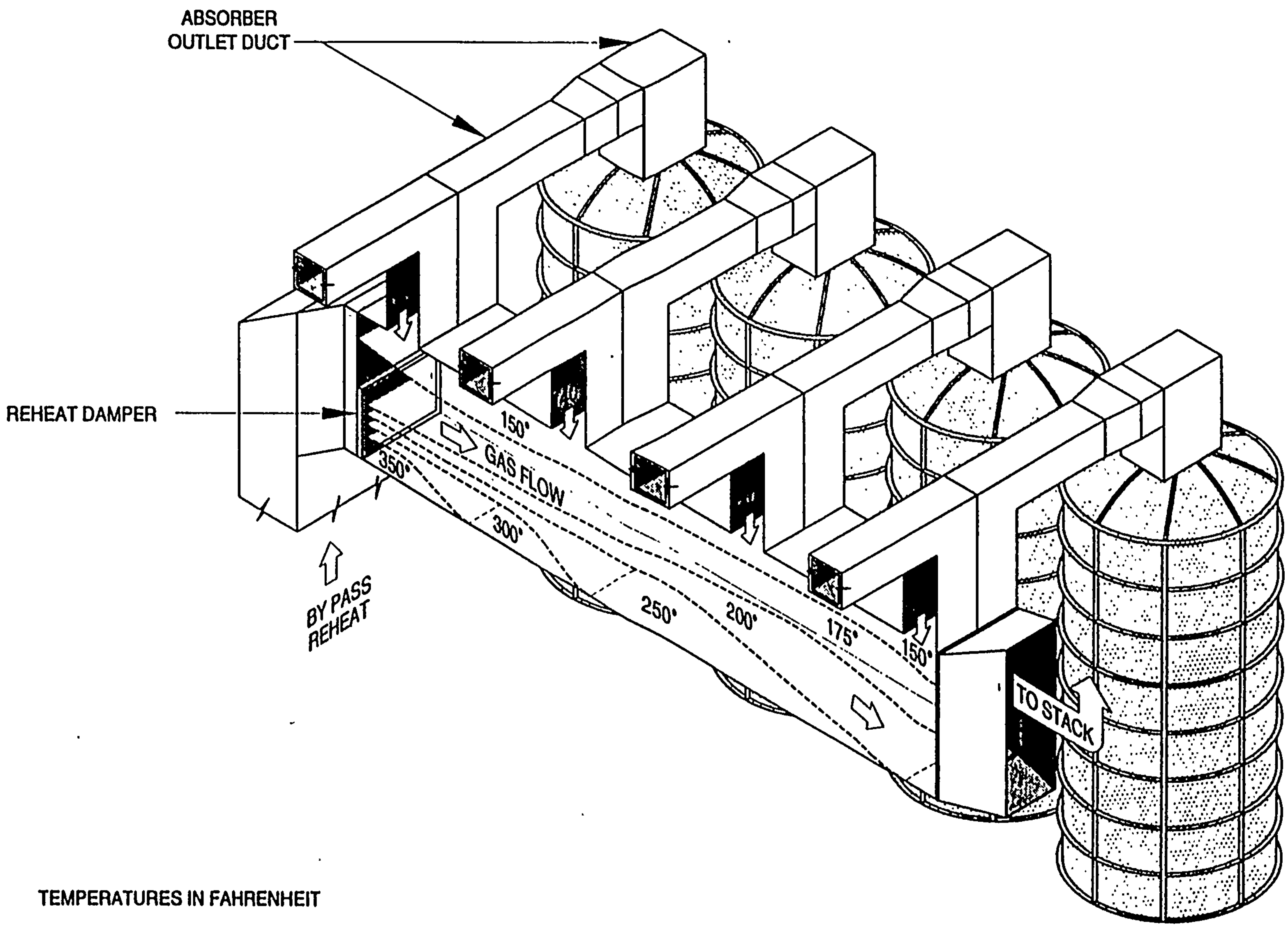
Mode	Mode Name	Description	Hostility Class
A	Wet Duct I	Operation such that hot flue gas is never injected into the ductwork between the absorbers and stack flue.	Class 1. Least aggressive conditions. Duct surfaces exposed to condensates at absorber temperatures with no potential wet/dry interfaces.
B			
C	Wet Duct II	Hot flue gas is injected into the ductwork between the absorbers and stack flue during startup and shutdown, but not during normal operations.	Class 2. More aggressive than Class 1. Ductwork subjected to severe thermal shocks during transient bypass events.
D	Indirect Reheat	Wet treated gas is heated by means other than injection of hot, untreated flue gas during normal operations. Hot gas bypassed around absorbers is injected into ductwork during startup and shut-down.	Class 3. More aggressive than Class 1 or 2. Duct surfaces subjected to heated moisture film with concentration of corrosive ions due to evaporation. Potential for wet/dry interface.
E	Direct Bypass Reheat	Hot flue gas is injected into the ductwork between the absorbers and stack flue.	Class 4. Potentially extremely severe conditions with the certain existence of wet/dry interfaces and formation of concentrated acid condensates.
F	Dual Reheat	Reheat by a simultaneous combination of indirect and direct-bypass methods.	

Reheat methods which do not involve the mixing of untreated and treated gas include some forms of cyclic reheat, in-line reheat, indirect hot air reheat, and direct-fired reheat. While all reheat options increase flue gas volume downstream of the absorber modules, the latter two options in particular greatly increase gas volumes and consequently duct size. In general, indirect reheat creates corrosive environments which are more severe than those created by wet operation, but less severe than those resulting from bypass reheat.

Experience with many different outlet duct configurations at existing FGD systems has repeatedly demonstrated that reheating does not effectively dry the flue gas for two reasons. First, the entrained moisture droplets do not have time to evaporate before the flue gas leaves the stack. Second, duct designs cannot produce enough turbulence to effectively mix hot dry gas or reheat air and the heavier, moist flue gas without also creating unacceptably high flue gas pressure drops. Thermal stratification can be severe, as illustrated in Figure 3-3, an actual example of thermal stratification from an outlet plenum of an FGD system at a lignite-fired plant (1).

The realization that reheat does not effectively dry the flue gas has led to increasing interest in wet (no reheat) operation to eliminate the parasitic energy loss due to reheat. It is important to note that true "wet duct" operation usually requires separate stack liners (flues) for untreated and treated gas, even if 100% of the gas flow is to be treated by the FGD system during normal operation. This is discussed further below and in Section 3.3--Material Selection.

Startup and Shutdown--Flue gas handling during startup and shutdown is another important process consideration. Bypassing the untreated flue gases to the FGD outlet plenum during FGD system startup and shutdown imposes severe thermal loads on the ductwork and creates corrosive operating conditions similar to those created by bypass reheat even if there is no reheat during normal operation (1). This is why some "wet duct" systems (systems with no reheat) have opted for separate stack liners for the untreated and treated flue gases.



TEMPERATURES IN FAHRENHEIT

Figure 3-3. Thermal Stratification in a Direct-Bypass Reheated Outlet Duct

Impact of Basic Operating Mode Decisions--Decisions concerning basic operating modes constrain materials selection for the ductwork, which can have a large effect on the capital cost of the FGD system. The materials of construction for FGD system ductwork are discussed in detail in Section 3.3 below and in Part I, Section 5.3.1--Corrosive Environment Zones.

The decision to reheat the flue gas also increases the flue gas volume downstream of the reheater, and the duct design must allow for the increased volume. Finally, the decision of whether or not to reheat also has major impacts on stack design, as discussed in Part I, Section 4.5.3--Wet Stack Equipment Design.

Limiting Flue Gas Flow Rates

The maximum design flue gas flow rate is dependent upon the location of the duct within the FGD system. Inlet plenum, absorber inlet duct, and bypass duct requirements are relatively independent of FGD system process design decisions, other than the requirement that the ductwork be properly sized to accommodate the gas flows. Design gas velocities of 15.2 to 18.3 m/sec (50 to 60 ft/sec) are typical for these ducts.

Regardless of the operating mode selected, the absorber outlet ducts and the outlet plenum are typically designed for gas velocities on the order of 12.2 to 15.2 m/s (40 to 50 ft/s), primarily to reduce moisture re-entrainment from the duct walls and any internal braces or turning vanes. Additional discussions of outlet duct velocity as a function of the duct materials of construction are presented in Part I, Section 4.5.3--Wet Stack Equipment Design.

Mist Eliminator Efficiency

Mist eliminator efficiency should be maintained as high as possible to minimize the formation of scaling and the accumulation of damp deposits (muck) in the outlet duct.

Muck is the mud-like deposition of absorber slurry solids on the duct floors. The quantities of muck which can accumulate on the floors of outlet ducts between scheduled outages can be significant even when the mist eliminators operate efficiently. Accumulations of over 150 mm (6 in.) have occurred throughout the lengths of outlet ducts at numerous existing utility FGD installations. These accumulations promote the corrosion of duct materials and add significantly to the structural loads on the floors and supports. In addition to "muck," hard gypsum-based scale can accumulate on the duct walls, turning vanes, and internal bracing, if present.

3.2.2 Mechanical Considerations

Mechanical considerations include the following:

- Basic mechanical considerations;
- Duct geometry; and
- Resonance, vibration, and "oil-canning."

Basic Mechanical Considerations

The basic mechanical considerations in the design of FGD ductwork are similar to those which apply to the design of any high-volume flue gas duct. Detailed discussion of these considerations is beyond the scope of this report; however, they must include several basic principles. The ducting must be sufficiently stiff and supported to withstand the maximum static loads imposed by the weight of the ductwork and any accumulated scale and deposits. The ductwork also must be able to withstand the maximum anticipated structural loads imposed by duct insulation, wind, snow, and maintenance activities. If the plant is located in a seismicly active region, allowance must be made for seismic loads. The relative duct motions at expansion joints must remain within the motion limits of the joints.

Duct Geometry

Ductwork may be either rectangular (or square) or circular (or elliptical) in cross section. Each geometry has advantages and disadvantages, and most FGD vendors have a specific preference for one or the other if the FGD system specification permits the vendor to make this decision.

Rectangular cross section ductwork is more commonly used than circular ductwork, because it is easier to fabricate in the field and easier to scaffold when outage maintenance is required. Rectangular cross section ducts also require less complicated supports on the structural steel. However, rectangular ductwork must be externally stiffened and may include internal bracing as well. Internal bracing reduces the amount of external bracing needed; however, the use of internal bracing imposes its own penalties. The bracework can accumulate significant amounts of scale that must be removed during scheduled outages, and promotes liquid re-entrainment in the flue gas. Historically, the internal bracing has also experienced major corrosion problems, and adds significantly to the complexity of construction when alloy wallpaper lining is used. Recent rectangular ductwork designs have tended to reduce the amount used as much as possible or to avoid internal bracing altogether.

Circular cross section ducts are intrinsically stiffer than rectangular ducts and require less supplemental stiffening and external support, but historically, are less common than rectangular ducts. A circular duct has significantly less wall surface area than a rectangular duct with the same gas carrying capacity, as illustrated by Figure 3-4. A circular duct has 11.25% less wall surface area than a square duct of equal capacity. Compared to a rectangular duct with an aspect ratio (height-to-width ratio) of 2:1, a circular duct of equal capacity offers a 16% reduction in wall surface area. Compared to rectangular ductwork with an aspect ratio of 3:1, a circular duct with equal capacity provides a 23% reduction in surface area. These reductions in surface area reduce both the cost of external insulation and the expense of costly alloys, if corrosion-resistant alloy construction is selected. Both fiber-

Impact of Basic Operating Mode Decisions--Decisions concerning basic operating modes constrain materials selection for the ductwork, which can have a large effect

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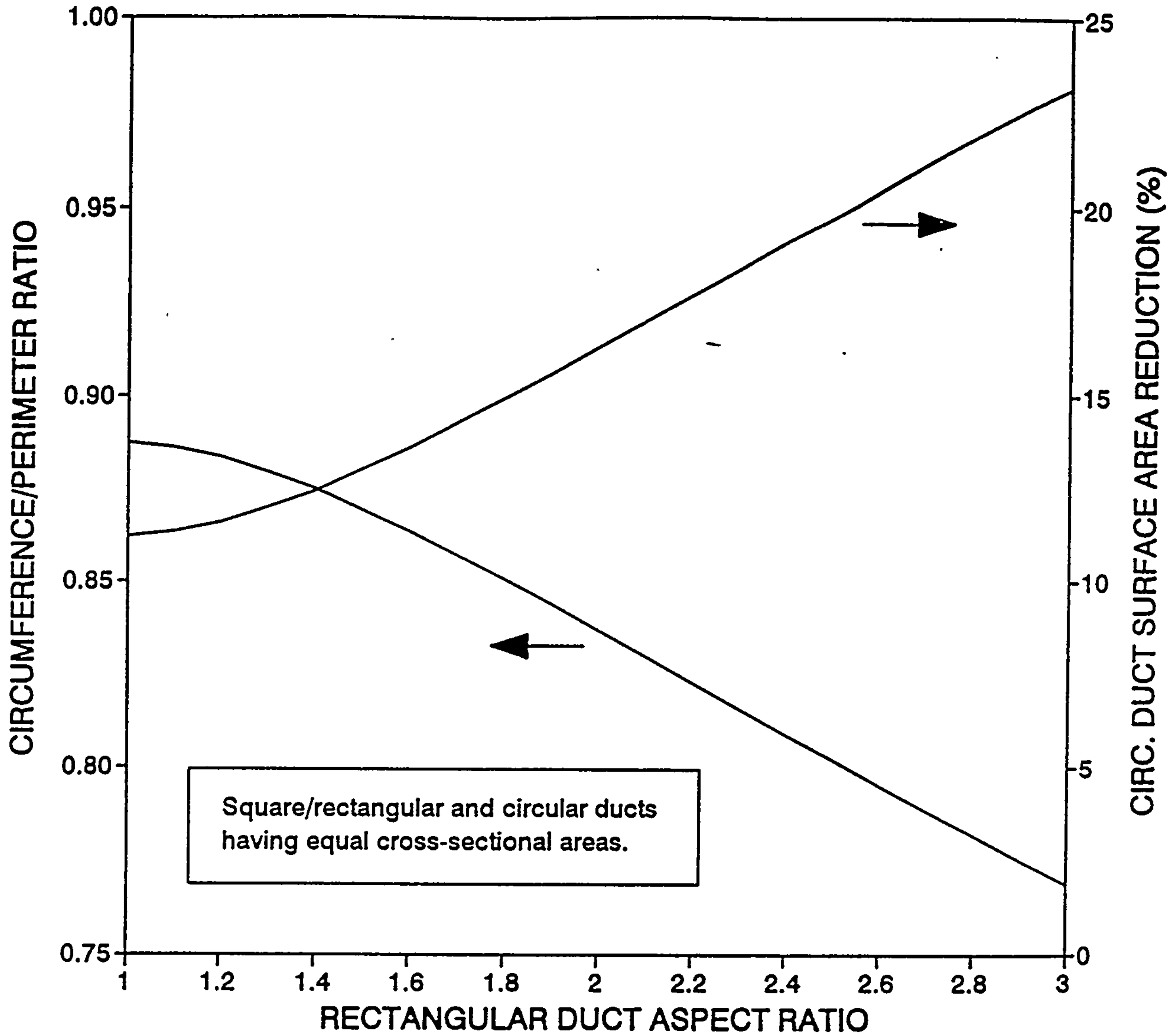

Figure 3-4. Comparison of Wall Surface Areas of Ducts Having Circular and Rectangular Cross Sections

reinforced plastic (FRP) and vitreous ceramic brick lined ducts are necessarily circular for structural and fabrication reasons.

Resonance, Vibration, and Oil-Canning

Other important mechanical considerations are resonance, vibration, and "oil-canning." There have been instances in which turning vanes within ductwork resonated with the induced draft fans, resulting in rapid weld failure of the adjacent ductwork. Remediation required a re-design of the turning vanes to alter their natural frequency and eliminate the resonance. Every reasonable effort should be made during design to assure that the natural frequencies of turning vanes and similar structures are significantly different than those of the ID fans (if resonance does occur, modification of the ductwork will be essential).

Flue gas pressure pulses within the ductwork can cause elastic bowing or flexing of the duct walls, a phenomenon called "oil-canning." The effect is common in rectangular ducts, and probably rare in circular ducts. Excessive oil canning has been implicated in the failure of reinforced resin linings in outlet ducts.[*]

3.2.3 Other Considerations

Other considerations include the following:

- Liquid re-entrainment;
- Drainage;
- Insulation; and
- Emergency quench provisions

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[*] Attribution to this mode of failure is anecdotal by coating manufacturers, but is consistent with the appearance of fracturing in some older, more brittle coating formulations.

Liquid Re-entrainment

As discussed in Part I, Section 4.5--Wet Stacks, liquid re-entrainment is an important aspect of duct design because re-entrainment is the primary mode by which rainout droplets are incorporated into the flue gas plume leaving the stack. Minimization of liquid re-entrainment is particularly critical in the design of wet duct systems. Internal bracing and sharp ledges greatly increase re-entrainment, and should be minimized, particularly in wet duct systems.

Drainage

Adequate drainage of the liquids from the duct is a critical aspect of good outlet duct design and is commonly inadequately addressed. Poor drainage contributes to droplet re-entrainment and solids accumulation. Poor drainage also increases corrosion of duct materials, particularly on the duct floors.

Repeated experience at existing utility FGD systems has shown that flat-bottomed ducts do not drain adequately. The inevitable bowing and warpage of the structural plates results in liquid pooling on the duct floors (2-5). Consequently, it is strongly recommended that rectangular ducts be constructed with dihedral false floors having at least 3° slopes at all points. The floors also need to slope longitudinally (lengthwise down the ducts) toward drains.

Circular ducts intrinsically provide better drainage than rectangular ducts, but should also be slightly sloped longitudinally and provided with adequate drains to prevent pooling at low spots.

As a practical matter, it may be desirable to conduct a pooling test after construction by washing down the duct with water. If undrained low spots are discovered, it may be necessary to add supplemental drains.

Turning vanes and internal braces, if present, also should be designed to minimize pooling of liquids.

While the potentially wet portions of the inlet ducts are short and of simple geometry compared to the outlet ducts, it is critical that these duct sections drain toward the absorbers. Otherwise, liquid can migrate from the sections designed for wet service to the hotter sections constructed of carbon steel, resulting in severe corrosion.

Insulation

FGD gas inlet ducts are insulated to prevent formation of acidic condensates upstream of the inlet breachings to the absorbers and for personnel protection from hot [150°C (300°F)] metal surfaces. Outlet ducts are insulated to minimize heat loss through the duct walls. In wet ducts, or the wet duct portions of reheated systems, insulation reduces the amount of liquid formed in the duct, reducing both drainage requirements and the potential for moisture re-entrainment. Insulation in reheated ducts conserves the heat of the gas stream.

Most ductwork is externally insulated with batten type insulation covered with metal lagging. Proper insulation of the external stiffeners of the ductwork is frequently overlooked. External insulation should be designed to insulate both the duct walls and the stiffeners. A common, but unacceptable, practice is to insulate between the external stiffeners, while securing the lagging to the stiffeners. This practice will result in cold areas on the duct walls and can lead to increased corrosion. It also will cause rapid failure of reinforced resin linings due to the cold wall effect described in Part I, Section 5.5.3--Modes of Failure.

Two materials-of-construction options for ductwork--vitreous ceramic brick and foamed borosilicate glass block--do not require external insulation because these materials are themselves quite good thermal insulators. The elimination of requirements for external insulation results in a significant cost reduction for ducts using these materials.

Emergency Quench

If outlet ducts are lined with reinforced resins, or are constructed of FRP, the design of the outlet ductwork should include provisions for fail-safe emergency quenching of the gas in the event of an emergency bypass around the FGD system or of a system upset such as simultaneous air preheater failure and loss of absorber sprays.*

3.3 Material Selection

Materials-of-construction options for FGD systems are reviewed in detail in Part I, Section 5--Materials-of-Construction Options. Materials selection options for duct construction are summarized below, using the corrosive environment zones defined in Part I, Section 5.3.1.

3.3.1 Ducts

The discussion of materials selection for ducts is divided into consideration of the following:

- Inlet ducts and plenum;
- Outlet ducts without reheat;
- Outlet ducts with indirect reheat;
- Outlet ducts with direct bypass reheat; and

* This unlikely sounding event actually occurred in an FGD system because of a lightning strike that cut all internal and external power to the plant. The accident destroyed the reinforced resin linings of the absorbers and outlet duct and melted the polypropylene mist eliminators. An even worse catastrophe is an absorber fire. In several cases, welders have inadvertently ignited resin or rubber tower liners, or in at least one case, scaffolding within the absorber. Temperatures in absorber tower fires are known to have exceeded 1260°C (2300°F). However, absorber fires are not the result of operational upsets and can be excluded from the maximum credible operational accident scenario.

- Bypass ducts.

Inlet Ducts and Plenum

The inlet plenum and absorber inlet ducts upstream of the point where moisture first forms on the duct surfaces is subjected to dry, SO_2-rich gas with typical temperatures of 93 to 166°C (200 to 330°F). Excursions to 316°C (600°F) may occur during air preheater failure. The preferred material of construction for this portion of the ductwork is unlined carbon steel.

From the point in the absorber inlet duct where moisture first forms on the duct surfaces until the gas enters the absorber or pre-scrubber, the duct surfaces are subjected to fluctuating temperatures as the gas quenches to adiabatic saturation, approximately 52 to 60°C (125 to 140°F). This creates extremely aggressive wet/dry zones on the duct walls and promotes the formation of extremely acidic condensates. There is also the potential for severe thermal excursion during boiler air heater failure.

The most widely used materials for this zone are the C-Class alloys, which include Alloys C-276, C-22™, 59™, 622™, 686™, and Allcorr 41™, typically erected as solid plate or mill-clad plate (see Part I, Section 5.6.2--Alloy Construction Options for a discussion of alloy construction options including solid plate, mill-clad plate, and wallpaper construction). Alloy 625 is used when high strength as well as corrosion resistance is required.

Although not widely used, vitreous ceramic brick over a urethane membrane on carbon steel (see Part I, Section 5.7.3--Vitreous Ceramic Tile and Brick) would also be quite suitable for this zone. Note, however, that for structural reasons, ceramic brick can be installed only in circular or elliptical ducts.

The G-Class nickel-base alloys, stainless steels, and resin-reinforced linings have frequently failed to yield satisfactory results in the wet portions of absorber inlet ducts. Gunited cement linings should not be considered for any FGD duct application except as an overcoat to foamed borosilicate glass block, as discussed later in this section.

Outlet Ducts Without Reheat

With some rare exceptions where reheat occurs within the absorbers above the mist eliminators, no reheat occurs in the outlet ducts leaving the absorber modules, and this portion of the duct work operates as a wet duct. In systems without reheat, this wet-duct condition extends through the outlet plenum through the stack breaching. The wet-duct environment is characterized by the presence of saturated gas with entrained moisture droplets that impinge upon and adhere to the duct wall. Moisture condensation also occurs on the duct walls, and the liquid films continue to absorb residual acid gases from the flue gas, producing highly acidic conditions. Unless drainage is good, highly acidic condensate pools form on the duct floor. Ionic solids, including chlorides and fluorides, tend to concentrate in these acid films even in the absence of evaporative concentration (5). In addition, temperature excursions to 316°C (600°F) are possible with simultaneous loss of air heater and absorber sprays or during an emergency bypass of untreated flue gas.

Non-reheated outlet ducts have historically been constructed of corrosion-resistant alloys or reinforced resin coated steel. G-Class alloys, and possibly superaustenitic stainless steels (those containing ≥6% molybdenum plus nitrogen), are the minimum recommended alloy grades for non-reheated outlet ducts of low-chloride systems. As discussed in Part I, Section 5.6.1--Alloy Products and Corrosion Resistance, the less corrosion-resistant grades of stainless steel (i.e., Type 316L, Type 317LM) have repeatedly demonstrated unsatisfactory performance in non-reheated outlet ducts of even low-chloride systems. The superaustenitic stainless steels have somewhat better resistance to the acidic outlet duct conditions than the lower grades of stainless steel, but experience with the superaustenitic 6% molybdenum stainless steels in non-reheated outlet duct service is too limited for an assessment of their performance at this time. Alloy 625 and C-Class alloys may be best for wet ducts of low-chloride systems. Alloy 625,* C-Class alloys, and titanium are the only alloys that should be considered for higher-chloride wet outlet ducts (6).

Historically, reinforced resin linings in non-reheated outlet ducts have yielded relatively poor performance, requiring major repairs or replacement at intervals of three to six years (6). Many of these systems used polyester-based and vinylester-based resins, with the vinylesters apparently giving better results than the polyesters. More recently, formulations based on Novalac epoxy-melamine-phenolic blends have shown promising results, and appear to be more durable than the vinylesters. However, these products have not been in use for a long enough period of time at a sufficient number of locations for an accurate prediction of their reasonable service life expectancy. Reinforced resins are discussed in detail in Part I, Section 5.5--Sheet Elastomer and Reinforced Resin Linings.

Note that many resin coating products may be reformulated in response to the Clean Air Act Amendments of 1990, particularly to reduce or eliminate the use of aromatic amine curing agents and styrene crosslinking agents. At this time, the effects of reformulation on long-term lining performance have not been demonstrated by years of utility operating experience (6).

If the product is flake-reinforced, glass flakes (glass mat where abrasion is high) should be specified. A variety of other reinforcing or filler materials, such as silicon carbide and alumina, are also sometimes used, particularly in abrasion-resistant (AR) formulations. Fillers should be non-reactive in sulfuric acid at 82°C (180°F), and should not themselves be porous. Mica flakes should be prohibited, because they react with sulfur oxides.

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* While the C-Class alloys have sightly higher resistance to chlorides than Alloy 625, this difference does not become apparent until chlorides reach very high levels, probably above 15,000 ppm. Alloy 625 has significantly higher strength than the C-Class alloys, and is used when mechanical and fatigue strength are important considerations, for example, in wet induced-draft fans.

The nominal thermal limit of resin-based liners is 82°C (180°F) in wet service. Dry service ceiling temperature vary with resin: 121°C (250°F) for polyester and epoxy, and 182°C (360°F) for vinylester. However, all of these linings will fail rapidly if exposed to sharp wet/dry thermal excursions (6).

A foamed borosilicate glass block lining (see Part I, Section 5.7.5) is an alternative to reinforced resin linings. The foamed borosilicate glass block system consists of sealed-cell borosilicate glass blocks, attached to the steel substrate by a thick polyurethane asphaltic mastic applied to the back and sides of each block and to the steel substrate. The urethane mastic provides the ultimate barrier against corrosive moisture. The foamed borosilicate glass block lining is an extremely efficient thermal insulator. The thermal stability and insulating properties of the block protect the urethane membrane and render the system immune to even severe and repeated thermal excursions. The need for external insulation is also eliminated. The borosilicate glass is also essentially chemically inert and is impermeable to moisture and acidic condensates (except hydrofluoric acid).

Borosilicate glass block is very light in weight and can usually be installed in steel ductwork without increasing the external stiffening or internal bracing. The entire system is slightly flexible and can tolerate slight flexing (oil-canning) of the duct walls. However, foamed borosilicate glass block has one significant shortcoming that must be considered. The standard block is extremely friable (brittle and easily crumbled). Block on the duct floor can be damaged by personnel walking in the duct or by wheelbarrows brought in to remove solids buildup. Walls can be damaged by accidental ramming or scraping by wheelbarrows. Instances of severe erosion have been reported in outlet ducts with geometries that created high-velocity flue gas impingement areas on lined surfaces. The material cannot be hydro-blasted or sandblasted to remove fly ash deposits.

To compensate for the extreme friability of the block, some utilities have installed foamed borosilicate glass block, then gunned approximately 12.5 mm (0.5 in.) of potassium silicate gunite over the floors and lower walls for protection against mechanical damage. In such applications, some cracking of the gunite is quite acceptable, since its only function is to dissipate point loads on the glass block.

Elf Atochem, the manufacturer of the foam borosilicate block, has produced a modified block product designed specifically to overcome the susceptibility to erosion. This block is provided with a skin of crushed borosilicate glass/silicate mortar on one side, providing a tough outer wear surface. The prevailing strategy is to apply regular block over the entire lined surface. If local erosion problems appear, the affected areas can be relined with the more expensive modified block.

In recent years there has been increasing interest in free-standing FRP ductwork for utility FGD applications, based on the diverse experience with FRP ducting in non-utility FGD-like applications in the metal smelting and pulp and paper industries. FRP for utility FGD applications is discussed in Part I, Section 5.8.2--Free-Standing FRP Structures.

Vinylester appears to be the current resin of choice for free-standing FRP structures. Improved performance can be obtained from brominated vinylester resins, and these should probably be specified for future ducts and stack liners. Thermal tolerance can be further increased by the addition of powdered graphite filler to increase the thermal conductivity of the composite laminate.

Despite its apparent potential, successful use of FRP in FGD duct applications has been hampered by a lack of clear standards for design and fabrication. The proper design of FRP equipment entails complexities beyond the typical issues confronting designers, and the special nature of FRP composites is easily overlooked, even by competent engineers. Consequently, large FRP structures are typically designed and fabricated as a package by a few highly specialized vendors. The very specialized engineering knowledge required for the design of large FRP structures can make it difficult for utilities to evaluate bid responses.

Outlet Ducts with Indirect Reheat

The corrosive environment created by indirect reheat methods, including inline reheat, is more aggressive than the non-reheated environment. As discussed above, indirect reheat rarely produces dry gas, but instead results in partially evaporated droplets suspended in the gas stream until they impinge on the duct surfaces. Thus indirect reheat increases corrosiveness by increasing temperature and concentrating dissolved solids in the remaining moisture films. The more corrosive indirect reheat conditions extend from the heat source or point of hot air injection through the stack breaching.

The alloys most widely and successfully used in this environment are the C-Class alloys and titanium, though Alloy 625 is perhaps the minimum grade suitable for reheated outlet duct applications (6).

G-Class alloys, the least corrosion-resistant grade of nickel-base alloy commonly used in FGD applications, has experienced severe pitting in reheated outlet duct service, requiring retrofit lining (wallpapering) with Alloy C-276 (6). The superaustenitic stainless steels may be expected to provide similar results because their resistance to acidic, high-chloride environments is similar. These alloys are not recommended for use in this application.

Although vitreous ceramic brick, discussed in Part I, Section 5.7.3, has not been widely used in FGD ducting, this option is worthy of consideration. The vitreous ceramic brick is applied in one or two courses over a urethane membrane within a circular or elliptical duct, and grouted with a furan mortar. The material is effectively immune to most acids and abrasive wear, and is immune to thermal excursion. The brick has significant insulation properties, protecting the urethane membrane which is the final corrosive barrier, and eliminating the need for external duct insulation. However, for structural reasons, vitreous ceramic brick linings can be installed only in circular or elliptical ducts, and the weight of the lining means that the duct supporting structures must be more robust than for other materials options.

The foamed borosilicate glass block described previously also can effectively resist the indirect reheat environment. Based on the information in Part I, Section 5.8.2, free-standing FRP ducting, especially if based on brominated vinylester, should withstand indirect reheat service. Reinforced resin linings on steel are not recommended for this service.

Outlet Ducts with Bypass Reheat

The mixing of SO_2-rich, untreated flue gas and wet, treated flue gas creates extraordinarily corrosive conditions. The sulfuric acid concentration of initially formed moisture films has been estimated to be 70% or higher, and the acid concentration of samples collected from pools in low spots on duct floors downstream of bypass mixing zones exceeded 12% sulfuric acid (2,3). Hydrogen chloride and hydrogen fluoride in the untreated gas are also effectively partitioned into the moisture films, adding to the corrosiveness. Even when perforated plates and other structures have been used to promote mixing, mixing of the treated and untreated flue gas appears to be universally poor, with the result that duct surfaces in the mixing zones are alternately exposed to moisture films and hot, dry gas that evaporates the films and increases the concentrations of corrosive constituents. The extremely hostile conditions extend from the point where the gas streams begin to mix all the way downstream to the stack.

Material selection options are extremely limited for bypass reheat zones and the downstream ducting. C-Class alloys and titanium are the current materials of choice, though failures of even these highly corrosion resistant alloys have occurred under bypass reheat conditions (2,3,6). Many of the installations of these alloys have been retrofits. Corrosion of Alloys C-22 and C-276 at rates of 100 to 250 μm/yr (4 to 10 mil/yr*) with broad, shallow pitting have been documented (2,3,6). Titanium has suffered similar attacks in comparable

* 1 mil = 1/1000 inch.

locations (7). Usually, the attack has been limited to a small fraction of the total duct surface, where conditions are severe enough to corrode these normally highly resistant alloys.

The vitreous ceramic brick discussed above may provide better resistance to direct bypass conditions than the C-Class alloys and titanium, but experience with this option is limited.

Bypass Ducts

Upstream of the bypass damper, the environment within bypass ducts is identical to that within the dry portions of absorber inlet ducts, and the preferred material of construction is unlined carbon steel. However, unless the bypass duct vents to a separate flue, the environment within the bypass duct downstream of the bypass damper becomes extremely corrosive as soon as moisture or acidic condensate begin to form. In these areas the materials-of-construction options for bypass outlet ductwork should be followed.

3.3.2 Expansion Joints

The function of expansion joints in FGD ductwork is to absorb relative motion between the different sections of the ductwork and fixed components such as the absorber modules. Corrosion and twisting have been major threats to metallic expansion joints. Consequently, virtually all expansion joints used in FGD ductwork downstream of the particulate removal system are made from reinforced fluoropolymer sheet, typically 4.8 mm (0.1875 inch) thick. Some expansion joint belts are coated on the process side with TFE for increased chemical resistance. The reinforcement may be aramid or glass-aramid fiber, woven glass mat, woven or knitted wire, or a combination of fiber and wire. Table 3-2 compares the mechanical properties of typical expansion joints made with the three reinforcing systems. Table 3-3 gives some nominal dimensions and movement allowances.

Table 3-2

Expansion Joints for FGD Ductwork

Property	Fabric-Reinforced Sheet Elastomer	Wire-Reinforced Sheet Elastomer	Fabric/Wire-Reinforced Sheet Elastomer
Polymer	Fluoroelastomer such as Viton™ or Fluorel™	Fluoroelastomer such as Viton™ or Fluorel™	Fluoroelastomer such as Viton™ or Fluorel™
Reinforcement	Aramid fabric plies	Wire plies	Aramid fabric and wire plies
Typical thickness	4.8 mm (0.1875 inch)	4.8 mm (0.1875 inch)	4.8 mm (0.1875 inch)
Typical upper temperature limit, wet gas	205°C (400°F) continuous, excursions to 345°C (750°F)	205°C (400°F) continuous, excursions to 400°C (750°F)	205°C (400°F) continuous, excursions to 400°C (750°F)
Typical upper temperature limit, dry gas	205°C (400°F) continuous, excursions to 345°C (750°F)	205°C (400°F) continuous, excursions to 400°C (750°F)	205°C (400°F) continuous, excursions to 400°C (750°F)
Typical lower temperature limit	-40°C (-40°F)	-40°C (-40°F)	-40°C (-40°F)
Typical maximum pressure differential	± 34.5 kPa (5 psi)	± 34.5 kPa (5 psi)	± 34.5 kPa (5 psi)

Table 3-3

Nominal Expansion Joint Dimensions and Motion Accommodations

Nominal Joint Size	150 mm (6 in.)	229 mm (9 in.)	305 mm (12 in.)	406 mm (16 in.)
Nominal Duct Breach Opening	140 mm (5.5 in.)	216 mm (8.5 in.)	279 mm (11 in.)	381 mm (15 in.)
Nominal Flange Width	127 mm (5 in.)	152 mm (6 in.)	178 mm (7 in.)	203 mm (8 in.)
Maximum Axial Compression	38 mm (1.5 in.)	70 mm (2.75 in.)	89 mm (3.5 in.)	127 mm (5 in.)
Maximum Axial Extension	13 mm (0.5 in.)	13 mm (0.5 in.)	25 mm (1 in.)	25 mm (1 in.)
Maximum Offset (Resultant)	38 mm (1.5 in.)	70 mm (2.75 in.)	89 mm (3.5 in.)	127 mm (5 in.)

The fluoropolymer sheet is highly resistant to the acidic condensates encountered in FGD ductwork, but has been attacked by calcium hydroxide in lime-based FGD systems in which a process upset transported unreacted lime onto the expansion joint.

The fluoroelastomer has enough abrasion resistance that protective baffles are not normally required. The life expectancy of high-quality reinforced fluoroelastomer expansion joints is typically about six years. Several factors contribute to shortened joint life:

- Excessive relative motion, especially excessive twisting and/or rocking;
- Flow-induced flutter in joints immediately downstream of louvers or dampers;
- Accumulation of cementitious fly-ash or slurry deposits in the bottom of the joint; and
- Improper torquing of the gasket retaining bolts, allowing gas leakage around the gasket.

3.4 Recommendations

- The decisions of whether to reheat and how to reheat the flue gas, and whether hot gas will be bypassed through the FGD ducts on startup and shutdown, should be made as early as possible because these have major impacts on duct design that can, in turn, have significant impacts on plant cost.
- Bypass reheat should be avoided if at all possible because of the probable materials-of-construction problems.
- The ducting must be sufficiently stiff and supported to withstand the maximum design loads, which include the following:
  - -- Ductwork weight,
  - -- Insulation and lagging,
  - -- Maintenance activities,

-- An allowance for anticipated accumulated scale or muck carryover, and

-- Natural phenomena such as wind, snow, rain, and seismic activity.

- Relative duct motion at expansion joints must remain within the motion limits of the joints.
- Interior bracing should be minimized or preferably eliminated entirely.
- Ductwork should be designed with rigorous attention to drainage.
- Rectangular ducts should be designed with sloping floors to assure drainage.
- Table 3-4 summarizes material selection recommendations.

3.5 References

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2. Ellis, P.F. "Unusual Failures of Corrosion-Resistant Alloys in Flue Gas Desulfurization (FGD) Service." Presented at Corrosion/93, New Orleans, Louisiana, March 7-12, 1993.

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4. Ellis, P.F., D.M. Anliker, and G.D. Jones. Causes of FGD Construction Materials Failures, Volume 2: August 1985-December 1986, Appendix F, EPRI GS-6396, Electric Power Research Institute, Palo Alto, California, 1989.

5. Electric Power Research Institute. Causes of FGD Construction Materials Failures, Volume 3: January 1987-May 1993, Appendix E. GS-6396. Palo Alto, California, 1989.

6. Ellis, P.F. "Conclusions from a Decade of FGD Materials Failure Analyses." Presented at the 1993 SO_2 Control Symposium, Boston, Massachusetts, August 23-27, 1993.

Table 3-4

FGD Duct Material Selection Recommendations

Duct Condition	Hostility Class/Corrosive Environmental Zone*	Preferred Materials	Marginal Materials	Not Recommended
Hot, Dry Ducts. Includes inlet ducts upstream of first moisture or acid condensation and bypass ducts. Does <u>not</u> include ducts downstream of reheat.	0/0	► Carbon steel		
Wet Inlet Duct. The portion of the inlet duct where moisture and/or acid formation occurs.	4/1	► C-Class alloys ► Titanium ► Vitreous ceramic brick		► Stainless steels (all grades) ► G-Class alloys ► Resin coated steel ► Gunited steel ► FRP ► Foamed borosilicate glass block
Wet Outlet Ducts (I). Includes individual and plenum ducts in systems without reheat (or upstream of reheat) <u>provided</u> that hot gas is never bypassed through the outlet ducts and an emergency quench system is present.	1/5A	► C-Class alloys ► Titanium ► Vinylester or brominated vinylester FRP ► Vitreous ceramic brick	► 6% Mo superaustenitic stainless steels ► G-Class alloys ► Vinylester or Novalac epoxy-melamine-phenolic resin coatings	► Foamed borosilicate glass block ► Polyester lined steel ► Gunited steel

Table 3-4

(Continued)

Duct Condition	Hostility Class/Corrosive Environmental Zone*	Preferred Materials	Marginal Materials	Not Recommended
Wet Outlet Ducts (II). Includes individual and plenum ducts in systems without reheat (or upstream of reheat) through which hot gas is bypassed during start up and shutdown.	2/5A	▸C-class alloys ▸Titanium ▸Vitreous ceramic brick	▸6% Mo superaustenitic stainless steels ▸G-Class alloys	▸Foamed borosilicate glass block ▸Polyester lined steel ▸Vinylester or Novalac epoxy-melamine-phenolic resin lined steel. ▸Gunited steel ▸FRP ▸Stainless steels with less than 6% molybdenum.
Indirect Reheated Ducts. Includes mixing chambers and downstream ductwork in systems with indirect reheat.	3/5B	▸C-class alloys ▸Titanium ▸Vitreous ceramic brick	▸Foamed borosilicate glass block	▸Polyester lined steel ▸Vinylester or Novalac epoxy-melamine-phenolic resin lined steel ▸Gunited steel ▸FRP ▸G-Class alloys ▸Stainless steels (all grades)
Bypass Reheated Ducts. Includes mixing chambers and downstream ductwork of direct bypass systems and cyclic reheat systems if there is slippage of hot gas to the treated side.	4/5C	▸Vitreous ceramic brick	▸Foamed borosilicate glass block ▸C-Class alloys ▸Titanium	▸Polyester lined steel ▸Vinylester or Novalac epoxy-melamine-phenolic resin lined steel ▸Gunited steel ▸FRP ▸G-Class alloys ▸Stainless steels (all grades)

* For definition of hostility class, see Figure 3-2 of this section. For definition of corrosive environmental zones, see Figure 5-1 and Table 5-2 in Part I, Section 5.3.1.

7. Cerny, M.X., M.A. Phillips, and D.K. Peacock. "Performance of Titanium Linings in FGD Stacks and Ductwork." In: Proceedings of the 1992 Air Pollution Seminar. NACE, Houston, Texas, 1992.

4.0 FLUE GAS DAMPERS

Flue gas dampers are used for two purposes: equipment isolation and flue gas flow control. In an FGD system, isolation dampers are located at the inlet and outlet of each absorber module to allow a module to be removed from service, either to reduce power consumption at low unit load or to perform internal maintenance. Isolation dampers may also be found in some FGD system bypass ducts. Flow control dampers are found primarily in the bypass ducts of systems using bypass reheating (see Part I, Section 4.6--Flue Gas Reheat). At one time, flow control dampers were commonly placed in the absorber module inlet ducts to regulate the flue gas flow or to balance the flow between modules. These dampers were only marginally effective and, in recent FGD systems, have been superseded by improved gas modeling and ductwork design.

4.1 Types Available

In general, the very different operating requirements of isolation and flow control service require the use of different types of dampers. Where "man-safe"* isolation is required, guillotine dampers are used. Where a minor amount of flue gas leakage across the damper is allowable, such as in a bypass duct, either guillotine or louver dampers are used. If quick opening of the damper is important, as is commonly the case in a bypass duct, only louver dampers are acceptable. Flue gas flow control is always provided by a louver damper.

While U.S. electric utilities have used guillotine and louver dampers almost exclusively for FGD system service, other types, including flap or door-type dampers, have been used in Europe. Additional information on the various types of flue gas dampers available and a glossary of specialized damper terms is available from the Air Movement and

* A "man-safe" isolation damper is designed to seal off equipment so that maintenance personnel without breathing apparatus or other special equipment may safely perform maintenance activities in the isolated section (1). Such dampers may also be termed "zero-leakage" dampers.

Control Association, Inc. in their publication "Flue Gas Dampers, Application and Specification Guide for Flue Gas Isolation and Control Dampers" (1).

4.1.1 Guillotine Dampers

A guillotine damper, as shown in Figure 4-1, is an isolation damper with a blade that can be completely withdrawn from the duct area when the damper is fully open. When fully closed, the damper blade serves as a blanking plate across the duct. The damper shown in Figure 4-1 is a zero-leakage guillotine damper designed to provide man-safe conditions downstream.

The damper blade protrudes though the internal damper frame into a circumferential seal air cavity. Ambient air at a pressure greater than the flue gas pressure is injected into this cavity to prevent flue gas from entering the seal air cavity. The damper blade slot in the internal frame is provided with thin sealing strips to reduce the volume of seal air required. These seal air strips are designed to close together when the damper blade is removed. Details of a typical blade seal system are shown in Figure 4-2. The details of damper manufacturers' seal designs are proprietary and differ widely. Additional information on seal air systems is provided in Section 4.2.2--Mechanical Considerations.

The most common method of positioning the damper blade in the duct is by a chain drive system using multiple chains located at both ends of the damper blade's upper edge. Either mining chain or high-strength chains specially engineered for this service are used. Typically two to four drive chains are used, depending on the size and weight of the damper blade. A drive torque tube connects the drive sprockets for each chain. The drive torque tube is moved by an electric actuator. The chain drive is arranged such that the damper blade is driven both open and closed. The weight of the damper blade, while reducing the actuator power consumed, is not relied upon to assist in closing the damper blade. As an alternative to chain drives, at least one damper manufacturer uses a rack and pinon drive, with rack elements positioned along both outside edges of the blade.

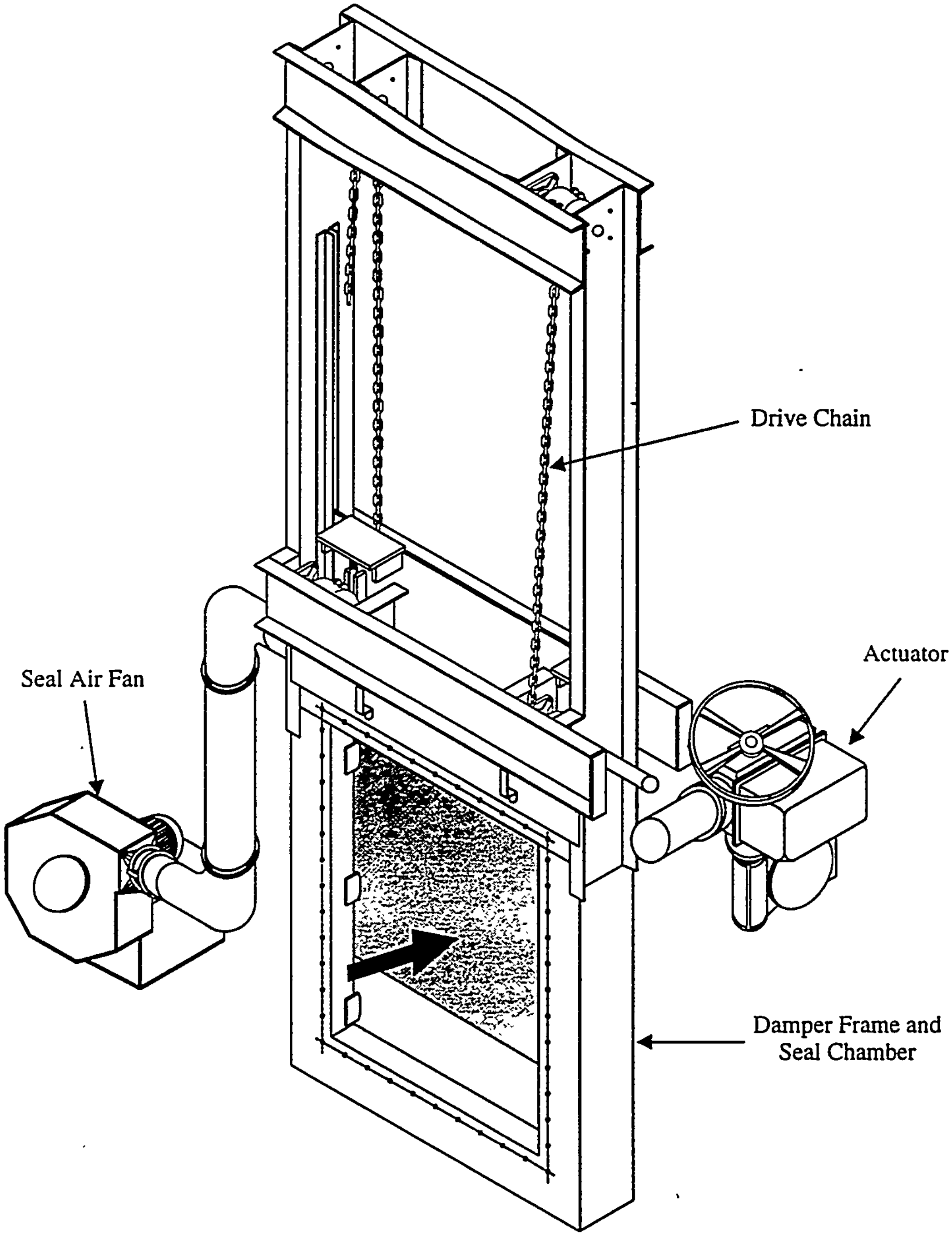

Figure 4-1. Typical Guillotine Damper

Source: EFFOX, Inc., Cincinnati, Ohio

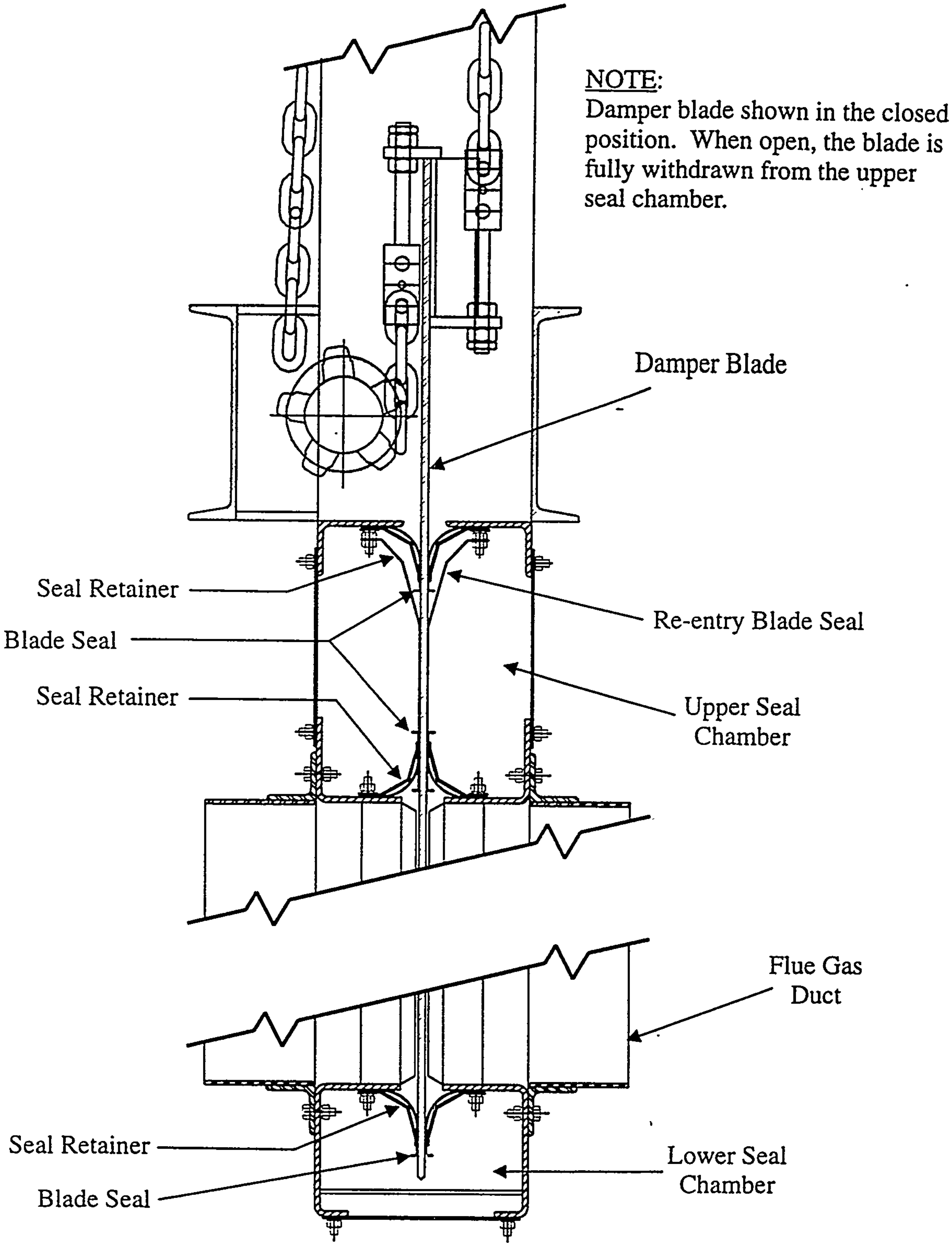

Figure 4-2. Typical Guillotine Damper Seal Design

Source: EFFOX, Inc. Cincinnati, Ohio

Pneumatic/hydraulic actuators are also available for guillotine dampers, but are seldom, if ever, used in FGD applications because of the magnitude of the actuating forces required. Very large diameter pneumatic/hydraulic cylinders would be required. The alternative methods are more compact and less costly.

Although the single-bladed guillotine shown in Figure 4-1 is the most prevalent in the utility FGD service, a double-bladed guillotine with two parallel guillotine blades is also offered by some damper manufactures. Seal air is provided in the space between the two blades as well as the peripheral blade seals. While this type-of guillotine damper protects maintenance workers from potential contact with a hot damper blade, this must be balanced against the disadvantages that the two blades result in more complicated drive systems, greater capital costs, and greater weight.

4.1.2 Louver Dampers

Whereas guillotine dampers retract their blades from the gas stream when open, a louver damper has one or more blades that rotate and remain in the gas stream at all times (1). Louver dampers vary in the number of blades and the relative directions of blade rotation as well as in a wide variety of manufacturer-specific details.

A single-bladed louver damper is also called a butterfly damper, and resembles a large butterfly valve. The single blade is usually round and rotates about its diameter. In most cases, the axis of rotation is horizontal so that the blade shaft seals are not exposed to any condensate or floor deposits that may form. Butterfly dampers can be used for either isolation or flow control service. In FGD systems these dampers are frequently used in damper seal air ducts and absorber module vent ducts, but are not used in the large flue gas ducts.

A "multi-louver" damper, such as shown in Figure 4-3, consists of several parallel damper blades and is the predominant louver damper type used in FGD system ducts.

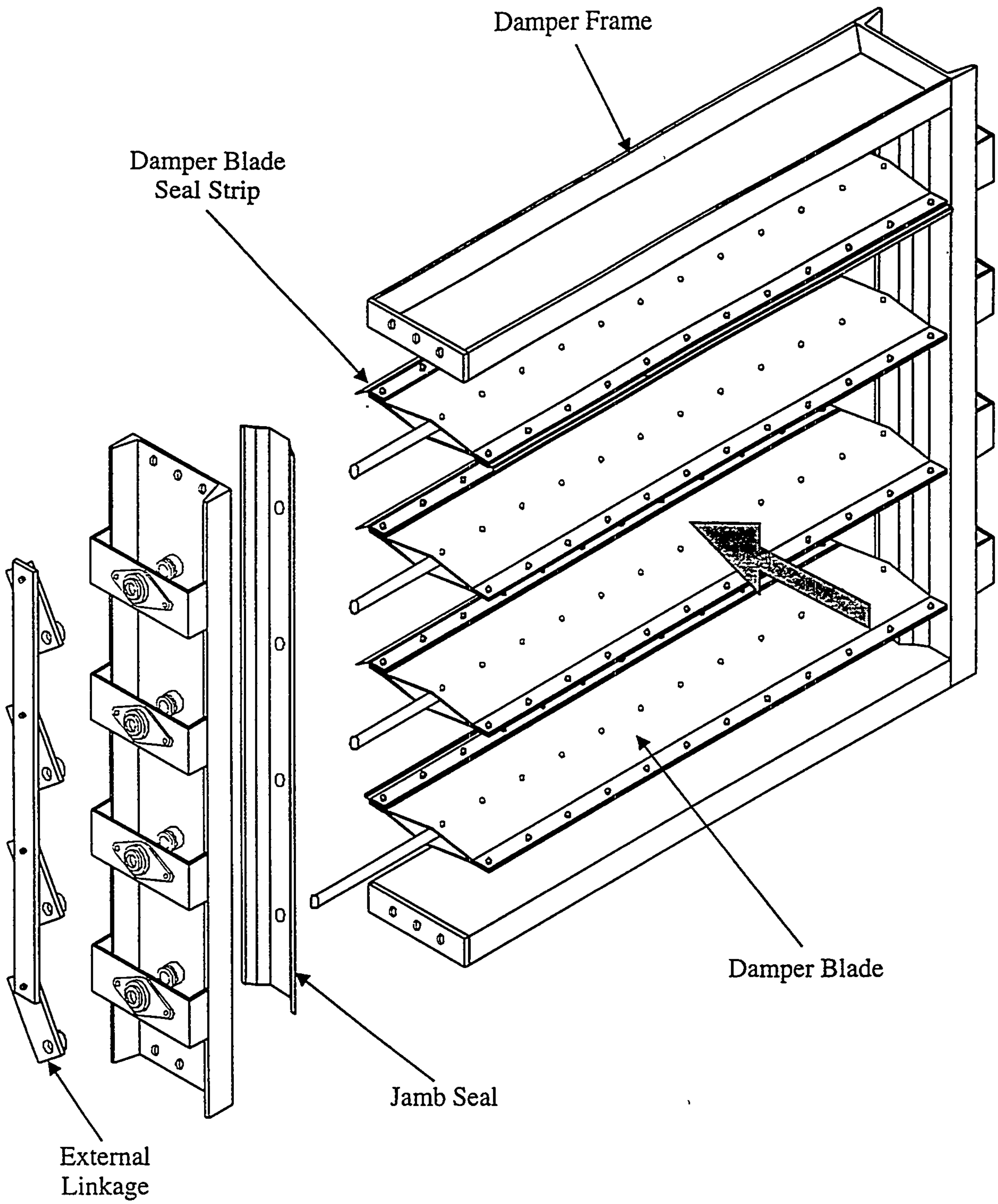

Figure 4-3. Typical Multi-Louver Damper

Source: EFFOX, Inc., Cincinnati, Ohio

Unless otherwise indicated, when the term louver damper is used in this manual, the damper is a multi-louver damper. The individual blades of a louver damper are connected by external linkages and are usually driven by an electric actuator. Pneumatic operator may be used on some installation where fail-safe opening of the damper during a power outage cannot be otherwise assured.

On most designs the edges of each blade are equipped with thin seal strips that form the blade-to-blade seal when the damper is closed. Frame seals (also called jamb seals) are located on the sides of the damper frame at the end of the blades. The jam seals prevent flue gas from leaking around the ends of the damper blades.

Louver dampers can be further categorized by the relative directions that adjacent blades move in, as illustrated in Figure 4-4. Opposed-blade dampers have broader and more linear flow control characteristics, and are used in flow control applications such as a bypass reheat control damper. Parallel-blade dampers have better sealing characteristics, and are used in isolation service. Although a single parallel-blade damper does not isolate as well as a guillotine damper with peripheral seals and cannot provide man-safe conditions downstream, it acts much more quickly than a guillotine. For this reason, parallel-blade dampers are often found in bypass ducts when the ability to quickly bypass the FGD system is desired and a small amount of leakage can be accepted.

In some cases, the capabilities of both an opposed-blade and parallel blade damper are desired at the same location. In such cases, these two damper types may be used in series, with an upstream parallel-blade damper providing isolation and the opposed-blade damper providing flow control. For zero-leakage applications, two parallel-blade dampers in series can be used and seal air injected between the stages. These arrangements may consist of two separate dampers with individual damper frames, or both sets of blades may be installed in the same frame, as shown in Figure 4-5.

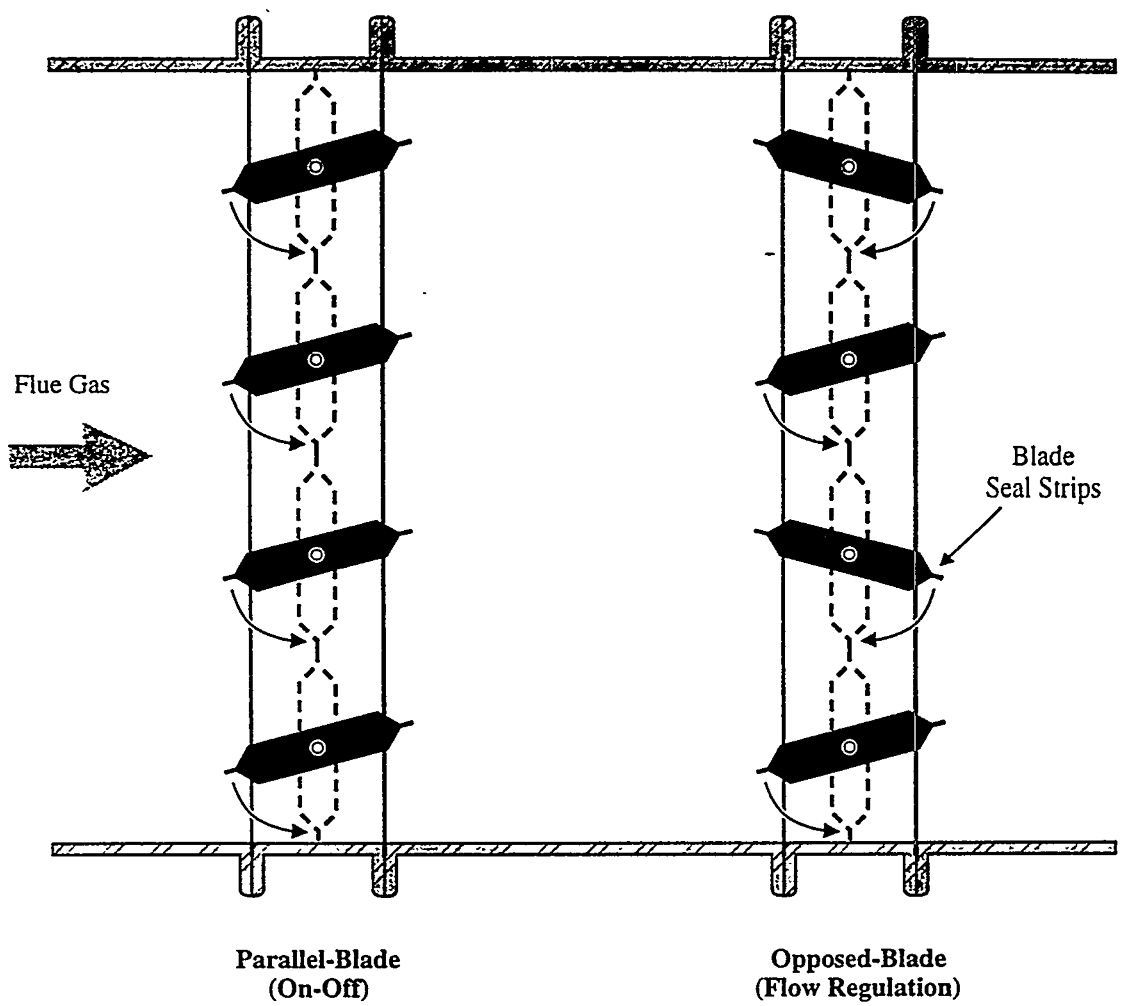

Figure 4-4. Parallel-Blade and Opposed-Blade Louver Dampers

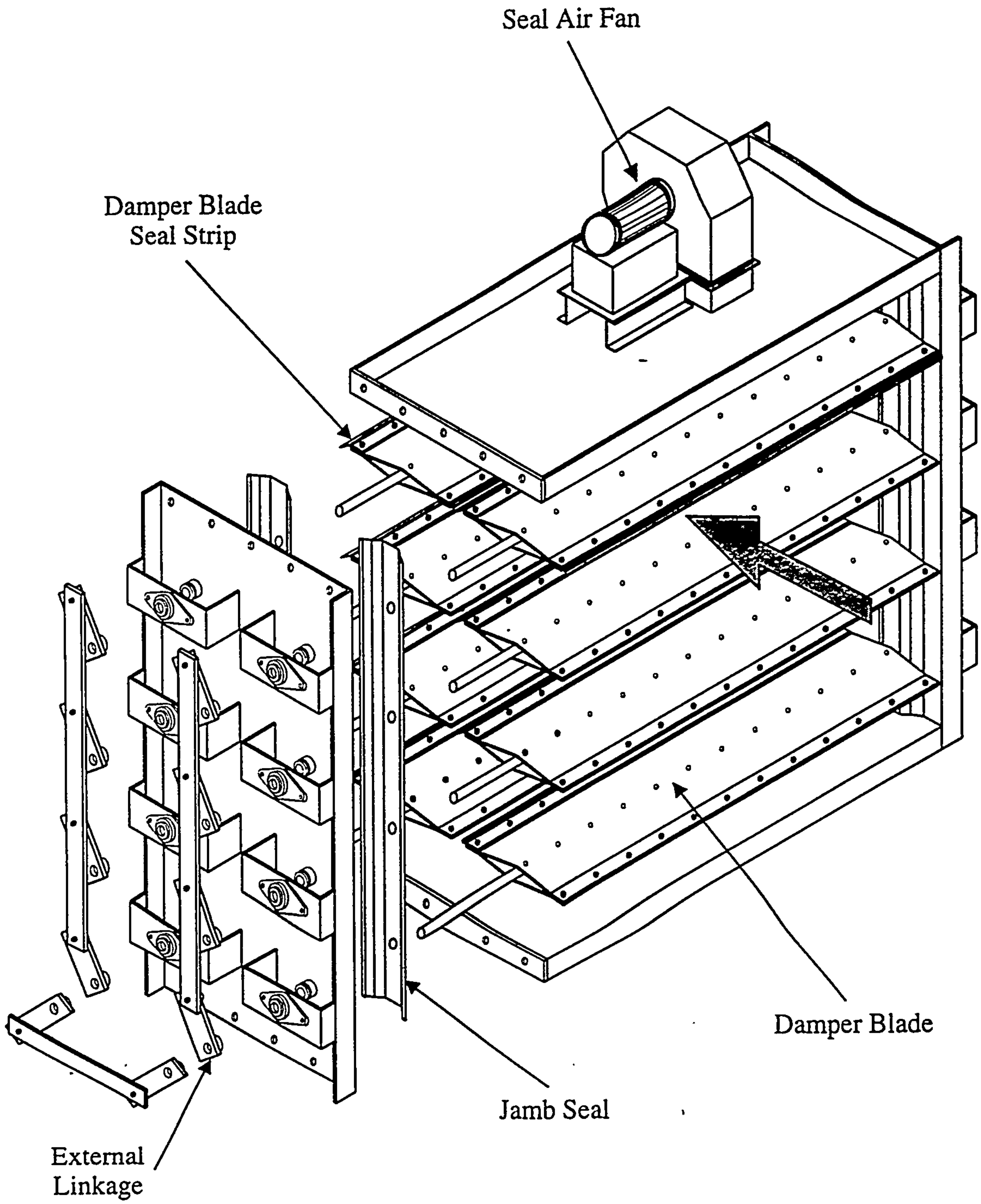

Figure 4-5. Typical Two-Stage Louver Damper

Source: EFFOX, Inc., Cincinatti, Ohio

4.2 Design Considerations

4.2.1 Process Considerations

The principal process considerations that affect the design of the flue gas dampers are the determination of whether the dampers will isolate equipment, control gas flow, or both. These considerations are discussed above. Other important process considerations are the following:

- Man-safe isolation;
- Flue gas pressure drop; and
- Damper orientation.

Man-Safe Isolation

Man-safe isolation of absorber modules is required in order to conduct internal maintenance of an isolated module with the boiler on line. Examples of potential internal maintenance activities include inspection, repair, or replacement of mist eliminators, spray nozzles, spray headers, and absorber linings. If a spare absorber module is installed, on-line maintenance of this module is impossible without the use of man-safe isolation dampers.

Man-safe isolation assumes that no flue gas can leak past the damper into the isolated area. Although two-stage louver dampers such as those shown in Figure 4-5 may provide man-safe conditions if all seals are in good shape and sufficient seal air is provided, guillotine dampers predominate for such applications in the United States.

Flue Gas Pressure Drop

Because the blade of a guillotine damper is completely withdrawn from the flue gas path and the damper frame has the same cross section as the duct, no appreciable drop in flue pressure occurs with the damper in the open position. Some very small pressure drop may occur if internal damper blade supports are used. Such supports are used on very wide guillotine dampers to resist bending of the blade during opening and closing and to guide the blade into the lower frame seals.

The blades of a louver damper block 10 to 25% of the duct cross section even in its full-open position and induce turbulence in the flue gas downstream of the damper. As a result, the flue gas pressure drops. The magnitude of the pressure drop depends on the shape and position of the damper blades and the velocity of the flue gas.

Damper Orientation

A damper's orientation can be classified by the orientation of the duct in which it is installed (vertical or horizontal), and by the orientation of the damper blades. Although other designs have occasionally been used in the past, virtually all guillotine dampers in FGD system service are installed in a horizontal duct, and the damper blade enters the duct from the top (i.e., top-entry). The few bottom-entry guillotine dampers that were installed had very poor performance because acidic condensate pooling in the bottom of the duct corroded the drive mechanisms, and most have been replaced with top-entry designs (2).

Louver dampers are also most commonly installed in horizontal ducts, and the damper blades run horizontally across the duct. If the blades were installed vertically, deposits on the duct floor would hinder the operation of every blade. Vertical blade design would also complicate the design of the damper shaft bearings. Louver dampers can be installed in vertical ducts with no special design changes. If such dampers are used in normally closed service, deposits may accumulate on the upper surface of the blade and fall into the lower duct when the damper is opened. This can present a maintenance hazard in some cases.

4.2.2 Mechanical Considerations

The mechanical design of dampers is very complex and a detailed discussion of all of the design factors is beyond the scope of this manual. Information on the mechanical design of dampers is available from major damper manufacturers and the technical literature (1-5). The following mechanical considerations are especially applicable to dampers used in conjunction with FGD systems:

- Seal air system;
- Damper actuation time; and
- Duct deposits.

Seal Air System

The seal air system prevents the flue gas in the duct from leaking around the closed damper blade and into the isolated component and, therefore, is a critical aspect of the design of man-safe isolation dampers. The critical nature of this system is illustrated by the fact that an isolated component (i.e., an absorber module) usually must be evacuated if the seal air fan to the damper(s) fails or is unable to meet its required performance. The following discussion is based on guillotine dampers since almost all man-safe damper applications in the utility industry use guillotine dampers. A seal air system for a two-stage louver damper such as was shown in Figure 4-5 would be very similar.

The performance of a damper seal air system is measured by its ability to maintain a pressure in the seal chamber of 750 to 1250 Pa (3 to 5 inwg) above the pressure on the flue gas side of the damper. The seal air flow rate depends on the total leakage path around the damper blade. This path is kept as small as possible by the thin damper seal strips

4.2 Design Considerations

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that were illustrated in Figure 4-2. The required seal air flow is based on the differential pressure and a calculated gas path considering some normal seal strip wear and damage. In sizing the seal air fan, a factor of safety of two or greater is then applied to the calculated flow rate.

Most frequently, the seal air for each isolation damper is provided by a frame-mounted seal air fan. In some cases, two fans will be supplied for redundancy or, on very large dampers, to reduce the size of fans. A butterfly damper is located in the short duct from the fan to the seal chamber to allow maintenance to the fan. In most cases, the seal air fan runs continuously even when the damper is in the open position. This prevents flue gas from entering the seal chamber. As the flue gas cools, acid gases would condense in the seal air chamber, creating very corrosive conditions. Even when the seal air fans are designed to operate continuously, the seal air fan, ductwork, and damper should be oriented to prevent any condensate that might form from running into the duct and damaging the damper and fan.

Some FGD system designs have elected to provide one or two central seal air fan systems capable of providing the seal air to several dampers. A central seal air fan may reduce capital and maintenance costs by replacing a number of smaller fans and motor drives with fewer, larger-capacity fans. Some of the money saved in the reduction in fans, however, is lost to longer seal air duct runs and the accompanying pressure losses.

In the past, some utilities installed seal air heating systems to raise the temperature of the seal air above the dew point of sulfuric acid [approximately 75°C (170°F)]. In theory, heating the seal air reduces the potential of acid condensation in the seal air chamber and on the damper seal strips. In practice, however, seal air heating equipment proved to be unreliable, and is no longer recommended (2).

Guillotine dampers can be purchased with or without bonnets that enclose the damper blade when in the open position. In some designs, the seal air system pressurizes this bonnet as well as the damper seal chamber. In most case, damper bonnets are not required and may provide a location for condensation of acidic flue gas.

The seal air pressure requirement must be met at all points in the seal chamber. This can be difficult if the lower seal chamber becomes clogged with deposits pushed into the chamber by the damper blade. Clean-out ports should be located at both ends of the lower seal air chamber to facilitate the periodic removal of these solids. The chamber should also be equipped with a drain to permit the removal of any duct or seal chamber wash water or of acidic flue gas condensate that enters the chamber.

In many cases, the pressure in the seal air chamber is continuously monitored and low pressure trips an alarm in the FGD system control room.

Damper Actuation Time

The times required for an isolation damper to go from its full-open to full-closed position or from its full-closed to full-open position are referred to as the damper actuation times. For a louver damper these times may be nearly identical. For a guillotine damper, with a heavy damper blade to move, closing times may be somewhat less than opening time.

Generally, when an actuation time of less than 30 seconds is required, a louver damper is used. The primary demand for such a quick actuation time is in a normally closed bypass damper that would be opened to provide an open gas path from the boiler to the stack in the event of the loss of electrical power to the FGD system or the entire plant. Obviously, in this eventuality, the damper's electric actuator should be placed on the plant's emergency power grid.

The travel speed of a guillotine damper blade during opening or closure is typically in the range of 1.3 to 2 m/min (4 to 6 ft/min). A large inlet duct may be over 3 m

(10 ft) high, and complete opening or closure of the damper may require two to three minutes. For this reason, guillotine dampers are used in services that do not require quick actuation times, principally absorber module isolation.

Duct Deposits

Deposits of fly ash and absorber slurry solids can be expected to accumulate over time in the FGD system ductwork, especially on duct floors. The design of the dampers must consider how the actuation of the damper will be affected by such deposits.

For a normally open guillotine damper such as an absorber inlet or outlet isolation damper, the damper blade must push through these deposits. The damper drive system, including the actuator motor, must be sized to provide sufficient power to break through a reasonable amount of deposits. Often this capability is tested in the manufacturer's shop by breaking through 150 mm (6 in.) or more of synthetic deposits placed on the damper floor. The damper seals must also be rugged enough to withstand this abuse without permanent deformation that would affect their performance.

For a guillotine damper that may remain closed for extended periods of time (such as an isolation damper of a spare absorber module), the damper drive system and actuator must provide sufficient break-away power to overcome any cementation of the blade to the frame that may have occurred. As discussed later, the opening power requirements of a guillotine damper are much greater than the closing power requirements.

For a normally open louver damper such as a bypass flow control damper or a normally closed damper such as a bypass isolation damper, the duct deposits may make movement of the damper blades difficult if the blades have remained in one position for a long period of time. This problem is particularly acute for the bottom damper blade for two reasons. First, the duct floor is the area where deposits are likely to be greatest. Second, if the other blades move more freely, the total torque of the actuator can be applied to this damper blade, which can result in damage to the blade and its linkages. For this reason, some louver dampers are fabricated with two damper actuators and drive linkages. One set positions only the lowest blade; the other, all of the remaining blades.

For any damper regardless of its service, it is a very good operating procedure to periodically move the damper blades through their complete range of motion in order to prevent the blades from becoming frozen in one position due to duct deposits.

4.2.3 Other Considerations

Maintenance access to the dampers must be addressed in the layout of the maintenance access platforms, ladders, and stairs; and of the overall FGD system. Routine maintenance access is required to the damper drive components, seal air fans, and seal strips. Replacement of damper drive actuators, louver damper bearings, and seal air fans should be considered when determining where to place platforms and hoists, and whether access should be by ladder or stairway. Some damper manufacturers design their damper seals to be replaced from inside the duct, in which case there are fewer access requirements imposed. All louver dampers and some guillotine dampers follow this design option. Some guillotine dampers, however, require replacement of the seals from outside the duct, in which case additional permanent or temporary platforms may be required to service the lower seal chamber.

Dampers represent some of the largest and heaviest removable components in an FGD system. While the complete replacement of a damper is not a common occurrence, the layout of the FGD system should provide access to each damper location by a crane capable of lifting the damper out of the duct and lowering it to the ground.

In designing the insulation and lagging system for the ducts in which the dampers are placed, consideration should be given to the required maintenance access to exterior drive components and seal chambers and to the potential for removal and replacement of the dampers.

4.3 Material Selection

Depending on their location in the FGD system, dampers may be exposed to the mildly corrosive conditions of the hot, untreated flue gas or the very corrosive conditions downstream of the FGD modules. The materials of construction used in the fabrication of FGD dampers must consider these operating conditions, the effect on FGD system reliability of damper failures, the long lead times and difficulty in replacing dampers, and the high capital cost of dampers fabricated from corrosion-resistant alloys.

4.3.1 Guillotine Dampers

The recommended damper frame material depends on the chloride content of the FGD system slurry. In low-chloride systems (less than 10,000 mg/L chloride), the bodies of guillotine dampers are frequently carbon steel clad on the process face with one of the 4% molybdenum austenitic stainless steels, such as Type 317LM, Type 317LMN, or Type 904L. Channels are of similar alloys. In higher-chloride systems (greater than 10,000 mg/L chloride), the clad would normally be Alloy 625, Alloy H-9M, or one of the C-276 family of alloys. Alloys of the 6% molybdenum superaustenitic family, such as Alloys 6XN and 254 SMO, may also be suitable where their exposures to the hostile FGD environment are relatively brief, but experience with these alloys is limited. With the exception of the damper blades, these recommendations apply to all portions of the damper that may be exposed to the flue gas, including the seal air chamber.

Guillotine damper blades are exposed to the corrosive flue gas environment only when the dampers are closed, but are exposed to weathering when the dampers are open. For inlet isolation dampers, ASTM A-242 carbon steel may be adequate. Some installations have selected one of the austenitic stainless steels listed above. The recommended material for the outlet isolation damper blades ranges from Type 317LM for low-chloride systems where all of the dampers are normally open (e.g., no spare absorber module), to Alloy 625 for high-chloride systems where one or more dampers are always closed. The most cost-effective blade material must be determined on a case-by-case basis considering all such factors of exposure conditions and durations.

The very thin, flexible seal strips can tolerate very little corrosion, and are typically Alloy 625 or one of the C-276 family alloys regardless of process chlorides or damper frame material.

The seal air ductwork from the damper frame to the seal air damper should be fabricated from the same materials as the inner damper frame cladding and seal air chamber. The portions of the seal air damper that could be exposed to flue gas should also be fabricated from these materials. The seal air fans and ductwork between the fans and seal air damper, which are not exposed to flue gas or high temperatures, may use materials such as carbon steel and FRP.

4.3.2 Louver Dampers

The internal frames and blades of louver dampers should be fabricated from the same materials that would be used to fabricate the duct in which they are located. For a two-stage louver damper where one side of the damper may be attached to a carbon steel duct and the other to a lined or alloy duct (such as in a bypass duct), each stage should use the same class of corrosion-resistant materials as its adjoining duct.

Blade and frame jamb seals should be Alloy 625 or one of the C-276 family alloys regardless of the damper blade material.

4.4 Recommendations

- Buying dampers as part of the overall FGD system may result in a competitive situation with the system vendors offering dampers that are acceptable for the application but possibly not the best choice over the lifetime of the facility. For this reason, the purchase of dampers under a separate contract or by technical specification may be beneficial and is recommended by some architect/engineers and electric utilities (2).

- Critical damper performance criteria should be verified by full-scale testing of the damper at the manufacturer's factory under simulated operating conditions. These criteria may include the following:

  -- Damper actuation times (open and close) under design differential gas pressures across the damper;

  -- Flue gas leakage rate (maintenance of man-safe conditions) under design differential gas pressure;

  -- Ability to close/open and seal despite deposits on the damper frame and blade(s);

  -- Ability of the drive system and actuator to withstand blade-stall conditions without damage or overload.

- The operating conditions of each damper should be reviewed very carefully, and materials of construction for each damper component appropriate to the expected service conditions should be selected.

4.5 References

1. Air Movement and Control Association, Inc. Flue Gas Dampers, Application and Specification Guide for Flue Gas Isolation and Control Dampers. Publication 850-84. Arlington Heights, Illinois, 1984.

2. Wess, Thomas J. "Upgrading FGD System Dampers to Improve Equipment and System Reliability." In: Proceedings of Power-Gen '94. Power-Gen International. Orlando, Florida, 1994. pp. 29-45.

3. Affatato, Andre. "Control and Isolation Dampers for Power Plants." Power Engineering. 85(4):87-90, 1981.

4. ASEA Brown Boveri-Combustion Engineering, Inc. Combustion, Fossil Power. Joseph Singer, ed. Windsor, Connecticut, 1991.

5. Babcock & Wilcox. Steam, Its Generation and Use. S.C. Stultz and J.B. Kitto, eds. Barberton, Ohio, 1994.

5.0 SLURRY PUMPS

The electric utility has extensive experience in pumping abrasive ash slurries; however, the erosive and corrosive conditions found in FGD systems make the successful application of slurry pumps a difficult challenge. FGD systems use large centrifugal pumps to recycle slurry from the reaction tanks to the absorber spray headers. Centrifugal pumps are also used to transfer a variety of other FGD slurries, including lime/limestone reagent slurry, slurry bleed, thickener underflow, and vacuum filter feed.

Since "clear-liquid" pumps are used in many non-FGD applications, and should therefore be familiar to utility engineers, this discussion will focus on slurry pumps. More specifically, this focus is on centrifugal slurry pumps. Other pump types are occasionally used in FGD slurry applications, including progressing cavity, disk, and variable vane pitch pumps; however, centrifugal pumps are the predominant choice for most utility FGD slurry applications.

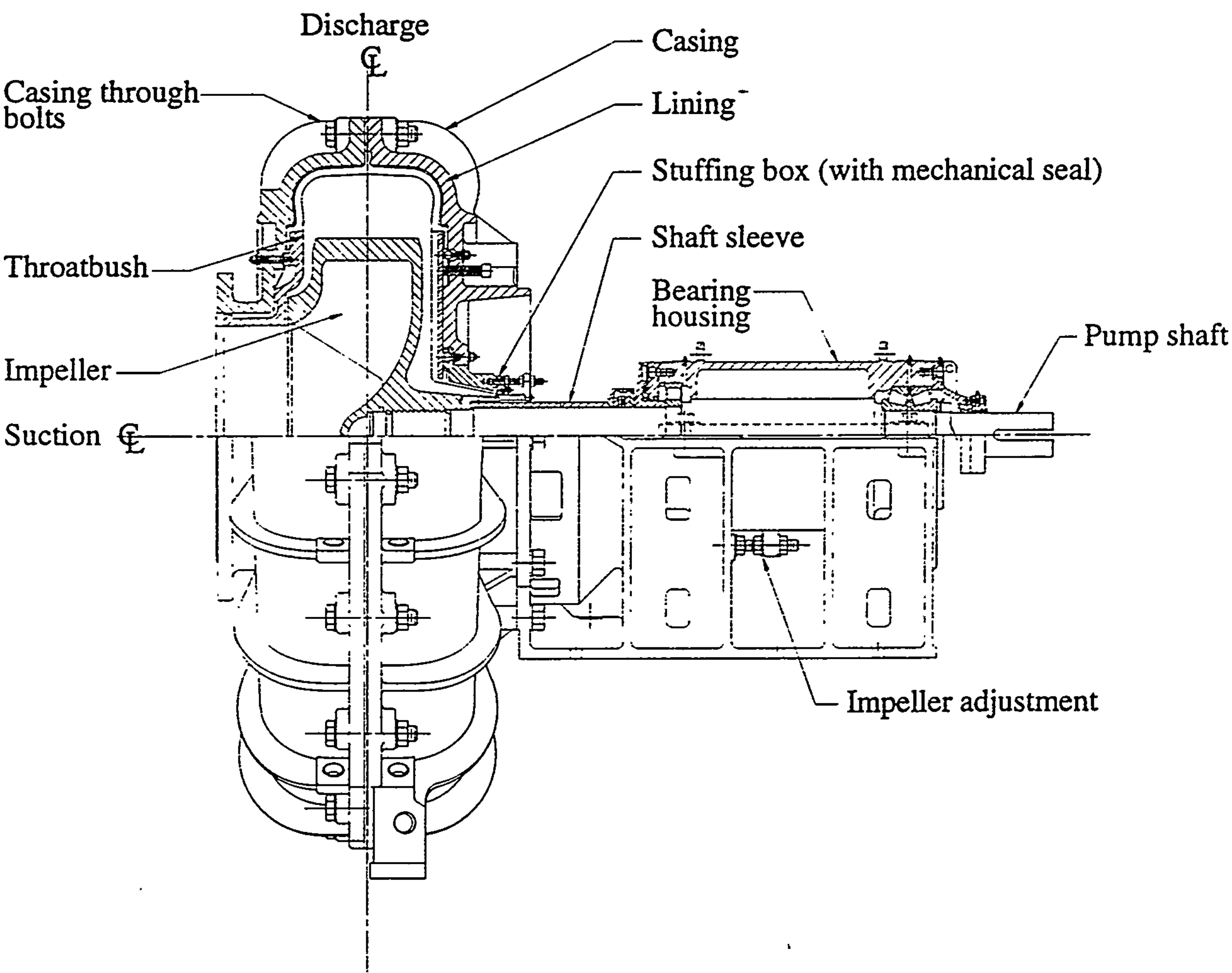
Much has been published on pumps in general and on centrifugal slurry pumps in particular. Section 5.5--References lists some information sources on centrifugal pumps that may be of interest to the utility engineer (1-5).

5.1 Types Available

The centrifugal slurry pumps used in FGD systems can be classified as either horizontal or vertical pumps. This section describes the available pump types and their typical applications in an FGD system.

5.1.1 Horizontal Pumps

The horizontal centrifugal pump, illustrated in Figure 5-1, is the most common pump type for FGD slurry applications. Worldwide, absorber module spray pumps use the



Discharge
℄
Casing
Casing through bolts
Lining
Stuffing box (with mechanical seal)
Shaft sleeve
Throatbush
Bearing housing
Impeller
Pump shaft
Suction ℄
Impeller adjustment

horizontal centrifugal design exclusively. Horizontal centrifugal pumps are also the most common pump type used for other FGD slurry applications, although vertical centrifugal pumps are commonly used in process and washdown sumps. Submersible pumps occasionally are used in these sumps, as well.

Two basic horizontal centrifugal pump designs are currently used in FGD applications. These are "clear-liquid" pumps and "slurry" pumps.

"Clear-liquid" pumps, derived from chemical process applications, are intended for pumping of abrasive-free liquids with specific gravities near 1.0. They lack wear allowances, are machined to close tolerances, and are generally direct-coupled to the drive motor with the result that they are driven at synchronous speeds. Clear-liquid pumps should not be used for FGD process fluids that contain significant amounts of suspended solids. Acceptable applications include pumps used in mist eliminator wash, seal water, and thickener overflow service.

"Slurry" pumps are designed for the worst possible operating conditions--handling abrasive slurries at high concentration with specific gravities approaching 1.6, containing large and hard particles, in aggressive (corrosive) solutions. In horizontal centrifugal pumps, the thicknesses of all wetted parts are substantial, and replaceable casing liners are standard. These pumps use large-diameter, low-specific-speed* impellers with relatively low tip speeds,** connected to the drive motor by drive belts or a gear box. Compared to clear-liquid pumps, the shafts and bearings of slurry pumps are massive. Another feature that distinguishes this type of pump is the use of pump-out vanes on the front

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* $N_s = N \times Q^{1/2}/H^{3/4}$

where:
N_s = Specific speed, expressed as a unitless number;
N = speed, revolutions per minute;
Q = Flow rate, m^3/min (gpm); and
H = Head, m (ft).

** Tip speed = impeller circumference times revolutions per minute.

and back of the impeller to reduce recirculation and wear across the suction-side liner, and to reduce fluid pressure in the shaft gland area.

Although most designs of horizontal centrifugal slurry pumps can achieve a total discharge head (TDH)* of about 40 to 50 meters (130 to 165 feet), some models are available to produce a head exceeding 90 meters (295 feet). Higher head is achieved by using a larger diameter pump casing and impeller. These very high head pumps are not typically required in an FGD system; typical absorber module spray pumps have a TDH of less than 23 m (75 ft).

The maximum flow capacity of absorber module spray pumps has been steadily increasing as pump manufacturers introduce new models. Pumps are now available that can provide flows of over 2500 L/s (40,000 gpm). The need for these large pumps was emphasized by the trend toward the use of fewer absorber modules with greater flue gas treatment capacity. The trend toward fewer, larger capacity modules and pumps has resulted in reduced FGD system capital costs. When using the typical design standard of dedicating one pump to each absorber module spray header, fewer spray headers (and pumps) are required to achieve the desired liquid-to-gas ratio in these larger modules. Fewer spray headers reduce the capital costs of the absorber modules, pumps, piping, valves, controls, electrical equipment, and FGD building.

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* TDH is the total pressure increase across the pump (total pressure at the pump discharge minus total pressure at the pump suction). Total pressure includes both the static pressure and the fluid dynamic head.

$$\text{Total Pressure} = p + h + (v^2/2g)$$

where:
- p = fluid pressure, meters (ft) of water column;
- h = height above a datum elevation, m (ft);
- v = fluid velocity, m/s (ft/s); and
- g = gravitational constant, m/sec^2 (ft/sec^2).

5.1.2 Vertical Pumps

Vertical centrifugal pumps, as shown in Figure 5-2, are often used in FGD system slurry sump applications. The cantilevered-design vertical pump is standard in this application. In a cantilevered design, the shaft bearings are located above the sump liquid level to prevent solids from damaging the bearings. Because of the distance between the lowest bearing and the heavy pump impeller, the design includes a stiff, large-diameter shaft and heavy-duty bearings. Impellers may use double suction, drawing slurry from above and below the impeller to prevent thrust loadings on the bearings. Inlet strainers prevent large solids from damaging or clogging the impeller. A small agitator can be fitted below the impeller to keep solids in suspension.

5.2 <u>Design Considerations</u>

5.2.1 Process Considerations

Process considerations that affect the design or operation of centrifugal slurry pumps include the slurry characteristics, pump flushing requirements, and pump startup/shutdown controls.

Slurry Characteristics

Slurry physical and chemical characteristics (such as density, chloride level, and the size and shape of the slurry particles) affect the choice of pump materials and pump type. Higher density slurries and more abrasive solids increase the rate of wear of the pump impeller and casing liner. Rubber-lined parts, particularly impellers, are susceptible to damage from large particles and debris (trash) in the slurry. As a result, the use of abrasion-resistant metal-alloy impellers has increased. High-chromium metal impellers have provided long life and high reliability at a number of FGD systems. Slurry chloride level plays an important consideration in the selection of pump materials. Historically, rubber-lined pumps

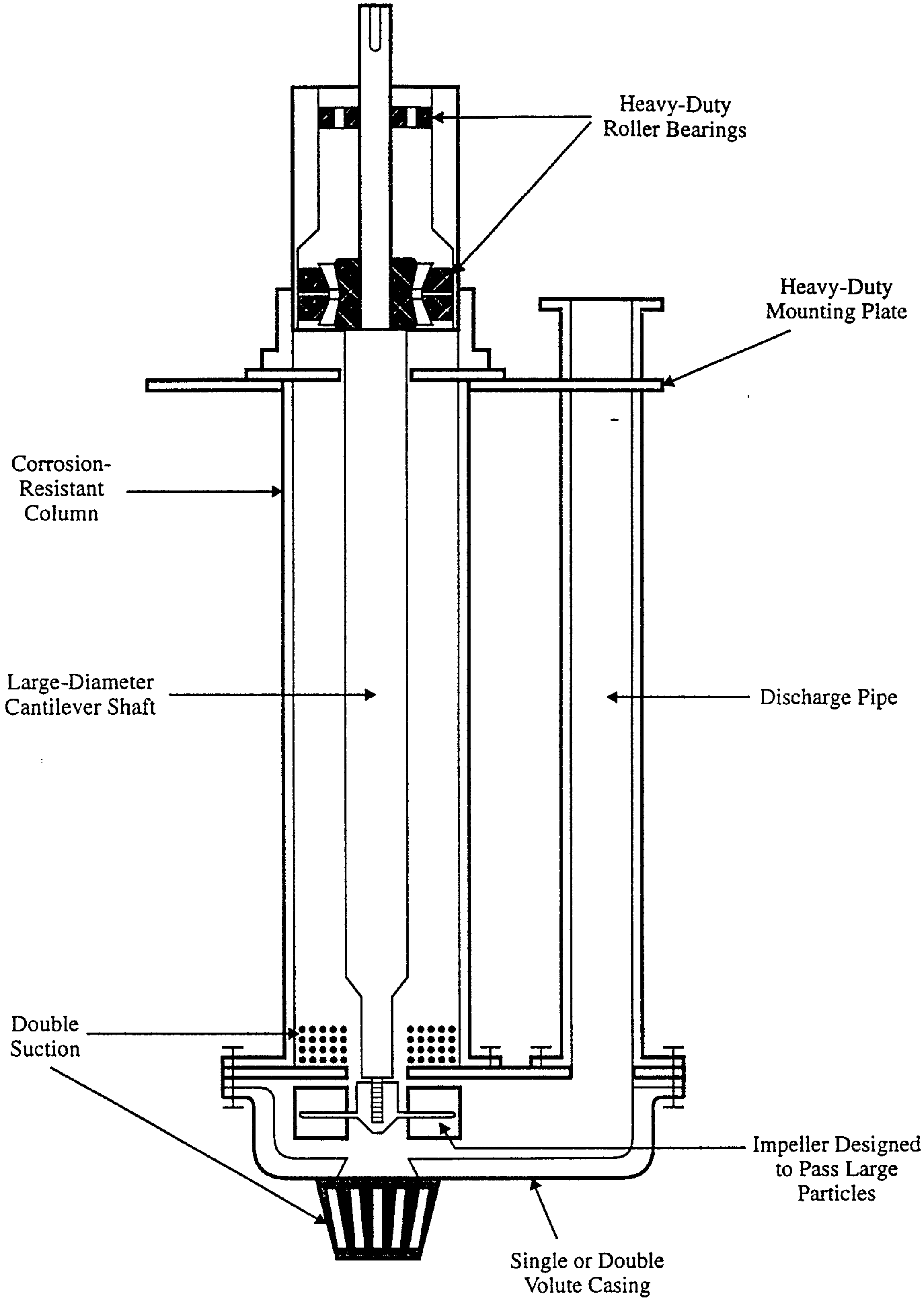


Figure 5-2. Vertical Centrifugal Sump Pump

were preferred for FGD systems operating at over approximately 10,000 mg/L chloride in the absorber module slurry. Recently, however, the better resistance of metal-alloy impellers to physical damage has led to their use even in applications with slurry chloride concentrations of 15,000 mg/L and greater.

Pump Flushing Requirements

Slurry pumps and their related piping should be drained and flushed with clear water to remove solids when the pump is taken out of service for an extended period of time. If this is not done, the impeller could be bound in the casing by the settled solids. Often, reclaim water from the byproduct solids dewatering system is used for flushing, to avoid adverse impacts on the FGD process water balance. Since isolation valves are not typically used on the discharge of absorber spray pumps, flue gas will fill any non-operating pump and its discharge piping. Any fluid that condenses from the flue gas is very corrosive, with a pH of less than 2.0. Therefore, after flushing, absorber spray pumps should be refilled with water to prevent corrosive damage to pump internals from contact with flue gas and to dilute any condensate that forms. Slurry pumps other than the absorber spray pumps do not require refilling after they are drained.

In some cases, depending on the piping arrangement, draining the pump without flushing with water may be sufficient to remove slurry solids. For instance, if a centrifugal pump casing is oriented with bottom discharge (the pump discharge is below the drive shaft), then a drain valve on the discharge line will empty the pump. The time required to allow all slurry to drain is usually determined in the field. However, even if they can be drained without flushing, absorber module spray pumps should still be refilled with water because of the effects of contact with the flue gas, as discussed above.

Pump Control

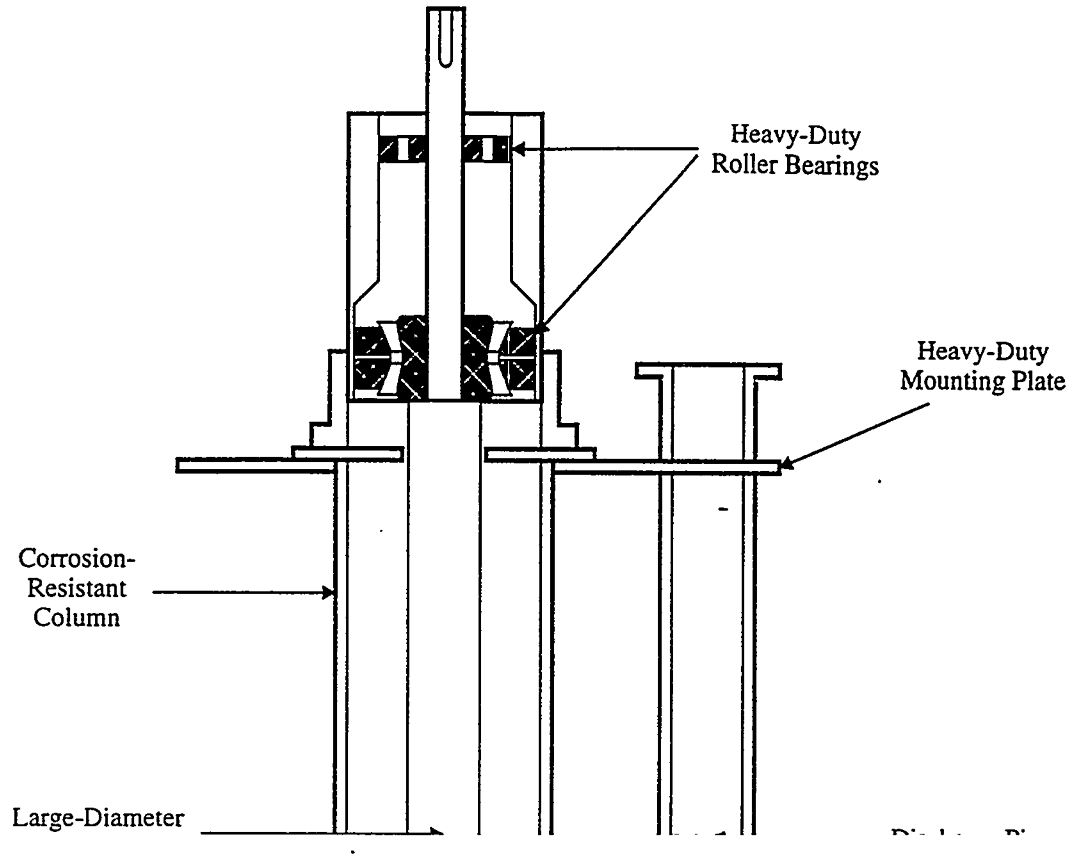
Most slurry pumps are single-speed design and are operated in on/off control, depending on the process needs. Two-speed or variable-speed designs may be desired for some applications, including bleed slurry or thickener underflow, particularly if the FGD system is designed for a wide range of SO_2 removal. The main advantage of being able to operate slurry pumps at more than one speed is that the shutdown/startup sequence can be avoided. When a slurry pump is removed from service, it must be drained and flushed, as discussed above, which may introduce additional water to the process. Also, starting a pump increases the mechanical loads (and the resulting wear) on the pump, motor, piping, and pipe supports, which can be avoided if the pump is allowed to continue running.

5.2.2 Mechanical Considerations

Many mechanical considerations must be addressed in the selection of slurry pumping equipment. Three major areas that must be considered when specifying centrifugal slurry pumps are pump construction, impeller design, and pump shaft seal type.

Pump Construction

FGD system slurry pumps have a far more heavy-duty construction than the clear-liquid pumps that may be more familiar to the utility engineer. The pump casing (or volute) is vertically split to allow replacement of the casing liners and impeller. Minimizing the number of bolts that hold the casing together is a desirable feature; therefore, external ribs are added to make the casing very rigid. As shown in Figure 5-1, the casing halves should have through-bolt construction, which means that threaded holes in the pump casing are eliminated. Through-bolts facilitate maintaining the pump because standard bolts tend to become corroded and frozen in threaded holes. Through-bolts should also be used at the suction and discharge flanges.



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5.2.2 Mechanical Considerations

Impeller Design

The following discussion of slurry pump impellers applies to the design of both hard metal-alloy and elastomer-lined steel impeller construction options.

FGD pump impellers can be either semi-open or closed. A semi-open impeller has a single shroud on the drive side; a closed impeller has two shrouds. Almost all slurry pumps in FGD service use the closed-type impeller. Semi-open impellers are better for pumping large solids, which may plug or damage a closed impeller, but they are much less efficient than closed impellers. When continuously pumping 2000 L/s at 20 m TDH, even small improvements in pump efficiency can provide significant reductions in electric power consumption. Using these typical design numbers, a 1% improvement in pump efficiency represents an electrical power savings of over 6,200 kilowatt-hours per day (kWh/day) per pump.

The impeller typically has four to six vanes, or pumping blades, that are situated between two parallel shrouds. The number of vanes depends on the characteristics of the solids being pumped and on the optimum pump efficiency for the application.

The front impeller shroud should be cast with expelling or pumpout vanes to minimize recirculation of slurry between impeller and the front pump casing, which causes erosion and reduces efficiency. The rear (drive-side) impeller shroud also has expelling vanes, except when mechanical shaft seals are used. The effect of rear-shroud vanes is to reduce the slurry pressure in the shaft seal or stuffing box area, which is desirable when using shaft seal water. However, mechanical seals need the liquid recirculation in this area to ensure proper cooling and lubrication of the seal faces. Pump seal options are discussed in greater detail in the following section.

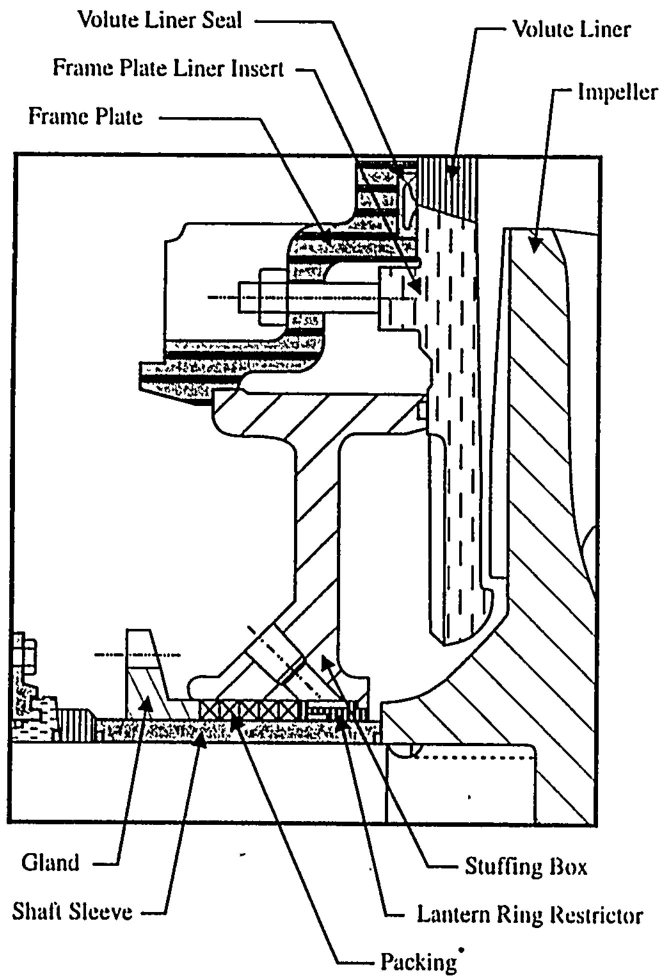
Pump Shaft Seals

A major problem area in slurry pumps is the need to provide a seal to keep process liquor or slurry from leaking between the rotating impeller shaft and the stationary pump casing. There is a variety of methods for achieving this goal; some require seal water and some do not. In recent years, mechanical seals have become the most common choice for sealing FGD slurry pumps.

Standard Stuffing Box with Seal Water--Figure 5-3a shows a standard gland seal, which consists of a metal lantern ring restrictor (where seal water enters), 4 to 7 rings of packing, and a packing gland to compress the packing. The seal water is used in slurry pumps to flush solids away from the stuffing box, while cooling and lubricating the pump packing. If seal water flow is insufficient, solids will enter the packing and cause wear on the shaft sleeve. This will increase clearances and lead to failure of the hydraulic seal and the pump itself. To ensure adequate seal water flow, the seal water pressure must be maintained above the pressure of slurry in the stuffing box at all operating conditions. Although slurry pumps experience changes in discharge pressure during normal operation, a 35 to 70 kPa (5 to 10 lb/in^2) differential between the stuffing box and seal water pressure should maintain an adequate seal water flow.

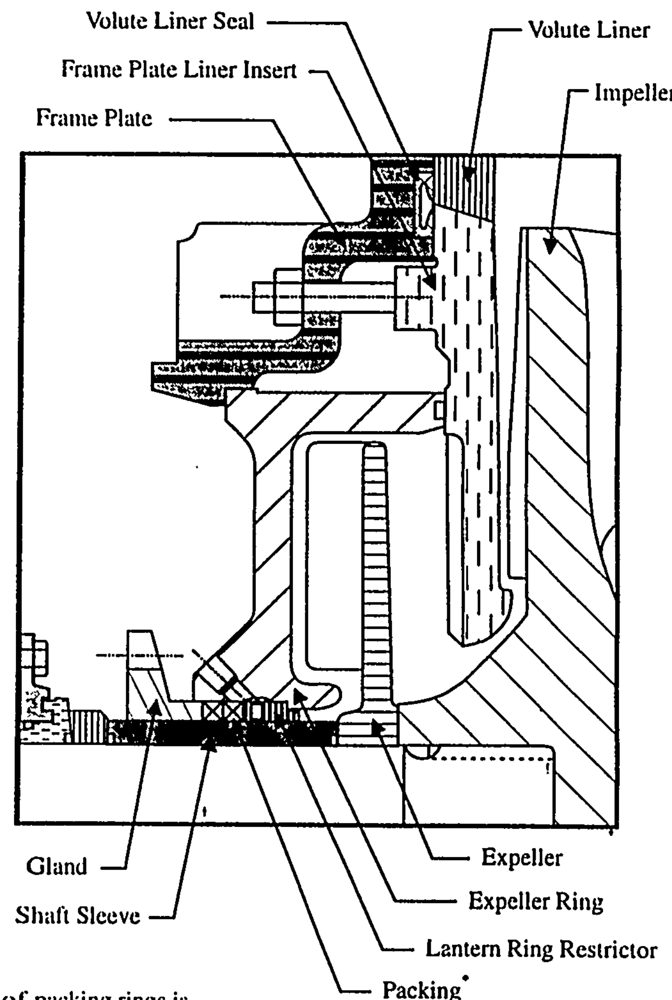
The seal water flow on large slurry pumps fitted with a standard gland seal is typically 1.3 to 2.2 L/s (20 to 35 gpm). A low-flow lantern restrictor is an option that consumes considerably less seal water, on the order of 0.6 L/s (10 gpm).

Centrifugal Shaft Seal with Seal Water--As discussed above, pumps using a standard seal water system often have expeller vanes on the drive-side shroud, to reduce stuffing box pressure. Some manufacturers install additional expellers on the shaft between the impeller and the stuffing box, as in Figure 5-3b, to reduce the stuffing box pressure even more. Centrifugal action by the expeller reduces slurry pressure in the gland area. This system is also referred to as a centrifugal shaft seal, and can reduce or eliminate seal water



*Number of packing rings is dependent on pump size.

a. Standard Gland Seal



*Number of packing rings is dependent on pump size.

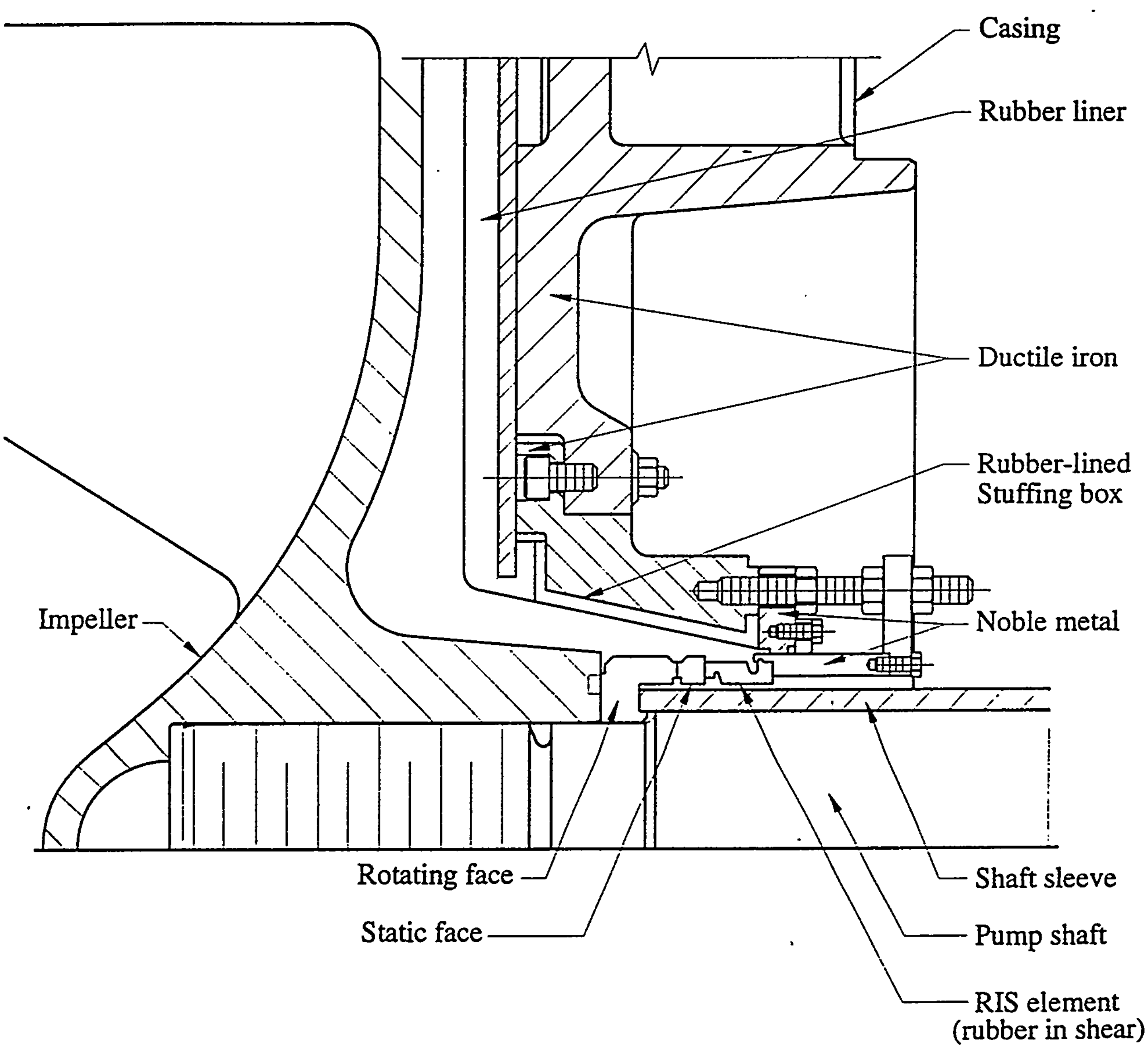
b. Water-Assisted Centrifugal Seal

Figure 5-3. Stuffing Box Alternative Seals
(Ref. Warman International, Inc., Madison, WI)

requirements in some situations. As a general guide, if the pump suction pressure is less than 10% of the discharge pressure, a centrifugal seal may be able to eliminate seal water (i.e., allow the pump to "run dry"). However, the suction pressure of an absorber module spray pump is typically greater than 10% of the discharge pressure. The combination of reduced slurry pressure and use of a low-flow lantern ring restrictor allows a very low seal water flow. Absorber module spray pumps using this technology may operate successfully at a seal water flow as low as 0.13 to 0.3 L/s (2 to 4 gpm). However, the use of centrifugal seals results in increased electrical power consumption, which may rise by up to 1% on the large spray pumps (6).

Mechanical Seals--Most pumps can be initially purchased with mechanical seals or converted from a standard stuffing box with seal water to mechanical seals. Mechanical seals used in FGD system slurry pump service typically have two smooth ceramic faces, one rotating and one stationary, as illustrated in Figure 5-4. A major consideration is to avoid using expeller vanes on the impeller drive-side shroud, since the use of any device that reduces stuffing box pressure is discouraged. One of the most critical factors affecting mechanical seal life is the temperature of the seal faces. Therefore, slurry should be allowed to circulate near the seals to remove heat. The tapered stuffing box shown in Figure 5-4 is recommended by most major pump and mechanical seal manufacturers. This tapered design has been found to effectively remove heat, large particles, and gases from the seal faces.

Many factors have contributed to the increase in the use of mechanical seals on slurry pumps during the past decade. Mechanical seal technology has improved, making the seals more reliable. Also, electric utilities have gained experience and confidence in using these seals. Probably the most significant driving force, however, has been the utilities' increasing interest in minimizing the addition of fresh water to the FGD system in order to maintain a negative (net makeup) water balance. The mechanical seal is very effective in helping reduce pump seal water flows.


Casing
Rubber liner
Ductile iron
Rubber-lined
Stuffing box
Noble metal
Impeller
Rotating face
Static face
Shaft sleeve
Pump shaft
RIS element
(rubber in shear)

5.2.3 Other Considerations

There are several other factors that should be considered in the application of a centrifugal pump to an FGD system:

- Minimizing erosion and other mechanical damage;
- Pump speed reduction;
- Pump operating margin;
- Pump manufacturer experience history;
- Pump isolation; and
- Pump operation in series.

Minimizing Erosion and Other Mechanical Damage

Large particles of FGD solids (e.g., gypsum scale) and debris can damage pump linings and impellers. Some utilities have installed screens on the pump inlet to prevent such damage, but the screens must be routinely cleaned to prevent the pump from being starved of flow. Screens may be particularly useful during the initial startup of a new FGD system, when construction trash such as pieces of welding rod is a greater problem.

Overspeed operation produces excessive stress at the impeller rim. Stresses on the rubber at the impeller rim increase at the square of the rim velocity, and overspeed operation frequently results in slinging of the rubber from the impeller core. Rubber hardness limits the maximum tip speed of rubber-covered impellers according to the following equation (7), which is valid over a rubber hardness range of Shore A 20 to Shore A 60:

$$\text{Maximum tip speed (m/min)} = 1160 + [6.1 \times \text{Hardness (Shore A)}] \qquad (5\text{-}1)$$

Applying Equation 5-1 to an impeller lined with a Shore A 55 hardness rubber, the maximum tip speed is 1490 m/min (4900 ft/min).

Because they do not experience the problems with loss of the lining, hard metal-alloy impellers can be operated at higher tip speeds of 1650 m/min (5400 ft/min) in rubber-lined casings and 2290 m/min (7500 ft/min) in metal-lined casings (6).

Speed Reduction

Most small clear-liquid pumps are direct-coupled and, therefore, turn at synchronous motor speeds. Slurry pumps, however, must operate at relatively slow speeds because of impeller tip speed restrictions. For example, a large absorber module spray pump may turn at just 300 rpm, with the motor turning at 1200 to 1800 rpm.

Both gear reducer and belt drives have been applied to FGD system slurry pumps. The gear reducer option is more efficient but also is more costly, especially for small pumps. Choosing between these speed reducer options depends mainly on the size of the motor. Belt drives are used for almost all motors rated below 300 kW [400 horsepower (hp)]. Above 300 kW, gear reducer drives are frequently used. Above 375 kW (500 hp), gear reducer drives predominate.

Pump Operating Margin

Every pump vendor offers a number of similar pumps that vary in the size of the suction and discharge lines and in the impeller diameter. Each pump has a set of characteristic operating curves that define the performance of the pump (in terms of flow and TDH) at several impeller speeds. The best pump for a specific set of operating condition is selected on the basis of the goals of attaining the best operating efficiency and operating at a reasonable impeller tip speed, as discussed previously in this section.

In actual practice, however, it is prudent to select a pump that can provide operating margins on both the pump flow and head design values to account for possible future changes in the pumping requirements. For example, at some point in the future, it might be necessary to increase the absorber module liquid-to-gas ratio (L/G) in order to compensate for increased coal sulfur content or to increase SO_2 removal efficiency in response to other conditions. It would be very desirable to provide the increased slurry flow without replacing the absorber spray pumps. For this reason, the slurry pumps and their drive motors typically are selected such that an increase in impeller speed can increase flow by 10 to 15% and TDH by 15 to 20% without exceeding the recommended impeller tip speed.

Pump Manufacturer Experience History

Slurry pumps are exposed to difficult operating conditions due to the abrasive and corrosive nature of FGD process slurries. Successful performance in this service is usually the result of years of experience in FGD systems or in a closely related, abrasive condition service such as mining. In selecting prospective slurry pump suppliers, the history of pumps of <u>similar flow and head capacity in similar service</u> should be closely examined and only manufacturers who have a demonstrated success with these pumps should be considered.

As stated earlier, however, the size of absorber module spray pumps has been increasing over time. In several recent applications, this has required the development of new, larger-capacity slurry pumps, which did not have the operating history recommended above. When considering the use of a slurry pump without a long operating history, the demonstrated performance of previous new pumps from this manufacturer may be the best indication of future performance.

Pump Isolation

Slurry pump installations are almost always designed with redundancy, so that a spare pump can be placed into service without disrupting FGD system availability. The pump must be isolated from the process slurry in order for maintenance to be performed. For most FGD applications, isolation valves are provided in the pump suction and discharge piping. For absorber module spray pumps, however, an isolation valve is typically used only on the suction side. Although some FGD installations have block valves on the spray pump discharge, most do not. Some utilities temporarily insert inflatable bladders into the discharge line to block the flue gas and protect crews who are maintaining the pump.

Additional information on pump isolation valves is presented in Part II, Section 8.0--Valves.

Pump Operation in Series

Slurry pumping systems typically use a single pump; however, the pumps can be arranged in series to achieve the higher heads necessary to transport slurry over long distances. For example, FGD slurry bleed may need to be pumped many kilometers to a disposal pond. The pumps in series can all be located near the absorbers if slurry piping is able to withstand the discharge pressure. Alternately, the pumps can be spaced along the piping, but this is more difficult with respect to pump operation, maintenance, and utility (electric power and seal water) supply.

5.3 Material Selection

As discussed in the previous sections, erosive wear is the major concern related to slurry pumps because it affects both pump life and pump performance. Materials of construction and pump geometry are the most important factors influencing the rate of pump erosion. Although a utility engineer has limited control over pump geometry, except in the choice of pump manufacturer, the materials of construction can be specified.

5.3.1 Impellers

The impellers of slurry pumps may be fabricated of corrosion- and abrasion-resistant metal alloy or they may be pressure-molded rubber with a carbon steel core. Molded rubber impellers have historically been the material of choice for FGD slurry applications provided that large particles (i.e., chunks of scale or agglomerates) and debris can be excluded from the slurry entering the pumps. However, hard metal-alloy impellers have been specified in the majority of recent FGD system installations.

Rubber-Lined Impellers--Natural (isoprene) rubber usually performs well unless the plant is a dual-fuel (coal and fuel oil) plant. Oil contamination of the slurry is a potential concern since oil will degrade natural rubber. Since natural rubber is softer than synthetic rubbers, it is also more prone to damage from hydraulic shock (pressure pulses). In those cases where a soft rubber does not perform well, neoprene (polychloroprene) is the material of choice, but it must be lead-cured. Some utilities have experimented with polyurethane molded to cast iron impellers, but the performance of this alternative has been mixed.

The most common modes of failure of rubber impellers result from cutting by pieces of scale or debris, or by operation of the pumps outside their design dynamic limits. Examples of operating outside these limits are increasing the pump speed to achieve increased TDH, operating at excessive flow rates, or operating with insufficient net positive suction head (NPSH) (i.e., cavitating the pump).

The hardness of rubber used in pumps may vary from Shore (durometer) A 20 to A 70 or higher. Shore A hardness of approximately 55 is typical of the pumps used in FGD systems.

Metal-Alloy Impellers--Where large particles cannot be kept out of the pump, or in cases where the utility prefers to reduce the risk of catastrophic failure that accompanies rubber-lined impeller use, impellers fabricated of a hard metal-alloy may be used. These alloys include 27%-chromium, white iron heat-treated to high hardness for higher pH/low chloride slurries; 27%-chromium, white iron heat-treated to moderate hardness for lower pH and intermediate chloride slurries; and CD-4 MCu and cast duplex stainless steels for lower pH/high chloride slurries. The abrasion resistance of this series of alloys decreases from the one listed first to the one listed last.

5.3.2 Pump Casings

The volutes (side liners) may be constructed using the corrosion- and abrasion-resistant alloys mentioned in the preceding paragraph; molded natural, chlorobutyl, or lead-cured neoprene rubbers; or molded polyurethane. The hardness of rubbers used in volute liners is typically 40 to 45 Shore A, slightly softer than that used for the impellers. Hybrid designs using both rubber and hard alloy components are common. Most recent systems FGD installations have specified metal impellers and rubber-lined casings for the absorber module spray pumps (6).

5.3.3 Service Life

Operation at excessive flow rates or with insufficient NPSH can result in rapid cavitation damage of both rubber and metal pump components. It is important that pumps with rubber-covered impellers be carefully sized and operated within the temperature-pressure-flow-velocity regime approved by the manufacturer. However, even if appropriate materials of construction are used and the pump is operated in the appropriate temperature-pressure-flow-velocity regimes, the life of slurry pump components (especially rubber casing liners and rubber-lined impellers) is typically only two to five years. Therefore, utilities should plan on periodic replacement of slurry pump liners and impellers.

5.4 Recommendations

- Absorber module spray pumps should be provided by a manufacturer that has extensive experience providing slurry pumps for FGD service.
- Two-speed pump operation should be considered for transferring bleed slurry to dewatering equipment and to minimize flushing requirements and the need for slurry valve throttling.
- In FGD systems where the rate of makeup water addition is a concern, slurry pumps should be fitted with low-flow or mechanical seals.
- Slurry pumps should be drained and flushed after being taken out of service. Out-of-service absorber module spray pumps on an operating absorber should remain filled with water to prevent corrosion by acidic moisture condensing from the flue gas.

5.5 References

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6.0 TANK AGITATORS

The proper selection and installation of tank and sump agitators are critical to the FGD process. The FGD process uses a variety of slurries that consist of suspensions of lime or limestone reagent, byproduct solids, and inert solids (e.g., fly ash) in a process liquor. These slurries are contained in the reaction tanks, reagent slurry storage tanks, thickener/ hydrocyclone underflow storage tanks, chemical additive tanks, and building sumps. The main reasons for installing agitators (also called mixers) are to prevent the solids from settling in a tank or sump and to produce a relatively homogenous slurry that can be transferred to the next step of the process. Agitators in reaction tanks also are designed to enhance forced oxidation air dispersion, crystal growth, and limestone dissolution.

6.1 Types Available

Agitators used in FGD service can be either top-entry or side-entry types, as shown in Figures 6-1 and 6-2, respectively. Both agitator types consist of an electric motor, speed reducer drive, shaft, and impeller. Most FGD system tanks and sumps use top-entry agitators. In reaction tanks, however, either top- or side-entry agitators can be used, depending on the configuration of the absorber and reaction tank. When the absorber and reaction tank are an integral unit, side-entry agitators are required. When the absorber and reaction tank are separated, top-entry agitators are often used. This is illustrated in the use of both side-entry and top-entry agitators in a dual-loop FGD system, Figure 6-3.

There are two major categories of impeller shapes: radial-flow and axial-flow. These two designs, along with other hybrid designs, are shown in Figure 6-4. Impellers used in FGD service can be of the axial-flow type (Figure 6-4a), the radial-flow type (Figure 6-4b), or a combination design. In general, axial-flow designs are the best choice for maintaining solids in suspension, while radial designs are best for gas-liquid mixing. The axial-flow hydrofoil (Figure 6-4c) is similar to a standard, pitched-blade impeller, but the blades are curved and tapered, resulting in a more efficient design (providing a similar axial flow rate at

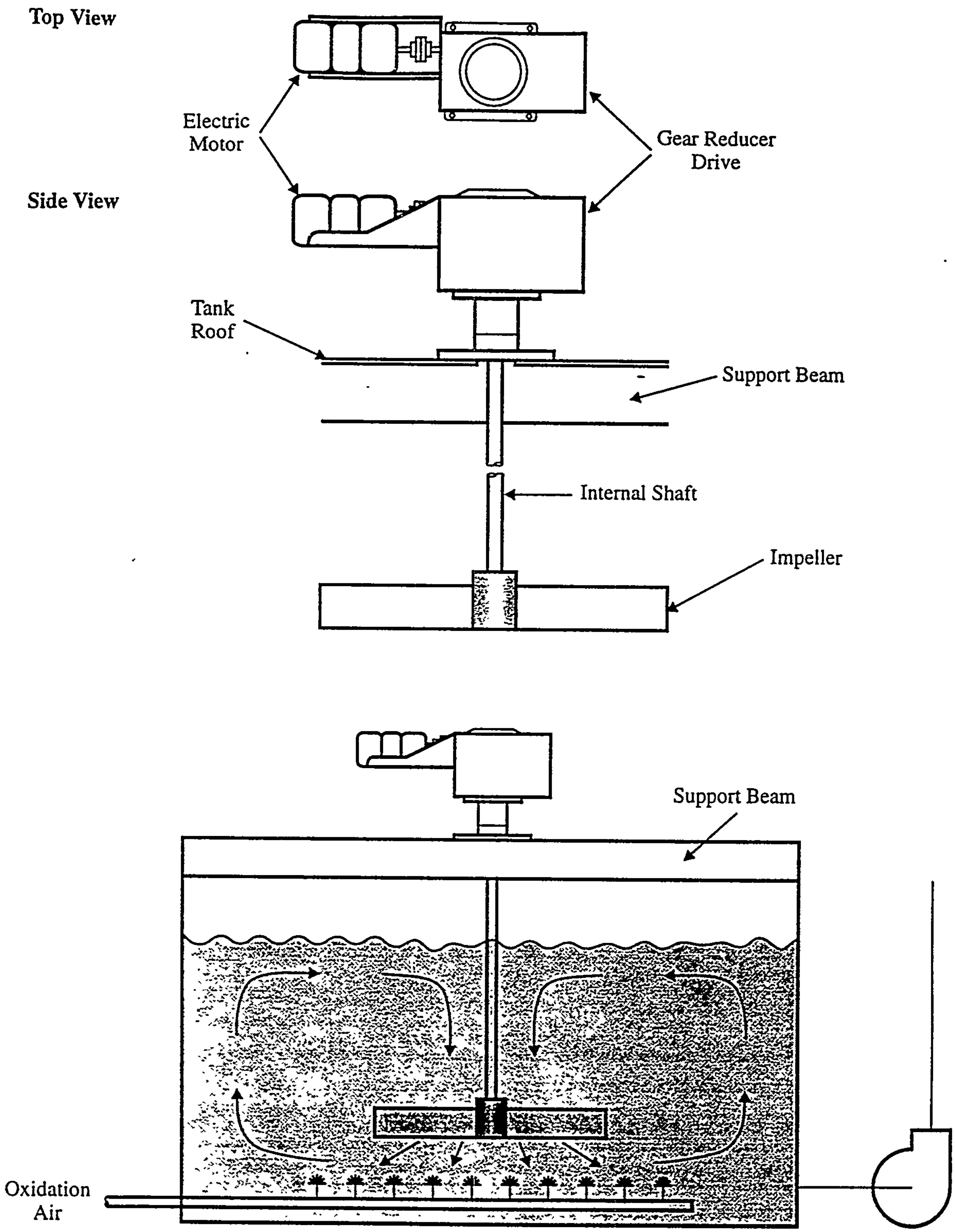


Figure 6-1. Top-Entry Agitators

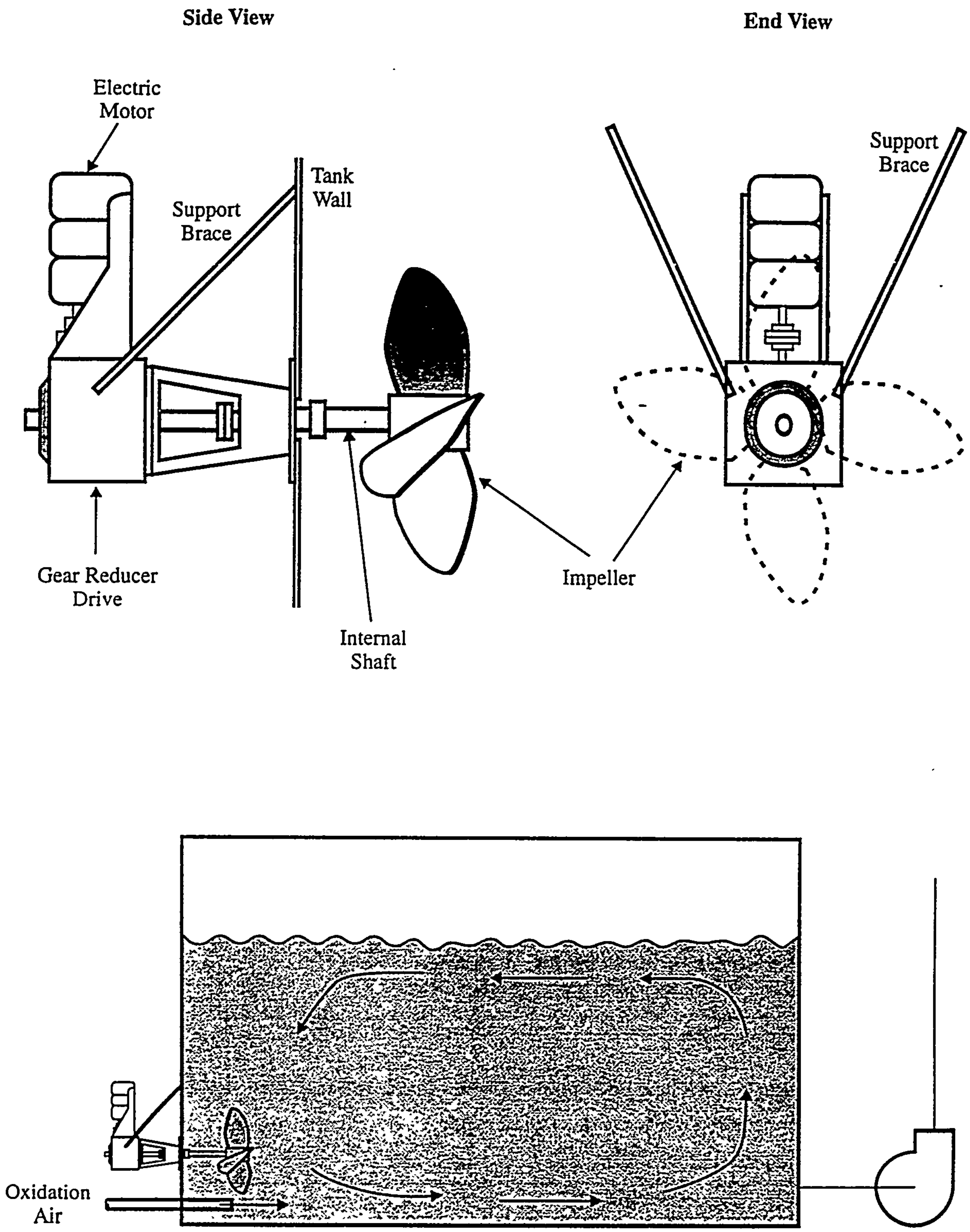


Figure 6-2. Side-Entry Agitators

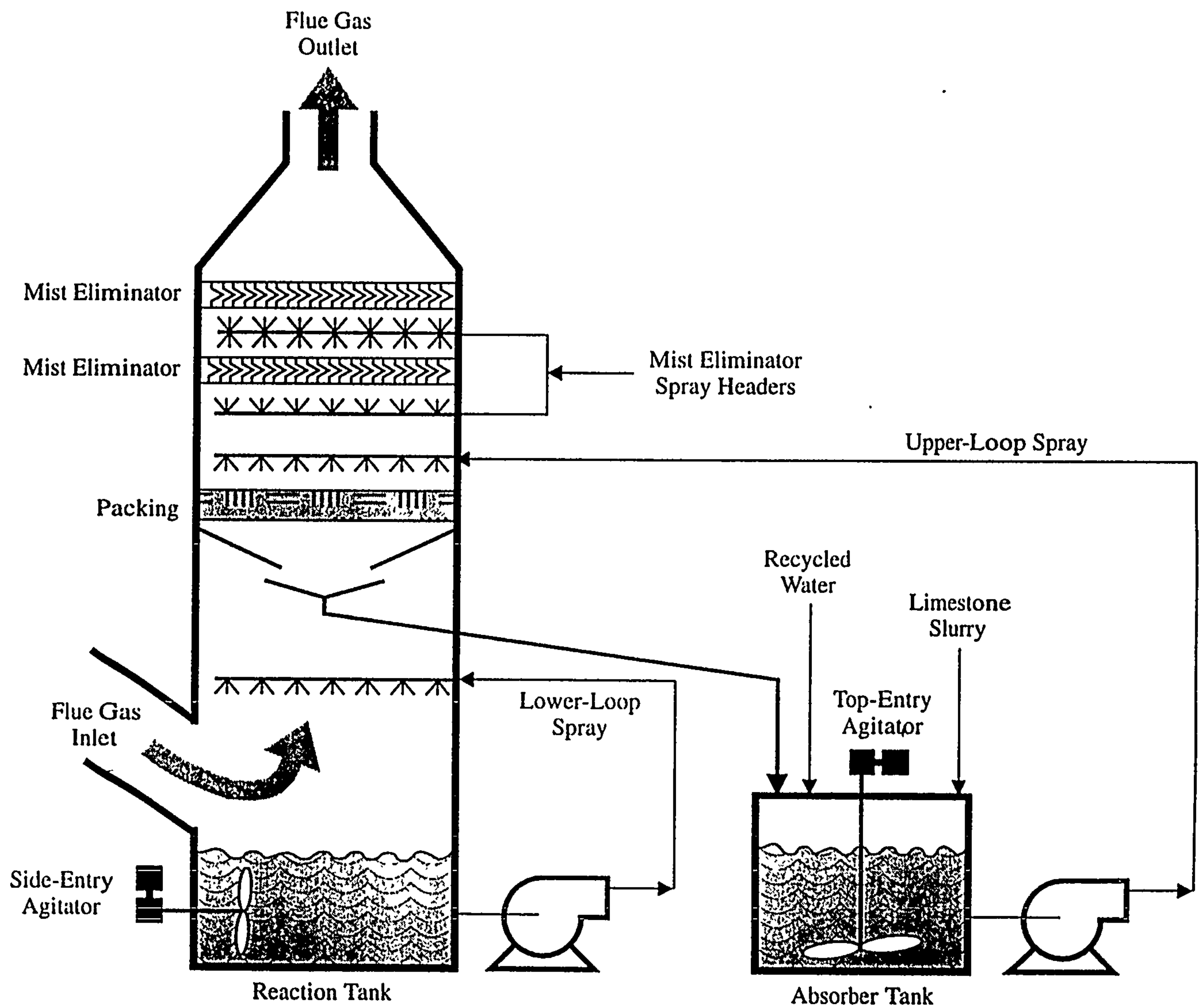
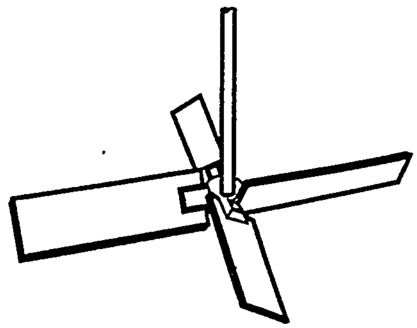
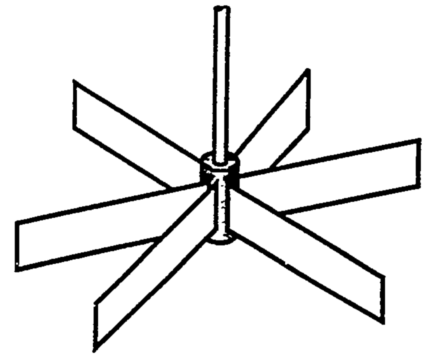


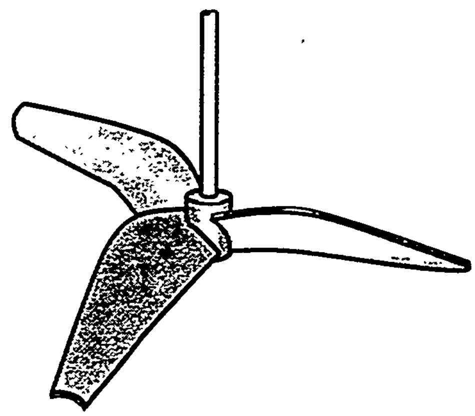
Figure 6-3. Top- and Side-Entry Agitators for a Dual-Loop Absorber



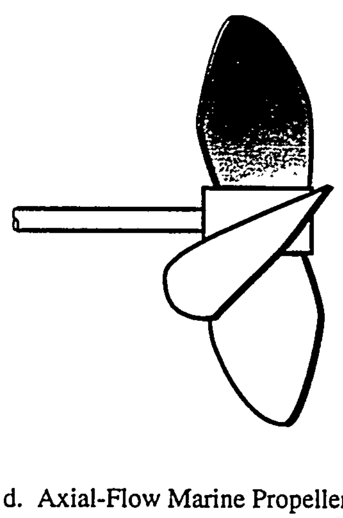
a. Axial-Flow, Pitched-Blade Turbine



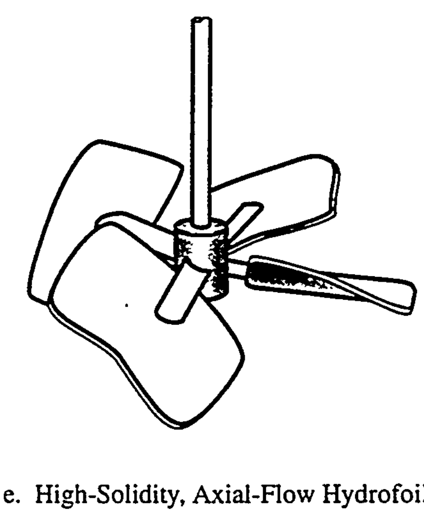
b. Radial-Flow, Flat-Blade Turbine



c. Axial-Flow Hydrofoil



d. Axial-Flow Marine Propeller



e. High-Solidity, Axial-Flow Hydrofoil

Figure 6-4. Alternative Impeller Designs

reduced power consumption). Side-entry agitators often use a marine propeller-type impeller (Figure 6-4d), which is very similar to a ship's propeller. The "high-solidity" axial-flow hydrofoil (Figure 6-4e) is one manufacturer's recent modification of the top-entry impeller design that takes advantage of wider blades to produce higher flow efficiency while preventing flooding.*

6.2 Design Considerations

Basic design considerations related to agitator selection can be found in vendor literature and in books published on the subject (1,2,3). Most of the published information is quite theoretical, and is beyond both the scope of this manual and the typical needs of the utility engineer. From a practical standpoint, the user should be aware of available mixing options and should ensure that a vendor with experience in the chosen FGD process is selected to provide the agitators.

6.2.1 Process Considerations

The three most important process considerations that affect agitator design are the slurry characteristics, the degree of agitation required, and whether the byproduct solids are forced-oxidized to produce calcium sulfate. These considerations are discussed below.

Slurry Characteristics

Most agitators for large tanks, especially top-entry types, are custom-designed for a particular application. Agitator design is affected by several slurry characteristics, including liquid density, viscosity, and solids content. Solid particle size and density are also important because large, dense solids are more difficult to maintain in suspension than are

* The impeller rotation must be greater than some minimum value in order to disperse the oxidation air in the slurry. This minimum rotation varies with the specific design of the impeller. "Flooding" occurs below this minimum speed when the gas bubbles rise through the impeller region without being dispersed.

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Slurry Characteristics

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Forced Oxidation

When forced oxidation is employed, the reaction tank agitators must provide gas dispersion in addition to solids suspension. In other industries, where gas dispersion is small, light solids. These factors will affect the impeller design, required number and locations of agitators, and the motor sizing.

Degree of Agitation Required

Generally, three degrees of agitation are possible:

- Partial suspension--some solids rest on the tank bottom for a short period of time, with a significant solids concentration gradient from the top to the bottom of the tank;
- Complete suspension--all solids are off the tank bottom, with a uniform solids concentration except for the upper 10 to 20% of the tank depth; and
- Uniform suspension--all solids are off the tank bottom, with a uniform solids concentration except for the upper 1 to 2% of tank depth.

In most FGD process services, the agitators are designed to provide complete suspension of the slurry. Sump agitators typically are designed to provide partial suspension. There is seldom any process justification for the very high power input required to provide uniform suspension in any FGD system process tank.

To maintain slurry solids in suspension, an adequate fluid velocity must exist throughout the tank. Fluid velocity is produced by impellers and by flow patterns that result from the tank geometry and baffles. The fluid velocity at all locations in the tank must be greater than the terminal settling velocity of the solid particles. Zones in the tank with insufficient fluid velocity will see a buildup of settled solids. Even when complete suspension of solids is required, most agitator specifications allow 2 or 3% of the tank bottom to be covered with solids. This most commonly occurs along the tank wall. At a minimum, the mixing system should be designed to keep the area near pump suctions clear of settled solids (4). Blockage of the pump suction can result in cavitation of the pump due to insufficient positive suction head and can damage the pump lining and impeller.

Forced Oxidation

When forced oxidation is employed, the reaction tank agitators must provide gas dispersion in addition to solids suspension. In other industries, where gas dispersion is the only concern (no suspended solids are present), a radial impeller is typically chosen for this service. However, FGD systems must maintain solids in suspension while encouraging air dispersion, and axial (or modified axial) impellers are used.

The method of adding oxidation air to the reaction tank depends on the FGD vendor's design. When top-entry agitators are used, oxidation air is added through a fixed grid of aeration pipes on the reaction tank floor beneath the agitator impeller (refer to Figure 6-1). When side-entry agitators are used, the oxidation air can be added by a fixed grid in the center of the tank or injected at locations in the tank wall just below each impeller, as shown in Figure 6-2. The turbulence in this area is used to break up the air bubbles to improve absorption in the process liquor.

6.2.2 Mechanical Considerations

Agitators are complex mechanical components that often are custom-designed for specific applications. An agitator design that performs well in a non-slurry application may not work well in an FGD slurry application. The tasks of suspending solids and dispersing air, with possible variations in slurry density and tank level, are a challenge for the agitator vendor. Major mechanical considerations include the following:

- Impeller design;
- Agitator shaft and drive construction; and
- Shaft seals.

Impeller Design

The function of an agitator impeller is to convert energy from the drive motor into flow and turbulence (shear rate). The three most important design factors that influence an agitator impeller's performance are the following (1):

- Impeller diameter;
- Impeller speed (tip speed); and
- Impeller geometry.

In the turbulent-flow regime, the flow capacity of geometrically similar impellers is proportional to ND^3 and the power requirement is proportional to $\rho N^3 D^5$; where N is the impeller speed, D is the impeller diameter, and ρ is the fluid density (3).

Impeller Diameter--As shown in the above relationships, at constant speed, increasing the impeller diameter significantly increases both the flow produced and the power required. The size of the impeller is limited by several factors, including weight, impeller tip speed (discussed below), and drive power rating. The diameter of impellers used in FGD service varies with the type of agitator. Side-entry agitators are most often used in reaction tanks, and their diameters can vary from as small as 460 mm (18 in.) to approximately 1 m (3 ft). Top-entry agitators used in reagent slurry storage tanks, reaction tanks, and underflow storage tanks can vary from less than 1.5 m (5 ft) to over 3 m (10 ft). Top-entry agitators for sumps are typically 305 to 610 mm (1 to 2 feet) in diameter. When an impeller larger than these typical ranges would be required for very large tanks, several smaller-diameter impellers are used instead.

Impeller Speed--The impeller speed (in revolutions per unit time) and the impeller diameter determine the impeller tip speed:

$$V = \frac{\pi \times N \times D}{60} \qquad (6\text{-}1)$$

where: V = Tip speed, m/s (ft/s);
N = Impeller speed, revolutions per minute (rpm); and
D = Impeller diameter, m (ft).

The maximum allowable impeller tip speed depends on materials of construction, but is usually in the range of 2.5 to 6.5 m/s (8.3 to 21.7 ft/s). This generally corresponds to an impeller speed of 15 to 30 rpm for top-entry agitators and 190 to 280 rpm for side-entry ones. Higher tip speeds can result in excessive erosion of the impeller blades. Agitators in dense slurries, such as the reagent slurry storage tank, operate in the lower end of this range; agitators in the less dense reaction tanks operate in the upper end.

Impeller Geometry--Impeller geometry relates to the shape, size, angle, and number of the impeller blades. As noted above, impeller design has a very important effect on mixing efficiency. The impeller geometry is an area of continuing research by agitator vendors, and numerous proprietary designs are offered for specific process conditions.

Agitator Shaft and Drive Construction

In operation, an agitator is somewhat similar to a centrifugal pump, but much less efficient and with a much longer shaft. The shaft, bearings, and drive must be designed to withstand the forces acting on the impeller. Gear drives are usually used to reduce motor speed on typical FGD system agitators, but belt-drive top-entry agitators may be used in sumps. Most aspects of agitator shaft and drive construction are the responsibility of the agitator vendor, and the utility engineer has relatively little input to this aspect of the agitator's mechanical design. The following information highlights the mechanical considerations that vendors use in their designs.

Agitator shafts must be designed to maintain rigidity when acted upon by the torsional and deflection loads that cause shaft stress. Torsional loads result from the drag forces created by the rotation of the impeller in the process fluid. Deflection loads result from unbalanced loads on the impeller due to unequal performance of each impeller blade and, in the case of side-entry agitators, the weight of the impeller at the end of a cantilevered shaft. Shaft design must also consider the critical speed of the shaft and impeller. The critical speed of a rotating device is the rotational speed equal to the natural lateral vibration frequency of the device. Mechanical equipment experiences large and violent oscillations as the critical speed is approached. Critical speed is mainly affected by shaft length and diameter, and, to a lesser degree, by bearing spacing, type of shaft material, and weight of the shaft and impeller. In most cases, the speed of the agitator should be less than 50% of its critical speed; however, the selection of the correct shaft to avoid critical speed problems is the responsibility of the agitator vendor.

The agitator drive performs two functions: motor speed reduction and support of the shaft and impeller. Although the drive may be overlooked, it usually represents the largest component of the total agitator cost. The drive is also the most common source of maintenance problems because of the extreme stresses transmitted between its moving parts. Although drive life will be extended by over-sizing the drive for the impeller duty, such action reduces drive efficiency. Therefore, the drive should be designed for the optimized balance between energy costs and maintenance and downtime costs (4).

The coupling that attaches the shaft to the gear drive can transmit movement and forces from the shaft to the drive. Obviously, it is important to isolate the drive from shaft movement. In top-entry agitators, this can be accomplished by using a quill design, as shown in Figure 6-5. In this design, the impeller shaft bearings are independent of the bearings supporting the final drive shaft. The two shafts are connected by a flexible coupling. Since the two shafts touch only at the coupling, bending loads from the impeller shaft are not transmitted to the drive.

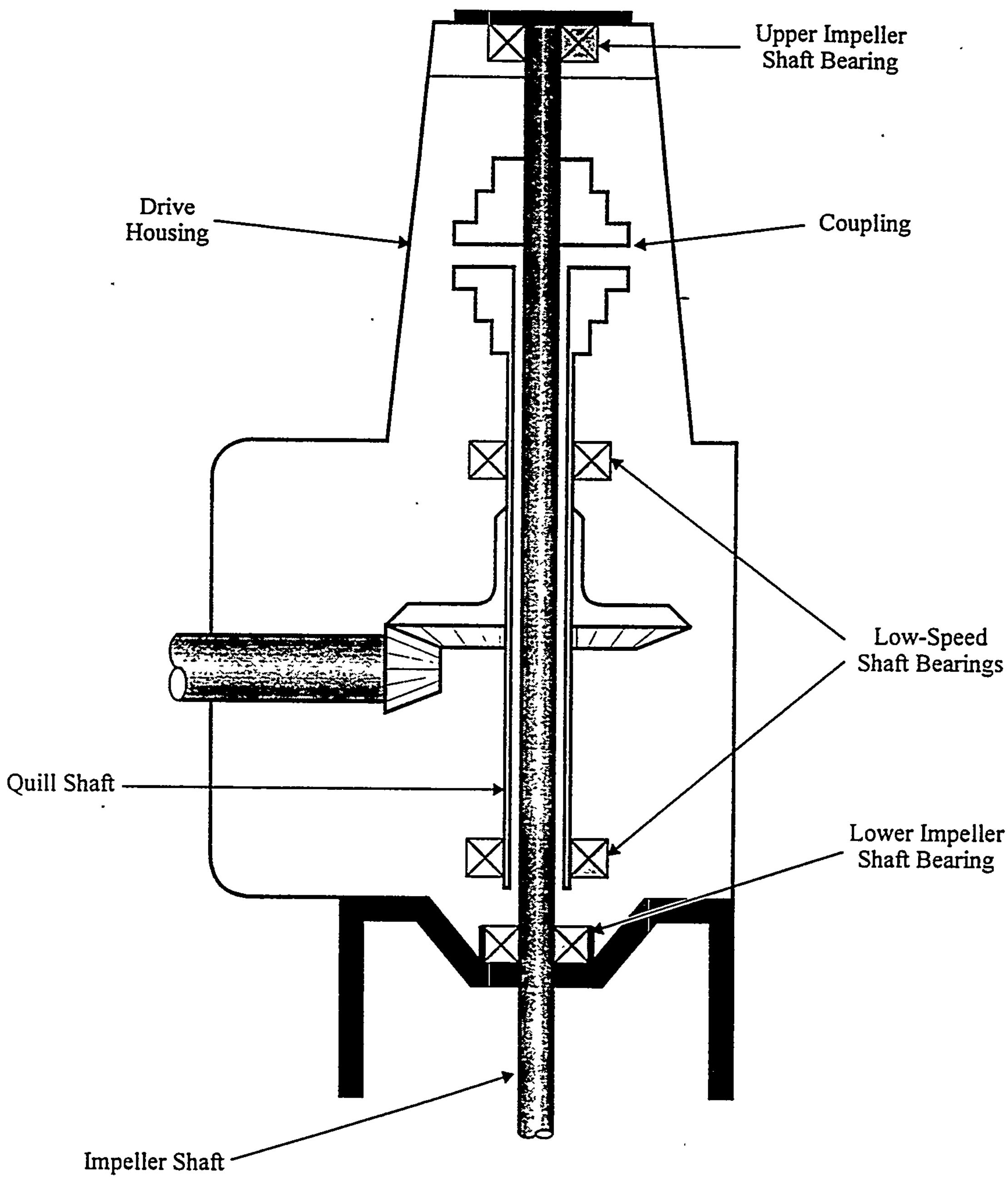


Figure 6-5. Quill Shaft in Speed Reducer

Side-entry agitators must withstand large bending loads and do not use the quill design. A typical side-entry agitator is shown in Figure 6-6.

Shaft Seals

Many top-entry agitators are installed on open-top tanks and there is no need for a shaft seal. Even on covered FGD tanks a liquid-tight seal is not usually necessary. However, a liquid-tight seal is very important on side-entry agitators to prevent leakage of the process slurry and damage to the shaft bearings. This seal can be either a stuffing box with seal water or a mechanical seal. This discussion will emphasize mechanical seals because most FGD vendors prefer mechanical seals in order to minimize makeup water requirements. The basic principles of sealing agitator shafts are similar to those for pump shafts (see Section 5.0--Centrifugal Slurry Pumps).

Most manufacturers of side-entry agitators offer mechanical seals in either a single- or double-seal configuration. The single seal is usually sufficient for FGD use. Double seals are used most often with high-pressure or hazardous fluids. A typical side-entry agitator mechanical shaft seal is presented in Figure 6-7. The seal faces are typically fabricated of silicon carbide, and the wetted metal parts are fabricated of Alloy C-276 or a similar very corrosion-resistant alloy. An important feature of side-entry agitators (with either type of seal) is the provision of a method for performing seal maintenance while the tank is full. This is typically accomplished by pulling the shaft out a short distance, which closes off an opening between the flange housing and the shaft shut-off collar, as shown in Figure 6-7. Using this design, all components of the side-entry agitator, except the internal shaft and impeller, can be replaced without draining the tank.

Although shaft stiffness is important for all agitators, it is especially important for side-entry agitators with mechanical seals. A very small amount of shaft deflection can damage or crack the hard seal faces.

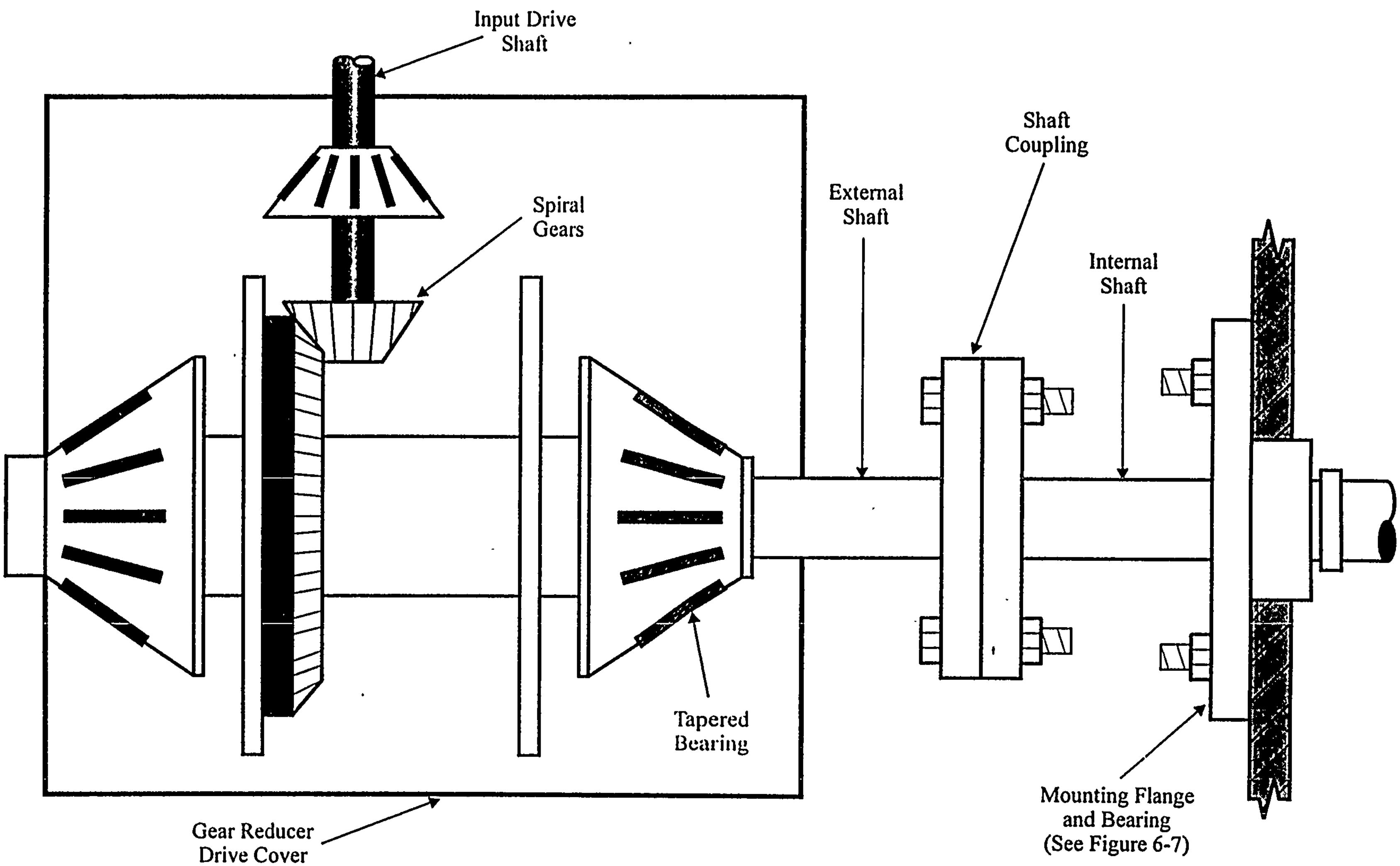


Figure 6-6. Side-Entry Impeller Bearings

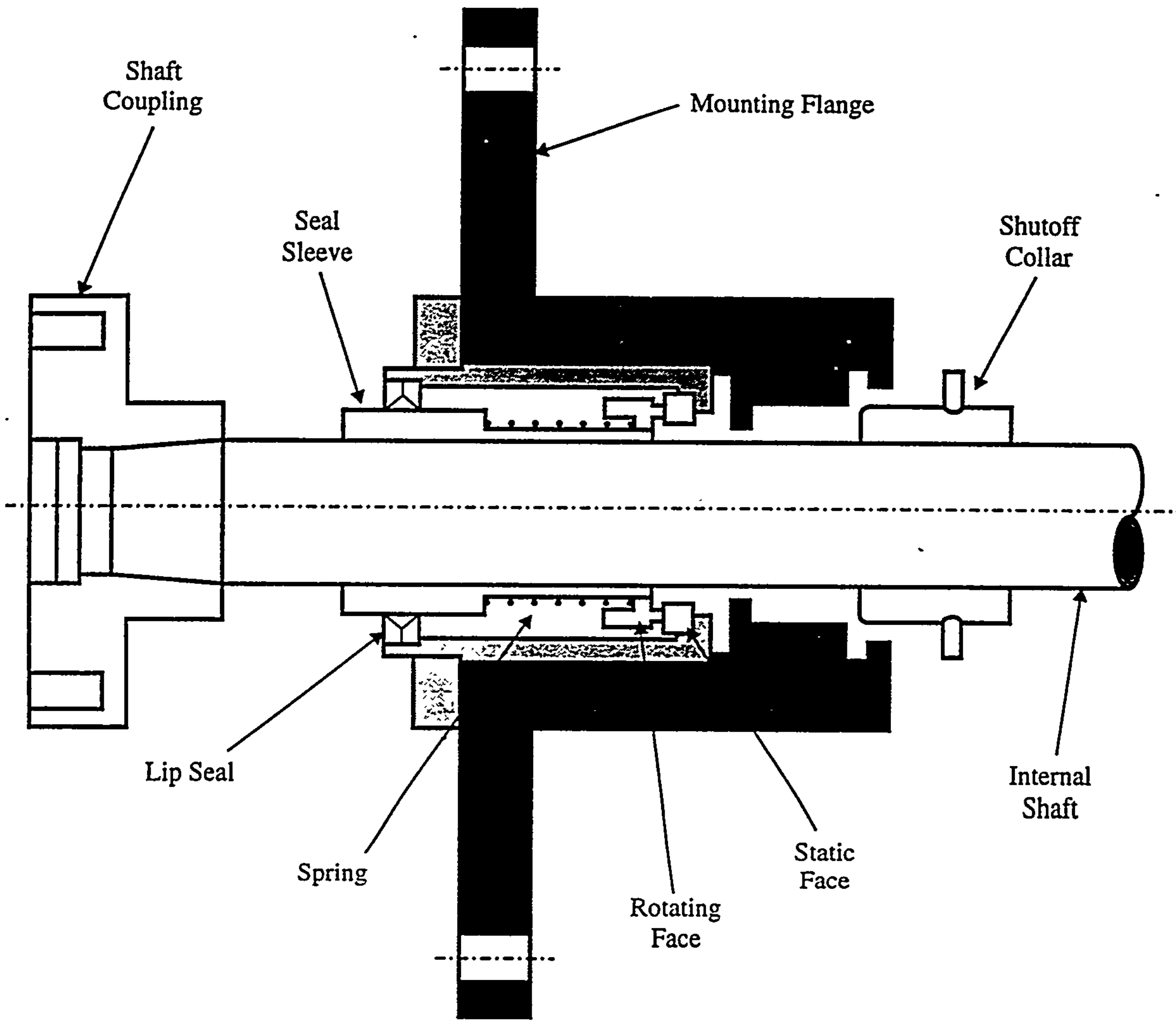


Figure 6-7. Mechanical Impeller Shaft Seal

6.2.3 Other Considerations

Other considerations include the number of agitators for each process vessel (redundancy), the use of tank baffles, and the arrangement of the agitators to provide the best performance. Also, the utility engineer should understand that agitators are designed for specific applications. For example, an agitator that performs well in a 40% solids slurry may have unacceptable vibration in a tank with 10% solids, especially during equipment startup.

Redundancy

Redundant top-entry agitators are not usually employed unless the tank is so large that the agitation requirements exceed the capacity of a single agitator. Top-entry agitators are relatively reliable, and, with the exception of the shaft and impeller, all mechanical parts can be replaced without draining the tank. Most agitator specifications include the provision that the agitator must be able to re-suspend material that has settled in the tank during a brief maintenance outage.

Side-entry agitators have less mixing capacity than top-entry types and most FGD reaction tanks require three or more agitators. As stated previously, if shaft shut-off collars are used, all components, except the internal shaft and impeller, can be replaced with the tank full. Tests have shown only minimal solids buildup when one of the three agitators is out of service for a short time (6), and these solids typically can be re-suspended when the agitator is returned to service. For these reasons, it is very uncommon to require the installation of a spare side-entry agitator.

Tank Baffles

Baffles are narrow, vertical, flat plates mounted on the tank walls. The typical application has four baffles equally spaced around the circumference of the tank. Baffles reduce swirling and vortex formation by improving the flow pattern throughout the tank, as shown in Figure 6-8. Baffles are almost always required in FGD tanks with top-entry agitators to help maintain a steady power draw by the agitator. Without baffles, a vortex will form in the tank centered on the agitator. This vortex can cause wide power variations and imbalance of the impeller, possibly resulting in agitator failure. Baffles are not normally required in tanks with side-entry agitators because the mixing patterns developed are less likely to form a central vortex.

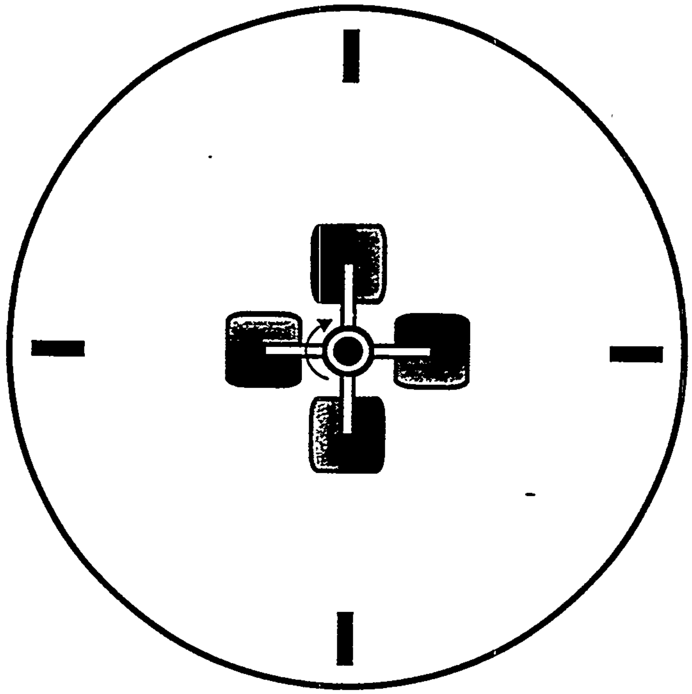
Where a single top-entry agitator is installed at the tank's centerline, the baffles are typically 1/12 the tank diameter in width and located 90° apart (1). In slurry tanks, baffles are usually spaced away from the wall at a distance equal to one-half their width to prevent solids buildup (2). In tanks with two or more top-entry agitators, four baffles are often located around each agitator, with none mounted on the walls.

Agitator Orientation

If a single top-entry agitator is used, it should be located in the center of the tank. Tanks with more than one agitator have them evenly spaced, so that each mixes a similar volume of liquid and their flow patterns do not interfere. Agitator spacing depends on factors such as impeller design and tank geometry and should be verified by scale-model testing.

Recent testing and full-scale installations have shown that "clustering" side-entry agitators into a 90° quadrant of the reaction tank provides improved performance when compared with even spacing (i.e., three agitators 120° apart). The optimum orientation was for all agitators to be angled down from horizontal and for the extension of their shaft centerlines to intersect at a point outside of the tank, as shown in Figure 6-9. The test found that the recycle pumps can be located anywhere opposite the cluster within an arc of 180° to 210° (5,6).

Top View



Side View

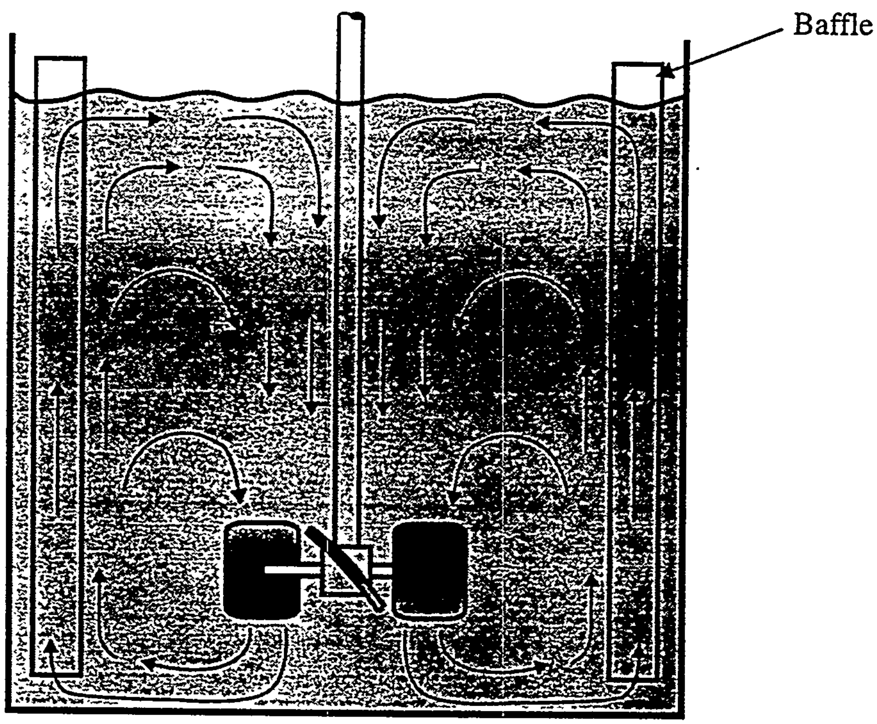


Figure 6-8. Flow Patterns in a Baffled Tank with Axial-Flow Mixer

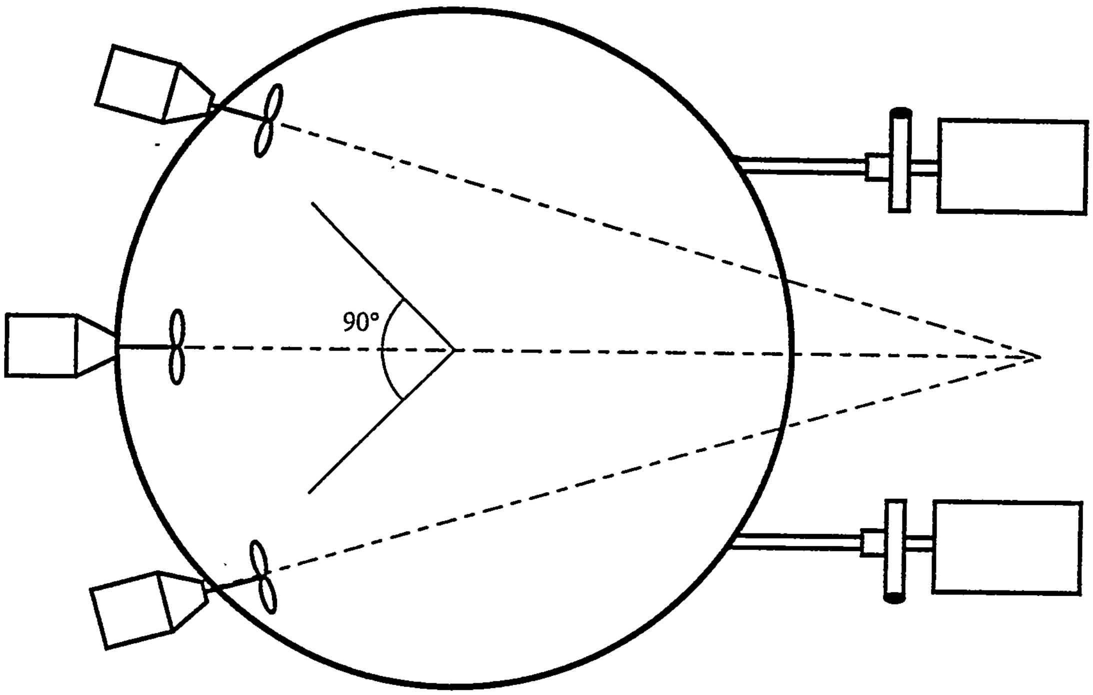


Figure 6-9. Side-Entry Agitator Orientation

6.3 Material Selection

For both top- and side-entry agitators, rubber-covered steel is the most common material of construction for the agitator internal shaft and impeller blades. Both natural rubber and chlorobutyl rubber are used in FGD applications. For applications on dual-fueled boilers (coal and fuel oil), where oil contamination of the FGD system process liquor is probable, natural rubber should not be used, and lead-cured neoprene may give better results than chlorobutyl rubber. Regardless of the rubber polymer selected, a Shore A hardness of 50 to 60 is typical.

The steel substrates of rubber-covered agitator shafts and impellers are typically carbon steel. High-strength low-alloy (HSLA) steels may be justified in some cases, especially for side-mounted agitators where the heavy, cantilevered impeller can impose a significant bending stress on the shaft, as discussed below.

Side-entry agitator shafts and marine propeller-style blades may be constructed of either rubber covered steel or alloy materials. Material selection for these components typically corresponds to the alloys selected for the reaction tank. Alloy selection is discussed in Part I, Section 5.6.1--Alloy Products and Corrosion Resistance. The resistance to erosion-corrosion is especially important in the selection of alloy impeller materials.

One additional factor that must be considered in the design of side-entry agitators is rotating-bending fatigue of the shafts. Side-entry agitator shafts are subjected to a significant bending load because of the cantilevered weight of the impeller. Low-carbon austenitic stainless steels typically have low resistance to rotating-bending fatigue, and may not be suitable for the shafts, depending on agitator design. Duplex or precipitation hardened stainless steels may be necessary in some cases.

6.4 Recommendations

- The proposed agitator impeller design and agitator orientation should be verified by scale-model testing or full-scale operation.
- Top-entry agitators should be designed with heavy-duty shafts and bearings. The drive should use a quill design.
- Side-entry agitators should use heavy-duty shafts and bearings and mechanical seals.

6.5 References

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2. Perry, R.H. and D.W. Green, eds. Perry's Chemical Engineers' Handbook, 6th ed. McGraw-Hill Book Company, New York, New York, 1984.

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4. Telephone conversation with Mr. Chris Cuprys of Philadelphia Mixers Corp., June 1995.

5. Philadelphia Mixers Corp. "Fluid Mixing: Optimizing the System and Scaling It Up." Palmyra, Pennsylvania, Brochure INPL-5M-4/94, 1994.

6. Hodel, A.E. "Cluster Agitator Arrangement Proves Best for Slurry Suspensions." Chemical Processing. June 1992.

7.0 PIPING

Piping within the FGD system is used to convey slurries, clarified process water (thickener/hydrocyclone overflow), mist eliminator wash water, service water, fire water, and, if used, chemical additive solutions. Design and material selection considerations for service water piping and fire water piping within the FGD system boundaries are no different than in other parts of the power plant, and will not be considered in this section.

7.1 Types Available

Piping within the FGD system can be classified in several ways. Most of the piping within an FGD system is external to the absorbers or ductwork, and only the inside surfaces are exposed to the FGD process stream. External piping requires little or no external protection. Piping such as that used for reagent spray headers, which is internal to the absorbers or ductwork, is exposed to the conveyed process stream on its inside surfaces, and to the process environment on its outside surfaces. Both environments must be taken into account in design of the internal piping.

All of the piping within the FGD system, both internal and external, conveys either clear water, slurry, or chemical additives. Table 7-1 describes the process streams typically conveyed by the FGD process piping system and indicates the typical operating conditions and slurry loadings.

FGD piping can also be classified according to material type. Guidelines for selection between material types is presented later in this section; but the basic material types must be defined before discussing design considerations. The types of pipe commonly used are the following:

- Carbon steel pipe (unlined);

Table 7-1

Process Streams Conveyed by the FGD Piping System

Process Flow Stream	Service Conditions		Aggressiveness*		
	Solids (wt%)	Temperature °C (°F)	Abrasive	Corrosive**	Scaling
Reagent slurry	25-40	<49 (<120)	3	1	2
Chemical additive	<5	<49 (<120)	0	2	0
Absorber recycle slurry	10-15	<60 (<140)	2	2-3	2
Thickener/hydrocyclone underflow	30-50	<49 (<120)	3	2-3	1
Thickener/hydrocyclone overflow	<10	<49 (<120)	0	2-3	1
ME wash water	<1	<49 (<120)	0	0-2	0

* Aggressiveness scale
  0 = minimal or none
  1 = mild
  2 = moderate
  3 = severe

** With respect to metals and alloys. Corrosiveness to nonmetallic piping is minimal or none.

- Rubber-lined steel for external applications, and rubber-lined, rubber-covered (RLRC) steel for internal applications;

- Corrosion-resistant alloys (including stainless steels, nickel-based alloys, and titanium);

- Glass fiber reinforced thermoset resin pipe (FRP); and

- Extra-high density polyethylene (EHDPE), an extruded thermoplastic pipe.

7.2 Design Considerations

7.2.1 Process Considerations

Table 7-1 provides information on the "aggressiveness" of the FGD process streams from the standpoint of abrasiveness, corrosiveness, and scaling tendency. Abrasiveness is a qualitative measure of the tendency of the process stream to cause erosive wear. The clear water streams, such as mist eliminator wash water and chemical additive feed, if used, are not abrasive. Likewise, the thickener or hydrocyclone overflow is generally not very abrasive if the solids separation efficiency is high. In the slurry streams, abrasiveness increases with solids loading, and the reagent slurry and thickener or hydrocyclone underflows are generally more abrasive than the recycle slurry. Corrosivity is a qualitative measure of aggressiveness toward the commonly used construction alloys, and does not apply to nonmetallic piping materials. Scaling is the tendency for deposition of layers or rings of mineral precipitates within the pipeline, particularly where process streams are blended or significantly cooled. Both corrosiveness and scaling tendency are strongly affected by process design decisions.

The process design decisions dictate the sizes and layout of the piping system, and the definition of the maximum chloride level constrains corrosion-resistant alloy selection if corrosion-resistant alloy piping is selected. The reagent type and preparation quality also affect piping design and material selection, as described later in this section.

7.2.2 Mechanical Considerations

The basic mechanical considerations for any piping system also apply to the FGD process piping. The piping design must be such that minimum and maximum velocities, discussed below, are maintained to keep slurries in suspension while minimizing erosion.

The piping must be adequately supported to withstand all dynamic and static loads. FGD systems typically contain long runs of piping handling large quantities of relatively dense slurry having considerable kinetic energy. The potential risk for damage by hydraulic hammer forces• is significant, and the design should expressly consider and minimize hydraulic hammer.

The motions and stresses created by differential thermal expansion should be carefully accounted for. Particular attention should be given to accommodation of relative displacements between transfer lines and their penetrations into the absorbers. The designer should remember that the coefficients of thermal expansion of FRP and extruded thermoplastic piping are considerably larger than those of steel. Particular care to accommodate the effects of thermal expansion are in order when designing piping systems of these classes of materials.

The manufacturer's design and installation guidelines for the specific products being used should be carefully reviewed and followed exactly, especially when designing nonmetallic piping systems.

• "Water hammer" or "hydraulic hammer" is a pressure shock wave created when the non-compressible water or slurry moving through a pipeline is suddenly halted, as, for example, by the sudden closing of a fast-action valve. The shock pressure increases with increasing fluid density, velocity, and length of pipe run upstream of the fast-action valve, and can potentially rupture the pipe system. Hydraulic hammer is best minimized by using surge tanks and eliminating fast-closing valves.

7.2.3 Other Considerations

Other factors that must be considered in designing FGD system piping include the following:

- Selecting flow conditions to minimize slurry abrasion;
- Sizing of pipe;
- Avoiding local flow accelerations;
- Pipeline cleanliness;
- Pipe burial; and
- Freeze protection.

Selecting Flow Conditions to Minimize Slurry Abrasion

The various slurries handled by the FGD process piping are potentially abrasive, and minimizing this potential abrasiveness is an important factor in FGD piping design. Abrasion limits the service life of nonmetallic piping through simple abrasive wear. Abrasion of alloys results in erosion-corrosion, the accelerated loss of material due to the synergistic effects of wear and corrosion. Without respect to the specific mechanism, damage due to abrasion will be referred to as abrasive wear in this discussion.

The abrasiveness of the slurry is a function of the kinetic energy of the particles, their hardness relative to the material being abraded, the incidence angle of the particles as they impact the abraded material, and the frequency of particle impact.

In pipeline operations, the incidence angle is low in most geometries and can be treated as a constant as a first approximation. All other factors being equal, the frequency of impact is proportional to the mass of particles per unit mass or volume of slurry, i.e., the weight percent solids in the slurry. From the above, it can be shown* that:

$$Abr = k \rho d_p^3 v^2 D_s \tag{7-1}$$

where:

Abr	= Abrasiveness, dimensionless;
k	= Proportionality constant;
ρ	= Density of the individual particles;
d_p	= particle diameter;
v	= Bulk fluid velocity; and
D_s	= Slurry particle loading (particle mass/unit slurry mass).

Equation 7-1 indicates that abrasiveness increases with particle density,** the cube of the particle size, the square of the fluid velocity, and the slurry particle loading. The relationship expressed by this equation demonstrates the importance of limiting velocities in slurry piping, specifying a finely ground reagent, and maintaining control of the reagent grinding process. At one facility, failure to maintain reagent grind quality shortened the life of stainless steel nozzles by a factor of 10 or more (5), and similar reductions in life could be anticipated in piping systems.

While increasing fluid velocity increases abrasion, decreasing the velocity too much also increases abrasion. Most of the slurries handled in well-run FGD systems will have particle diameters less than 200 μm. If the fluid velocity is sufficiently high, *homogenous flow* results, in which the particles are evenly dispersed in the liquid phase and have minimal contact with the pipe walls. This is the most desirable state from an abrasion standpoint, resulting in the lowest rate of abrasive wear, but it is costly and difficult to maintain.

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* Equation 7-1 is a composite of generally accepted erosion equations presented in References 1 through 4.

** The densities of the individual particles in FGD process slurries range from about 2.3 to 3.0 g/cm^3, and are little affected by process design decisions. The fact that the various particle phases are of similar density means that the flow velocities required to keep the particles suspended is similar for all FGD process streams.

If the velocity is reduced somewhat, the slurry develops *heterogenous flow*, in which the slurry particles are still suspended in the liquid, but slurry density is greater in the lower quadrant of horizontal pipe than in the upper. Heterogenous flow results in a slight increase in abrasion in the lower quadrant of horizontal pipe, and along the outside radii of elbows regardless of orientation, but is more economical to maintain than homogenous flow because less pumping power is required. FGD process piping is generally sized for bulk fluid velocities of 1.5 to 2.4 m/s (5 to 8 ft/s) to maintain heterogenous slurry flow.

If the velocity is allowed to drop below the critical transition velocity for heterogenous flow, corresponding approximately to the transition from turbulent to laminar flow, *saltation flow* occurs as the particles settle to the point that they begin to bounce along the bottom quadrant of the pipe, resulting in a significant increase in abrasive wear. *Sliding bed flow* occurs when the particles have fallen out of suspension and are rolled or dragged along the bottom of the pipe by the liquid phase. Sliding bed flow results in very high abrasive wear.

Particles larger than 200 μm generally cannot be maintained in homogenous flow regardless of velocity, and heterogenous flow is the best condition that can be obtained. Saltation flow and sliding bed flow of larger particles are increasingly difficult to avoid and are particularly damaging.

Sizing of Pipe

As described above, FGD piping is generally sized to maintain bulk velocities of 1.5 to 2.4 m/s (5 to 8 ft/s), though at least one system operate's slurry lines at 18.3 m/s (60 ft/s) (6). Specification of pipe sizes to maintain the desired bulk velocities is not as simple as it might be because of peculiarities in the way pipe size is denoted.

Pipe product sizes in the United States are denoted by the Nominal Pipe Size (NPS),* formerly designated as the Inch Pipe Scale (IPS). For NPS pipe sizes of 14 and above, the pipe size equals the outside diameter (OD), but this is not true of smaller pipe sizes. This makes providing metric equivalents of NPS pipe sizes difficult. Table 7-2 shows the metric equivalent of NPS sizes 2 through 24, as well as the actual outside diameters in inches and millimeters.

Far more important from a design standpoint is the internal diameter (ID), because the ID defines the relationship between bulk fluid velocity, volumetric flow rate, and pressure drop. The IDs of different pipe products having the same nominal ODs vary considerably. For example, while NPS size 4 pipe (approximately 102 mm nominal OD) of all materials will have the same actual outside diameter (4.5 in. or 114.3 mm), the internal diameter differs from material to material because of differences in wall thickness.

Figures 7-1 through 7-3 compare the capacities of pipe of different sizes and material according to three criteria:

- Relative volumetric flow as a function of pipe diameter at a constant bulk fluid velocity (Figure 7-1);
- Relative volumetric flow as a function of pipe diameter at a constant pressure drop (Figure 7-2); and
- Relative pressure drop as a function of pipe diameter at a constant volumetric flow rate (Figure 7-3).

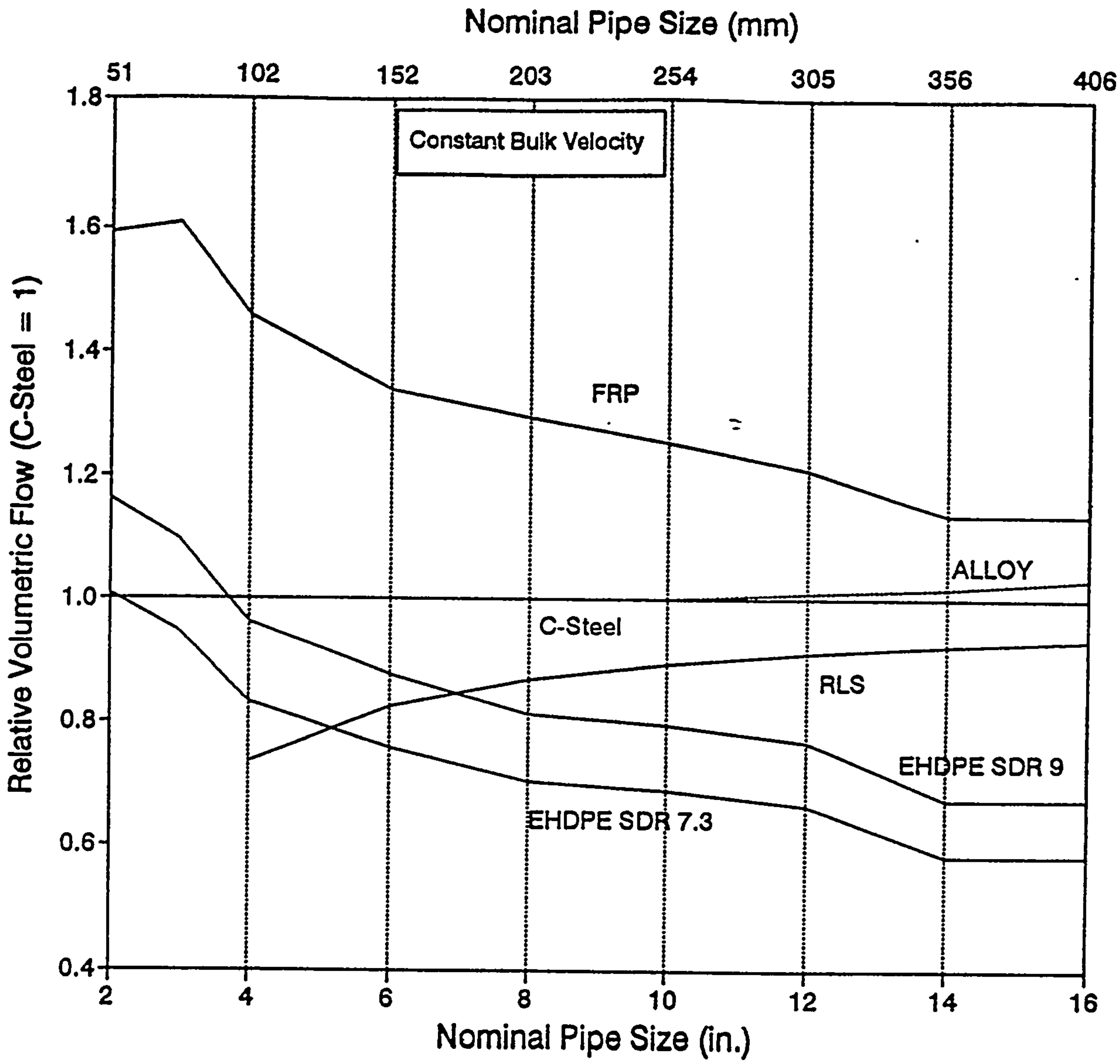
The equations for the curves in these figures were derived by normalizing a general equation for turbulent pipe flow with respect to Schedule 40 carbon steel pipe of the

* Nominal Pipe Size (NPS) actually designates the size of the die used to externally thread the pipe. All pipe of a given NPS size can be externally threaded with the same die.

Table 7-2

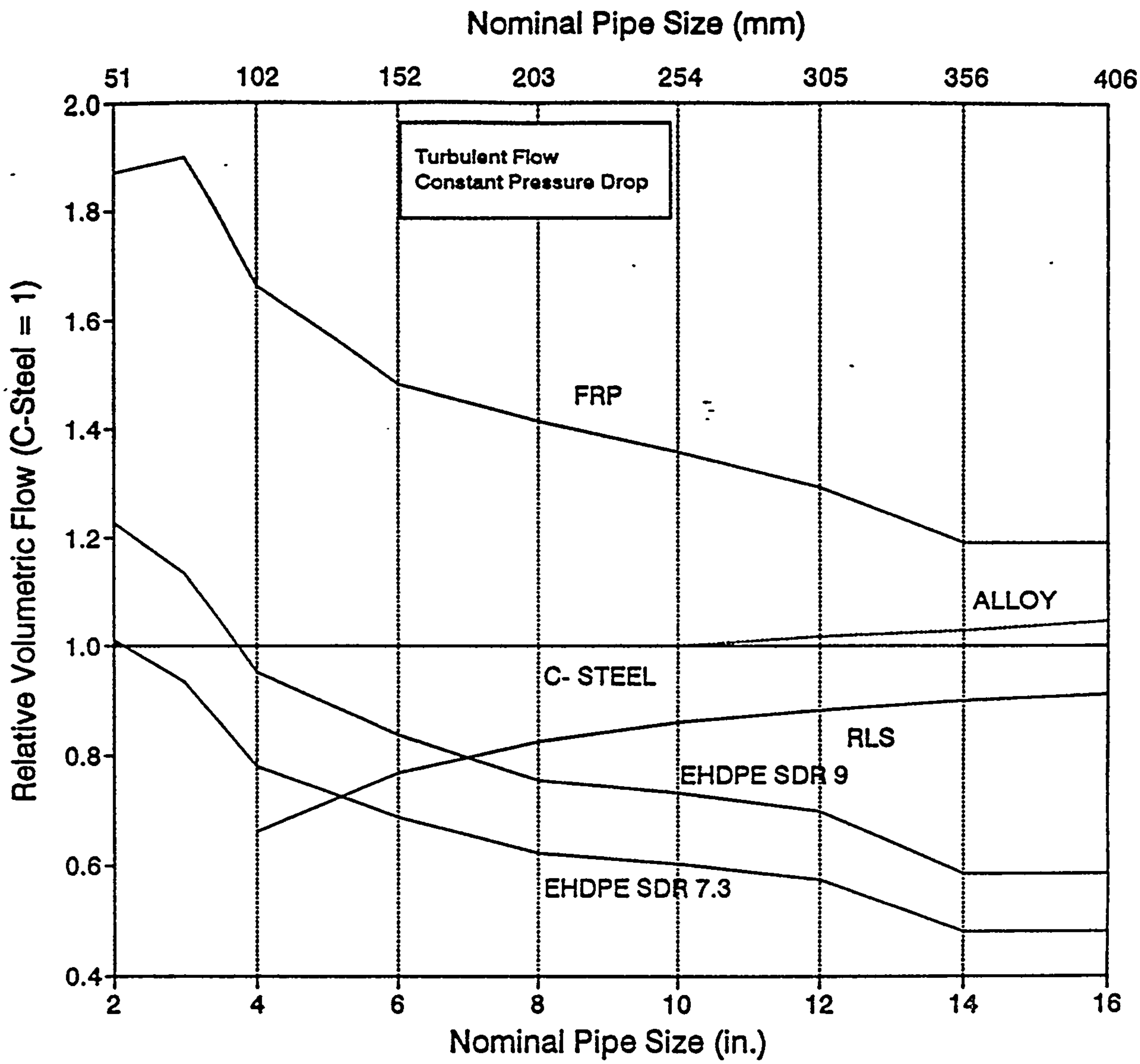
Nominal and Actual Pipe Sizes

Nominal Pipe Size		**Actual OD**	
NPS size	**mm**	**inch**	**mm**
2	51	2.375	60.3
3	76	3.500	88.9
4	102	4.500	114.3
6	152	6.625	168.3
8	203	8.625	219.1
10	254	10.75	273.1
12	305	12.75	323.9
14	356	14.00	355.6
16	406	16.00	406.4
18	457	18.00	457.2
20	508	20.00	508.0
22	559	22.00	558.8
24	610	24.00	609.6



C-STEEL = unlined carbon steel, Schedule 40
ALLOY = stainless steel, nickel-base alloys, or titanium
RLS = carbon steel with rubber liner
FRP = fiber-reinforced plastic pipe
EHDPE = extra-high-density polyethylene

Figure 7-1. Relative Volumetric Flow Rates of FGD Pipe Materials at Constant Bulk Velocity



C-STEEL = unlined carbon steel, Schedule 40
ALLOY = stainless steel, nickel-base alloys, or titanium
RLS = carbon steel with rubber liner
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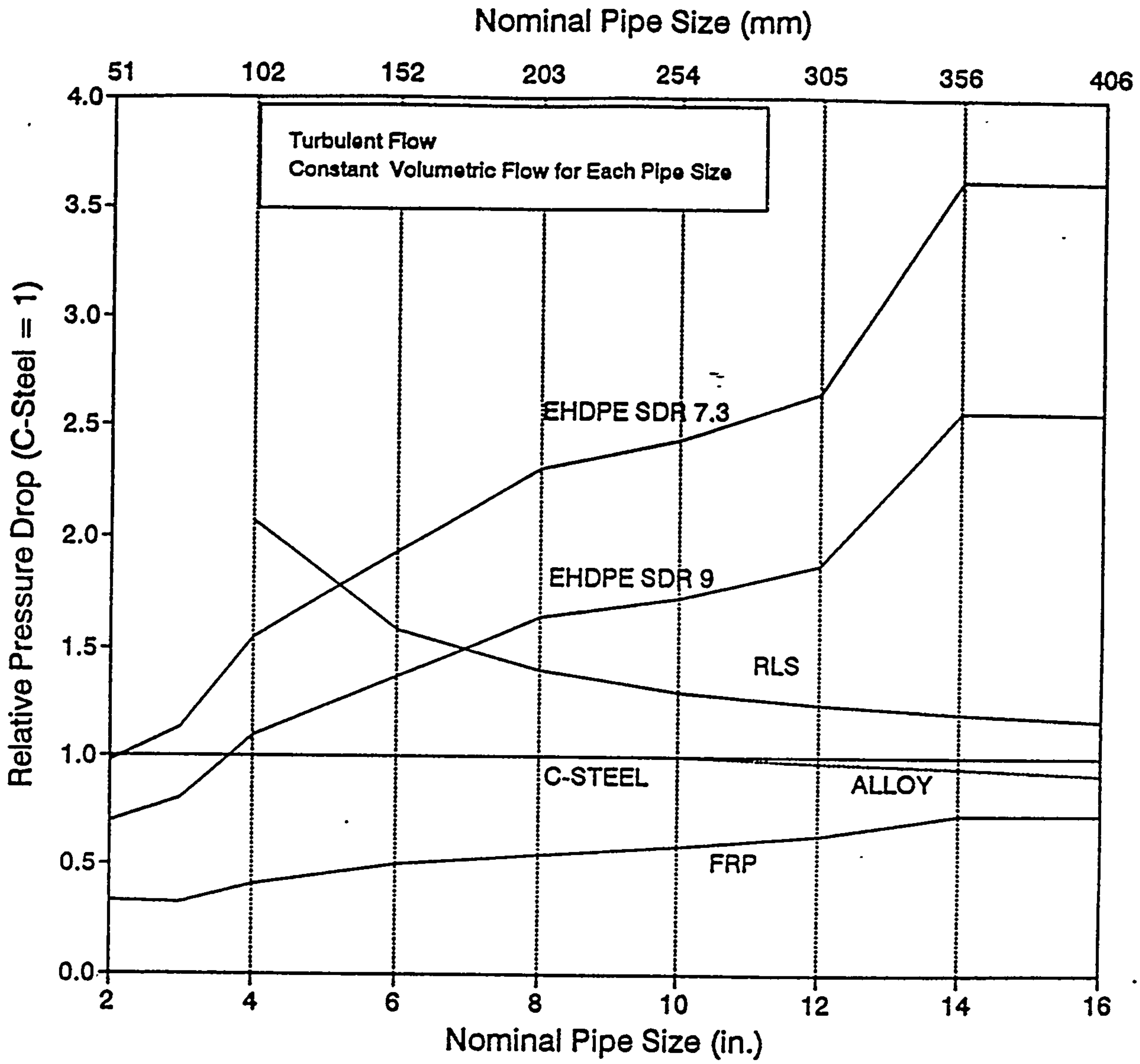
Figure 7-2. Relative Volumetric Flow Rates of FGD Pipe Materials at Constant Pressure Drops in the Turbulent Flow Regime



C-STEEL = unlined carbon steel, Schedule 40
ALLOY = stainless steel, nickel-base alloys, or titanium
RLS = carbon steel with rubber liner
FRP = fiber-reinforced plastic pipe
EHDPE = extra-high-density polyethylene

Figure 7-3. Relative Pressure Drops of FGD Pipe Materials at Constant Volumetric Flow Rates in the Turbulent Flow Regime

same nominal pipe size.* The general equation for turbulent flow in a cylindrical pipe, taken from Reference 7, is:

$$\Delta P_f = k\ G^{1.76}\ \mu^{0.24}\ \rho^{0.76}\ D^{-4.76} \tag{7-2}$$

where:

ΔP_f = Pressure drop per unit length of pipe;
k = A proportionality constant which includes a correction for pipe roughness (friction factor);
G = Volumetric flow rate;
D = Actual inside diameter;
μ = Fluid viscosity; and
ρ = Fluid density.

Equation 7-2 is applicable to both metric and U.S. customary units of measure; only the value of the proportionality constant, k, would differ. The normalization assumed that the friction factor was material-independent, a reasonable first approximation. The dimensionless normalized equations are, respectively:

$$\frac{V_2}{V_1} = \left(\frac{d_2}{d_1}\right)^2 \quad \text{at constant bulk fluid velocity} \tag{7-3}$$

$$\frac{V_2}{V_1} = \left(\frac{d_2}{d_1}\right)^{2.70} \quad \text{at constant differential pressure} \tag{7-4}$$

* ANSI Standard B36.10 defines pipe dimensions according to nominal pipe size (NPS), actual OD, and wall thickness. The wall thickness is defined in terms of "schedules." Pipe of increasing diameter within each schedule has increasing wall thickness. Schedule 40 has the thinnest wall which can be threaded, and is the most commonly specified thickness of carbon steel pipe.

$$\frac{\Delta P_2}{\Delta P_1} = \left(\frac{d_1}{d_2}\right)^{4.76} \quad \text{at constant volumetric flow rate} \tag{7-5}$$

where:

ΔP	= Pressure drop;
d	= internal diameter; and
V	= volumetric flow rate.

The subscript "1" denotes carbon steel pipe, and the subscript "2" denoting the alternate pipe material.

Equation 7-3 is valid for any non-zero flow rate, while Equations 7-4 and 7-5 are valid only in the turbulent flow regime. As discussed above, slurry flow must be maintained in the turbulent regime to avoid severe abrasive wear.

Figures 7-1 through 7-3 show that rubber-lined steel pipe suffers a significant penalty in capacity compared to unlined carbon steel pipe because of the reduction in internal diameter resulting from the rubber lining. Therefore, the designer may need to specify a larger nominal pipe size when designing with rubber-lined steel pipe than when designing with unlined carbon steel pipe.

Extra-high-density polyethylene (EHDPE) pipe, an extruded thermoplastic, must have robust walls to withstand FGD operating pressures at normal slurry temperatures. Pipe dimensions for this product are defined by both the pipe diameter and the standard dimension ratio (SDR).* Figures 7-1 through 7-3 show the normalized flow and pressure drop parameters for the two SDRs most likely to be used in FGD applications. It is highly probable that larger nominal pipe sizes will be needed when designing with EHDPE or similar thermoplastic piping.

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* The standard dimension ratio is the ratio of the pipe outside diameter and the nominal wall thickness. For FGD applications, SDRs of 9.3 or less should be specified to avoid long-term creep failure.

On the other hand, FRP pipe has a larger relative capacity than Schedule 40 carbon steel at all diameters, and the designer can sometimes specify a smaller size of FRP pipe.

The designation "ALLOY" in Figures 7-1 through 7-3 refers to stainless steels, nickel-based alloys, and titanium. Schedule 40S was used to calculate the relative flows and pressure drops for alloy and titanium pipe. However, thinner-walled material is frequently specified to save money. This also has the effect of increasing the internal diameter for the same nominal pipe size.

Avoiding Local Flow Accelerations

The designer needs to be particularly aware of piping geometries and configurations which can lead to local acceleration of the slurry flow, since erosion associated with local acceleration is probably the most common cause of piping failure. In particular, abrupt reductions in diameter should be avoided and long-radius pipe fittings should be used.

Pipeline Cleanliness

Maintaining the internal cleanliness of pipelines is extremely important to process reliability. All sections of the pipeline should be inspected for foreign objects prior to startup and after outages. Such objects, in addition to causing pump or valve failure, can produce erosive failure of the pipe, whether it is carrying slurry or clear water. Pipe inlets should be protected by screens or sieves to prevent the entry of foreign objects or chunks of scale. Many FGD systems have been incapacitated by scraps of rubber liner that are drawn into the piping.

FGD process piping is subject to scaling if the slurry supernatant becomes supersaturated as a result of mixing of process streams, decreasing temperature, or evaporation. Even minor scaling can drastically increase the amount of pumping effort required to maintain flow.

Scale will have the greatest tendency to adhere to rubber-lined, carbon steel, and alloy piping; a lower tendency to adhere to FRP piping; and the least tendency to adhere to extruded thermoplastic piping such as EHDPE.

The risk of scaling and plugging of slurry lines is greatly increased if the lines are allowed to "silt up" during outages when the slurry settles and may become cemented by precipitating minerals. All FGD slurry piping should be designed with provisions for purging at design velocities with clear process water. All piping should be designed so that it can be drained during major outages.

It is also desirable that long runs of slurry line piping in FGD systems, such as lines running to and from ponds, be designed with provisions for pigging.* Designing a piping system for pigging requires installation of pig launchers and catchers, and requires that there be no sharp turns in direction or reductions in internal diameter between pigging stations.

Carbon steel and alloy piping can be pigged with hard pigs equipped with brushes and scrapers. FRP and extruded thermoplastic piping should be pigged only with soft pigs. Rubber-lined piping should not be pigged.

* "Pigs" are devices inserted into and propelled through the pipeline to mechanically clean the interior surfaces of scale and deposits in a process called "pigging." The simplest pigs look like large rubber bullets. Pigs come in a variety of types and sizes and may be smooth or equipped with various scrapers and brushes. Pigs are either pushed through the piping by hydraulic pressure, or pulled through by a cable carried through the piping by a lightweight pilot pig.

Pipe Burial

Some of the FGD piping is commonly buried, either directly within the soil or in culverts or lined trenches. Buried steel pipe requires protection against external corrosion, particularly where there is a potential for exposure to spilled FGD process liquids or road-salt runoff. At a minimum, the external protection should include an anti-corrosion barrier wrap or polyethylene coating. If practical, cathodic protection should also be applied, although cathodic protection of buried structures in a power plant environment can be difficult. The problem result from the proximity of the piping to the buried structures of other (electrically separate) systems, as well as large stray current fields from the plant's electrical grounding system. Corrosion-resistant alloy piping requires similar external protection when buried, especially if there is the potential for exposure to road-salt runoff.

Nonmetallic piping, such as FRP and EHDPE, does not require external corrosion protection when buried, but does require special protection against point loading by rocks in the backfill. This protection is achieved by the use of special backfills. These materials are also less resistant to external collapse, and their collapse strength limitations must be carefully considered. The manufacturer's product-specific design and installation guidelines should be reviewed and followed exactly.

One final consideration: EHDPE pipe is lighter than water and will float. Special weights must be attached to the pipe if it is run into or through ponds.

Freeze Protection

Entire FGD systems have been taken out of service for the long periods of time because of freezing of long slurry lines exposed to ambient winter weather conditions (8). While the lines in question were not susceptible to freezing during normal operations, line freezing did occur during a brief plant outage in very cold weather. Freeze protection should be considered for FGD process piping which might freeze in the event of upset or plant outage conditions. The need for freeze protection will depend on plant location and exposure of the piping to the elements.

Designers also should be aware that the gelation, pour-point, and pumpability temperatures of organic additive solutions may be significantly different than those of water.

7.3 Material Selection

Material selection considerations for carbon steel, stainless steel and nickel-based alloy pipe, titanium, FRP, and EHDPE pipe are summarized in Tables 7-3 through 7-8.

7.4 Recommendations

- Vinylester-based glass fiber reinforced-plastic (FRP) pipe is recommended for first consideration in most FGD applications external to the FGD absorbers.
- For slurry service the FRP must have an abrasion-resistant (AR) liner.
- FRP pipe with both an abrasion-resistant liner and abrasion-resistant outer coat is recommended for absorber spray header service *provided that* adequate protection from structural damage during maintenance activities can be assured by design. Alloy or rubber-lined rubber-covered steel piping is recommended if the headers cannot be fully protected from mechanical damage during maintenance activities.
- Slurry velocities must be adequate to maintain homogenous or heterogenous flow, but not so high as to cause severe high-velocity abrasion. For most materials of construction, the bulk velocity should not exceed 3.7 m/s (12 ft/s). Titanium is recommended for situations where slurry velocity will exceed 3.7 m/s (12 ft/s) up to 18.3 m/s (60 ft/s).
- EHDPE pipe may be attractive for long runs of buried thickener overflow or underflow piping to ponds or related points.

Table 7-3

Carbon Steel Pipe

Description	Carbon steel pipe generically described as black iron pipe.
Applications	Fire water, service water, mist eliminator wash water external to absorbers if ME wash water is service water.
Method(s) of joining	Welding, flanges, threaded connections.
Temperature limit	None within FGD operating temperatures.
Chemistry limits	Low TDS water with pH $\gtrsim$ 6. Reagent slurry in some systems.
Upper bulk velocity limit for slurry	Typically 1.5 to 2.4 m/s (5 to 8 ft/s).
Linear weight	Relatively high.
Friction factor	Medium.
Coefficient of linear thermal expansion	~11.8 μm/m-K (6.6 μin/in-°F).
Thermal derating of pressure limits	Nil within the FGD operating temperature range.
Thermal changes in intermittent support/anchor requirements	Little change from room temperature requirements.
Scaling tendency	Scale will tend to nucleate on and adhere to steel, particularly once corrosion has roughened the surfaces.
Piggability	Hard pigs with scrapers and brushes as well as soft pigs can be used.
Considerations not addressed above	None.

Table 7-4

Rubber-Lined and Rubber-Lined, Rubber-Covered Steel Pipe

Description	Carbon steel pipe lined with natural or chlorobutyl rubber for abrasion resistance. If used within absorbers, the pipe is also covered with rubber.
Applications	Rubber-lined pipe has been widely used to convey slurries within the FGD system. Rubber-lined, rubber-covered pipe is used as headers within the absorbers.
Method(s) of joining	Bolted flanges.
Temperature limit	93°C (200°F).
Chemistry limits	No chemistry limits. Exposure to oil is detrimental.
Upper bulk velocity limit for slurry	Typically 1.5 to 2.4 m/s (5 to 8 ft/s).
Linear weight	Slightly higher than steel.
Friction factor	Significantly higher than steel.
Coefficient of linear thermal expansion	~11.8 µm/m-K (6.6 µin/in-°F).
Thermal derating of pressure limits	Nil within the operating limits of the FGD system.
Thermal changes in intermittent support/anchor requirements	Little change from room temperature requirements.
Scaling tendency	Somewhat higher than steel.
Piggability	No.
Considerations not addressed above	► Very high levels of abrasion resistance. ► Over-tightening flanges can rupture the rubber liner. ► Should liner rupture occur, strong tendency for the liner to slough and then plug pipes, valves, and pumps. ► Liners have been sucked off the pipe walls at pump intakes with excessively low NPSH. ► Frequently necessary to select nominal pipe size one step larger than equivalent steel or alloy pipe to allow for the thickness of the rubber liner and increased pipe friction coefficient.

Table 7-5

Austenitic Stainless Steel and Nickel-Based Alloy Pipe

Description	Pipe of austenitic stainless steel or nickel-based alloys.
Applications	Primarily used as headers within absorbers.
Method(s) of joining	Welding, flanges. Threaded connections should be avoided.
Temperature limit	None within the operating limits of FGD systems.
Chemistry limits	Alloy selection dictated by chloride levels--see Part I, Section 5.6.1. Alloy selection should be dictated by the worst environment to which the pipe will be exposed.
Upper bulk velocity limit for slurry	Typically 1.5 to 2.4 m/s (5 to 8 ft/s).
Linear weight	Slightly higher than carbon steel.
Friction factor	Slightly lower than carbon steel.
Coefficient of linear thermal expansion	15.3 to 18.8 μm/m-K (8.5 to 10.4 μin/in-°F), grade dependent.
Thermal derating of pressure limits	Nil within the operating limits of FGD systems.
Thermal changes in intermittent support/anchor requirements	Nil within the operating limits of FGD systems.
Scaling tendency	Slightly lower than steel because pipe surfaces are smoother.
Piggability	Hard or soft pigs can be used. If scraper or bristle pigs are used, the scrapers or bristles must be austenitic stainless steel or nickel-base alloy.
Considerations not addressed above	Flange gaskets must be of the non-wicking type.

Table 7-6

Titanium Pipe

Description	Pipe of titanium grade 2.
Applications	Limited use as external piping where very high velocities must be accommodated.
Method(s) of joining	Welding, flanges. Threaded connections should be avoided.
Temperature limit	None within the operating limits of FGD systems.
Chemistry limits	Limits probably not encountered in most FGD applications.
Upper bulk velocity limit for slurry	Up to 18 m/s (60 ft/s).
Linear weight	58% of equivalent carbon steel pipe.
Friction factor	Slightly lower than carbon steel.
Coefficient of linear thermal expansion	~8.6 µm/m-K (4.8 µin/in-°F).
Thermal derating of pressure limits	Nil within the operating limits of FGD systems.
Thermal changes in intermittent support/anchor requirements	Nil within the operating limits of FGD systems.
Scaling tendency	Slightly lower than steel because pipe surfaces are smoother.
Piggability	Hard or soft pigs can be used. If scrapper or bristle pigs are used, the scrapers or bristles must be titanium, austenitic stainless steel or nickel-base alloy.
Considerations not addressed above	Flange gaskets must be of the non-wicking type.

Table 7-7

FRP Pipe

Description	Fiber-reinforced plastic pipe. Vinylester is the preferred resin. Pipe must have an AR lining. If used within the absorber, must have AR external coat as well.
Applications	Very widely used for slurry transport outside the absorbers. Used to a lessor extent for spray headers. Also usable for chemical additive transfer lines.
Method(s) of joining	Solvent bonding is the preferred method. Flanged transitions to other materials.
Temperature limit	93°C (200°F).
Chemistry limits	None as pertains to FGD operations.
Upper bulk velocity limit for slurry	Do not exceed 3.65 m/s (12 ft/s). Design velocities of 1.5 to 2.4 m/s (5 to 8 ft/s) typical.
Linear weight	11 to 14% of carbon steel.
Friction factor	Much lower than carbon steel.
Coefficient of linear thermal expansion	19.1 μm/m-K (10.5 μin/in-°F).
Thermal derating of pressure limits	30% reduction with temperature increase from 24°C (75°F) to 93°C (200°F).
Thermal changes in intermittent support/anchor requirements	Reduce maximum allowable spacing between anchors or supports by 14% at 66°C (150°F), 23% at 93°C (200°F).
Scaling tendency	Somewhat less than carbon steel.
Piggability	Soft pigs only.
Considerations not addressed above	▸ FRP pipe is easily damaged by point external loads. ▸ Particular care should be taken that FRP piping within absorbers not be used as load-bearing structures during maintenance. ▸ Walking on FRP piping or laying scaffolding planks across it can cause failure.

Table 7-8

Extra-High-Density Polyethylene (EHDPE) Pipe

Description	Extruded thermoplastic piping of extra-high molecular weight polyethylene.
Applications	External slurry transfer lines. Would be a good candidate for chemical additive lines.
Method(s) of joining	Thermal fusion. Special fittings for flanged transition to other materials.
Temperature limit	66°C (150°F) for pressurized service.
Chemistry limits	EHDPE is inert to the chemicals and constituents present in FGD process streams.
Upper bulk velocity limit for slurry	2.1 m/s (7 ft/s) for pipe under 10 inches (254 mm). 3 m/s (10 ft/s) for pipe between 10 inches (254 mm) and 28 inches (711 mm).
Linear weight	25 to 50% of the weight of equivalent carbon steel pipe.
Friction factor	Lower than steel pipe.
Coefficient of linear thermal expansion	162 µm/m-K (90 µin/in-°F).
Thermal derating of pressure limits	Severe; see **Figure 7-4**.
Thermal changes in intermittent support/anchor requirements	Requirement for support increases rapidly with decreasing temperature. Continuous support required at 150°F.
Scaling tendency	Scale has little tendency to adhere to this material.
Piggability	HDPE pigs only.
Considerations not addressed above	▸ The high coefficient of thermal expansion, coupled with material softening at FGD process temperatures, means that particular care must be given to anchoring and support. ▸ The extremely thick walls of EHDPE pipe relative to other options means that larger nominal pipe sizes must be selected.

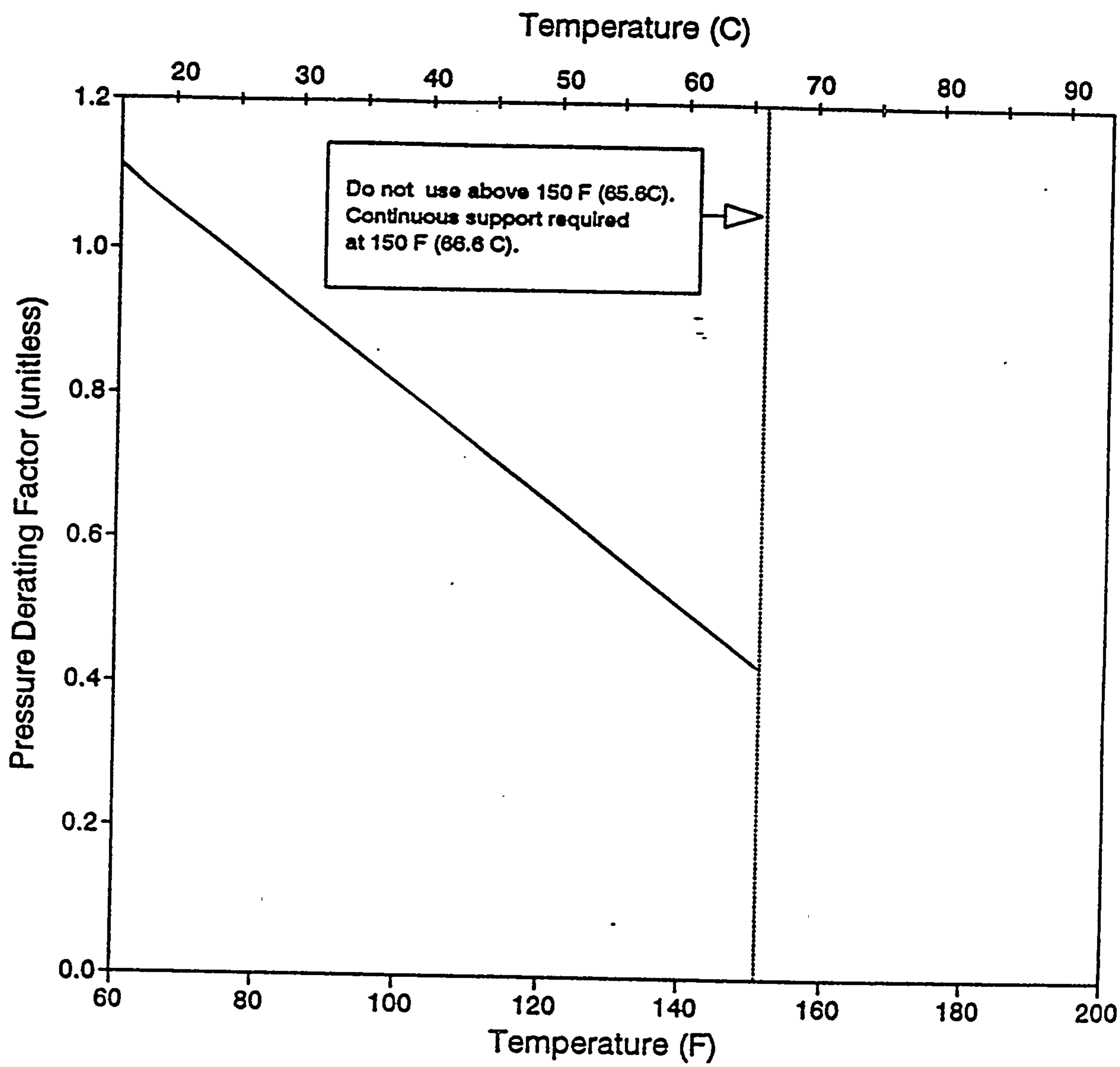

Figure 7-4. Pressure Derating Factor for EHDPE Pipe as a Function of Process Temperature

7.5 References

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8.0 VALVES

Like the flue gas dampers discussed in Part II, Section 4, the FGD system valves are used for two purposes: equipment isolation and flow control. Isolation (shut-off) valves are located throughout the various piping systems to permit isolation and maintenance of piping, pumps, tanks, instruments, and control valves. The use of control valves in FGD systems is more limited, and throttling service in particular is avoided as much as possible in piping systems handling abrasive slurries. In many cases, variable flow pumps, on/off valve operation, and other process alternatives are preferred over flow control valves to avoid excessive valve wear.

The types and designs of both isolation and control valves used in FGD systems are dependent upon the characteristics of the fluid handled. The service conditions present in several FGD process streams were presented in Table 7-1 in the Section 7.0--Piping (the previous section).

8.1 Types Available

Unlike flue gas dampers, of which there are only two basic types, a wide variety of valve types are used in an FGD system. All of the standard types of valves found around a power plant may be used in clear-water service [i.e., FGD system makeup water lines and mist eliminator (ME) wash water lines] within the FGD system. However, specialized valves are required for corrosive, abrasive, and scaling fluid services. Because the same valve types are rarely suitable for both isolation and flow control, valves of different types are frequently used in series to achieve both functions. The valves found in an FGD system generally are one of the following four types:

- Knifegate valves;
- Pinch valves;
- Butterfly valves; and

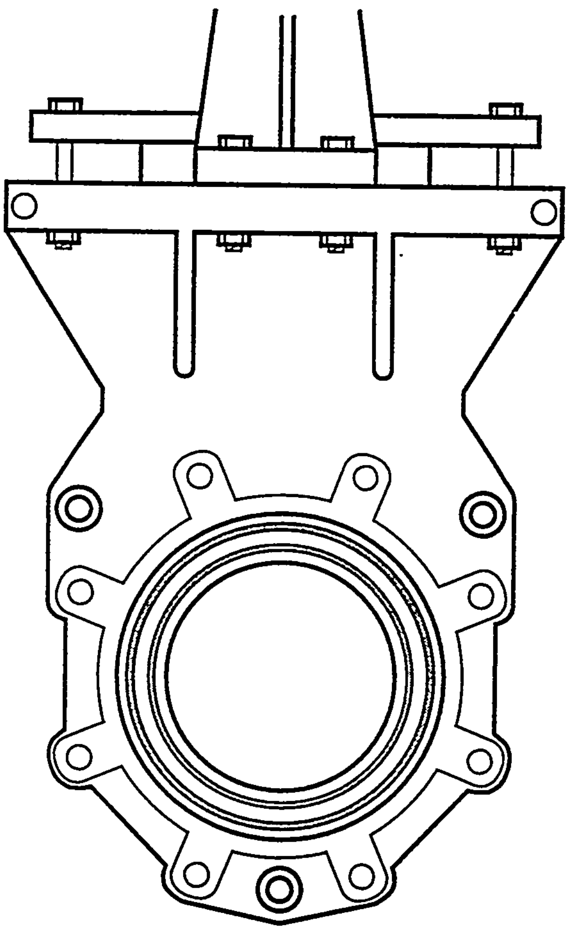
- Plug/ball valves.

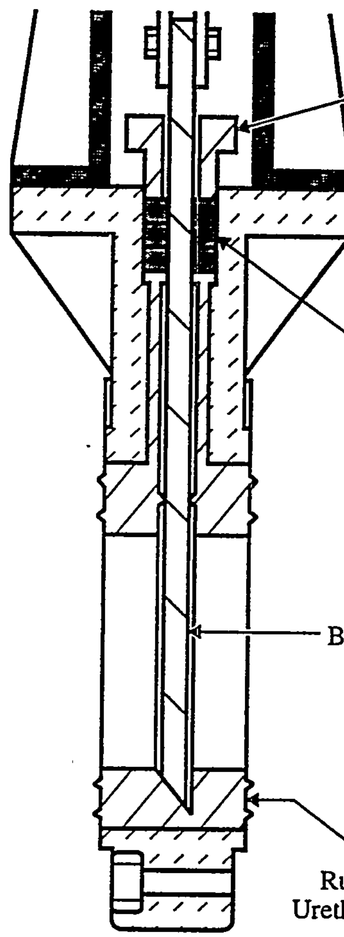
FGD system vendors typically base their designs around specific valve types, and even specific valve suppliers, on the basis of the operating experience at their existing FGD system installations. In some cases, the vendors have designed specialized valves for use in their systems to address unique or especially difficult operating conditions. Because of the very wide variety of these unique valve types, this manual will limit discussion to the four general types listed above. Additional discussions of valves used in FGD systems and other pollution control equipment is available from sources in the technical literature (1,2) and from valve manufacturers.

8.1.1 Knifegate Valves

A knifegate valve, shown in Figure 8-1, uses a thin blade of alloy steel to shear through any solids that may have deposited in the valve body. The knifegate valves used in first-generation FGD systems were typically standard, process water, knifegate valves and had blades that seated against an internal rubber gasket, as shown in Figure 8-1. These valves required packing around the blade entrance to prevent leakage. This packing was susceptible to damage when deposits on the blade were dragged though the packing material. Also, these valves were prone to leaking around the blade to the environment if the packing gland was not correctly tightened. In addition, solids deposition in the internal valve seats often prevented the blade from seating tightly, which resulted in fluid leaking past the valve into the isolated line.

Today, most of the knifegate valves used in FGD service are of the "packingless" type shown in Figure 8-2. The valve blade on this style of valve is completely withdrawn from the slurry when in the open position. The two pieces of the valve's internal liner are held tightly together with stiffeners to form a leak-tight seal. As the valve closes, the blade separates the mating liner faces around the entire periphery of the valve. In knifegate valve designs of this type, this sealing system results in a small amount of leakage





Cross-Sectional View

Figure 8-1. Knifegate Valve

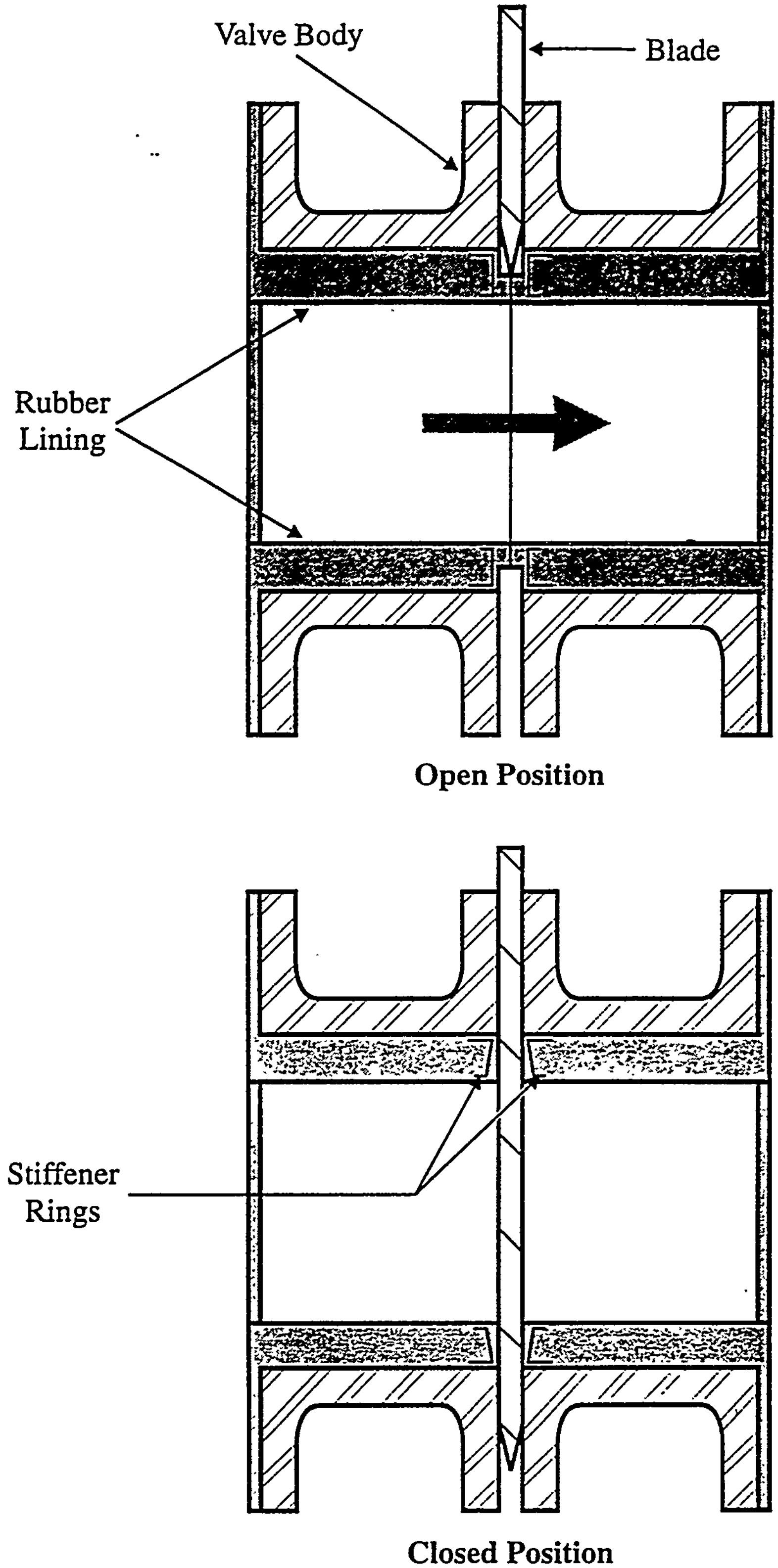


Figure 8-2. Cross-Section of a Packingless Knifegate Valve

when the valve is opened or closed; however, the leak volume is relatively minor and the design eliminates the potential that solids deposition could prevent the blade from closing. Unless otherwise stated, all of the following discussions of knifegate valves refer to the packingless type.

Knifegate valves are available for piping from less than 76 mm (3 in.) in diameter to over 1 m (39 in.) in diameter.

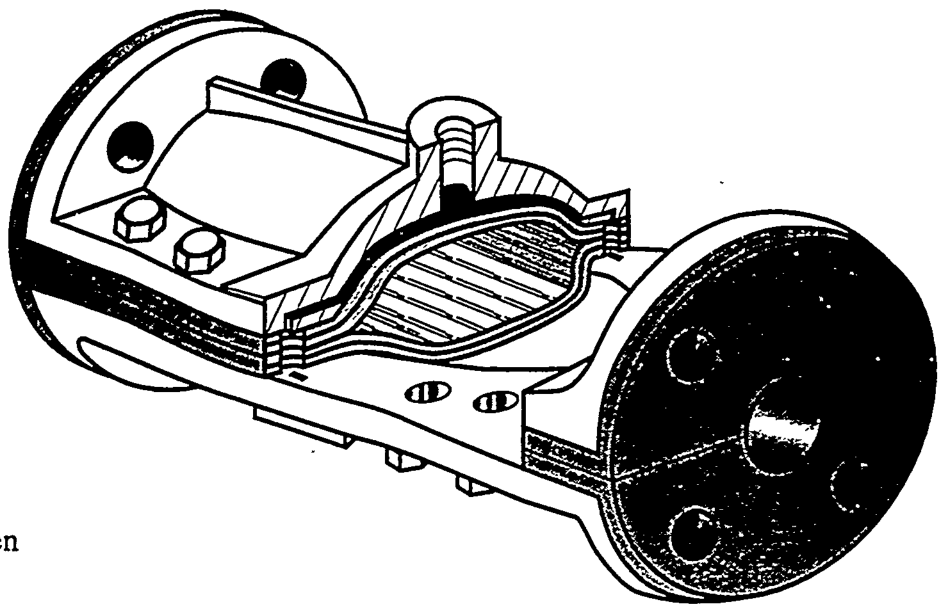
8.1.2 Pinch Valves

The term "pinch valves" describes a class of valves that use an elastic liner that collapses to "pinch" off the process flow. Valves in this class include pinch valves, diaphragm valves, and concentric-orifice valves, as shown in Figures 8-3, 8-4, and 8-5, respectively. The valve closure force may be manual, electric, pneumatic, or, less frequently, hydraulic.

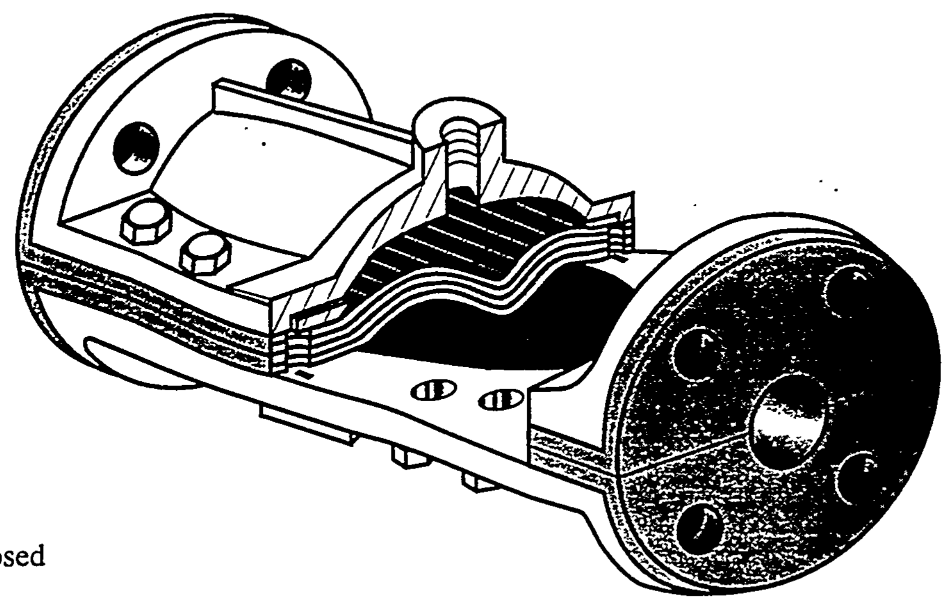
These valves are more limited in size than knifegate valves. The pinch and diaphragm type valves are available for piping up to 406 mm (16 in.) in diameter and the concentric-orifice valve is available for piping up to 203 mm (8 in.).

8.1.3 Butterfly Valves

The sealing elements of butterfly valves are disks that rotate on an axis transverse to the fluid flow, as shown in Figure 8-6. Rotating the disk varies the effective open area of the valve. The valve disk seats against seals around the periphery of the valve body. Additional seals are used at the blade shaft to prevent solids from entering this area. Because the disk and seals remain in the fluid flow at all times, these areas are subject to erosive wear, especially when the valve is nearly closed.



Open



Closed

Figure 8-3. Pinch Valve

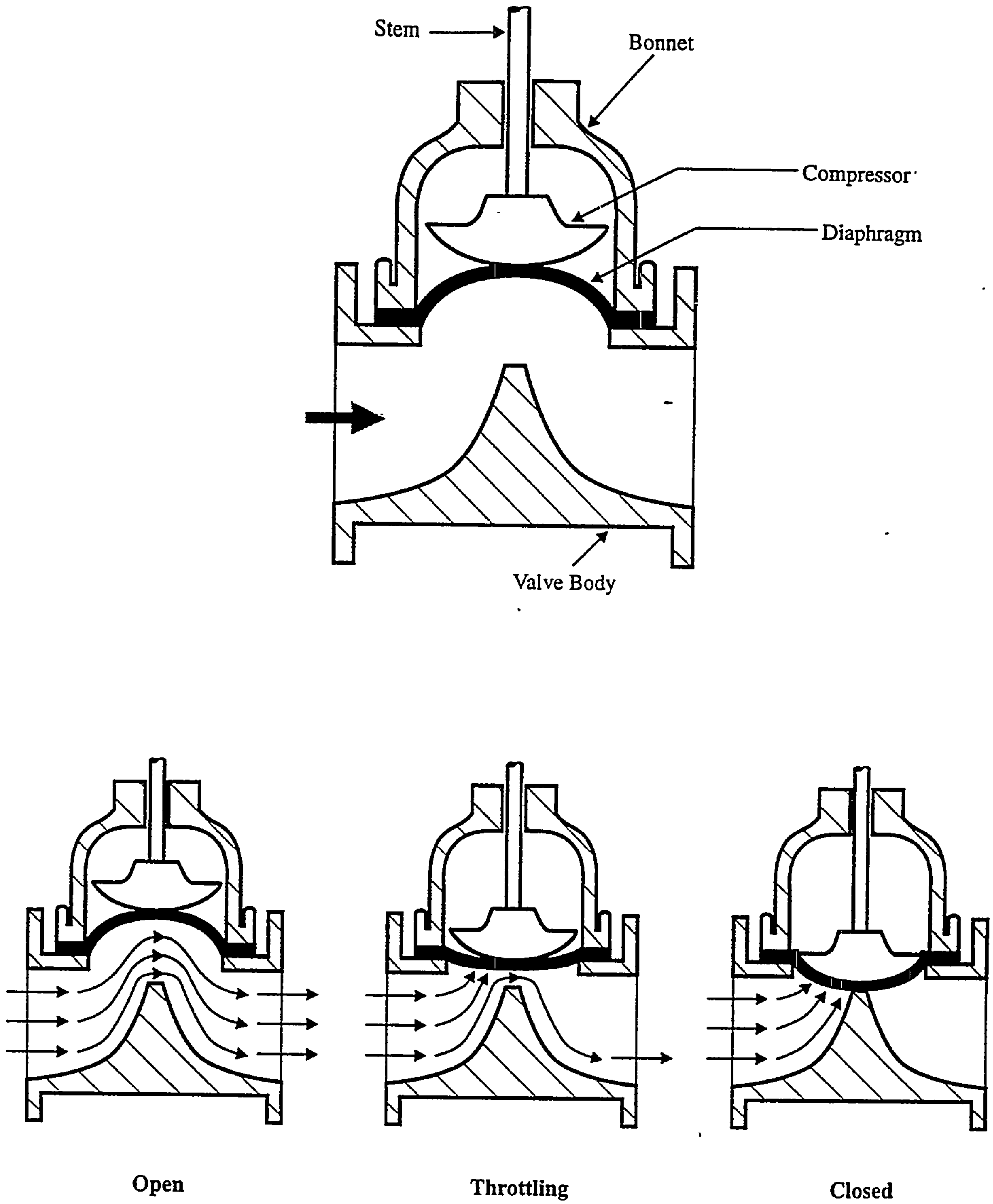


Figure 8-4. Diaphragm Valve

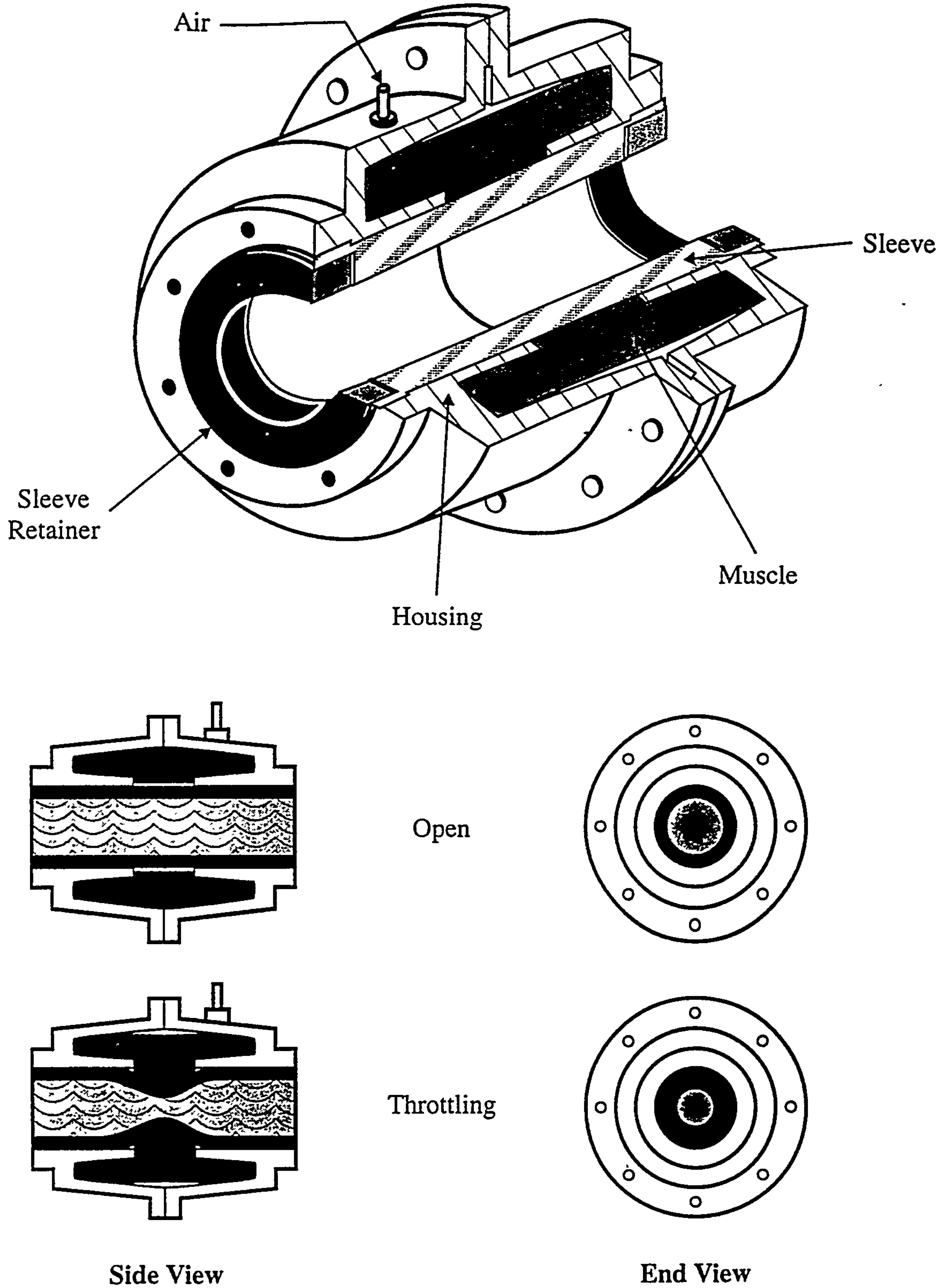
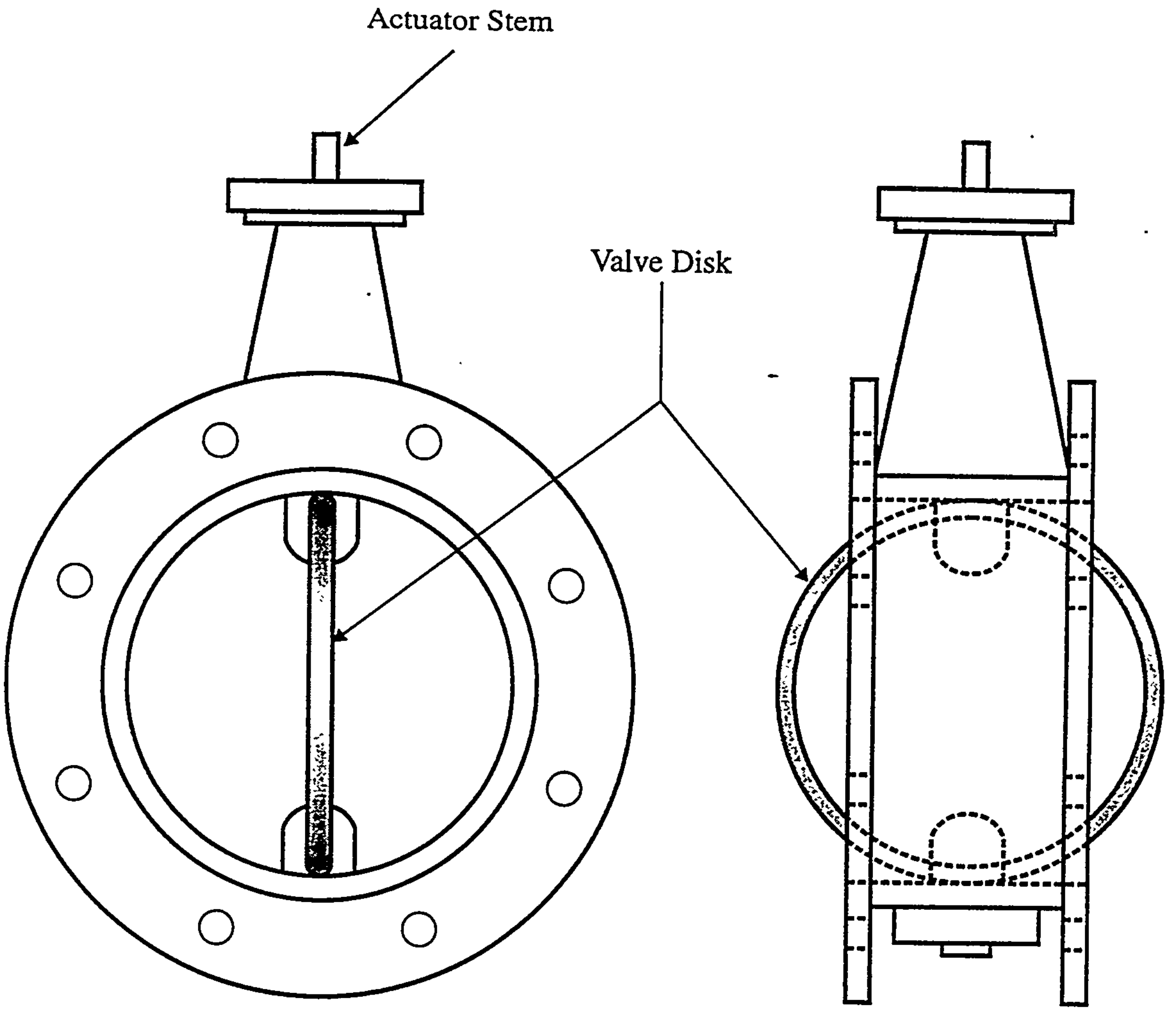


Figure 8-5. Concentric Orifice Valve
(Ref. The Clarkson Co., Reno, Nevada)



Valve shown in open position.

Figure 8-6. Butterfly Valve

Butterfly valves are available for piping diameters from less than 50 mm (2 in.) to over 1 m (39 in.).

8.1.4 Plug/Ball Valves

Plug and ball valves are very similar in their design, differing primarily by the shape of the internal sealing component (the valve plug). A plug valve uses a tapered conical plug with a generally rectangular flow passage, as shown in Figure 8-7; a ball valve uses a spherical plug with a circular flow passage. The shape of the flow passage may be varied by the valve manufacturer to enhance the performance of the valve in flow-control service. Seals are required around the plugs of both types to prevent the fluid from leaking past the plug.

Plug and ball valves are available for piping diameters from less than 50 mm (2 in.) to over 203 mm (8 in.).

8.2 <u>Design Considerations</u>

8.2.1 Process Considerations

The most important process considerations related to valve selection are the following:

- Valve service (isolation, flow control, or both);
- Fluid characteristics (abrasive, corrosive, scaling, or clear water); and
- Operational frequency.

Valve Service

The isolation and flow control characteristics of the four valve types in various process service conditions are presented in Table 8-1. Where a range of service suitability

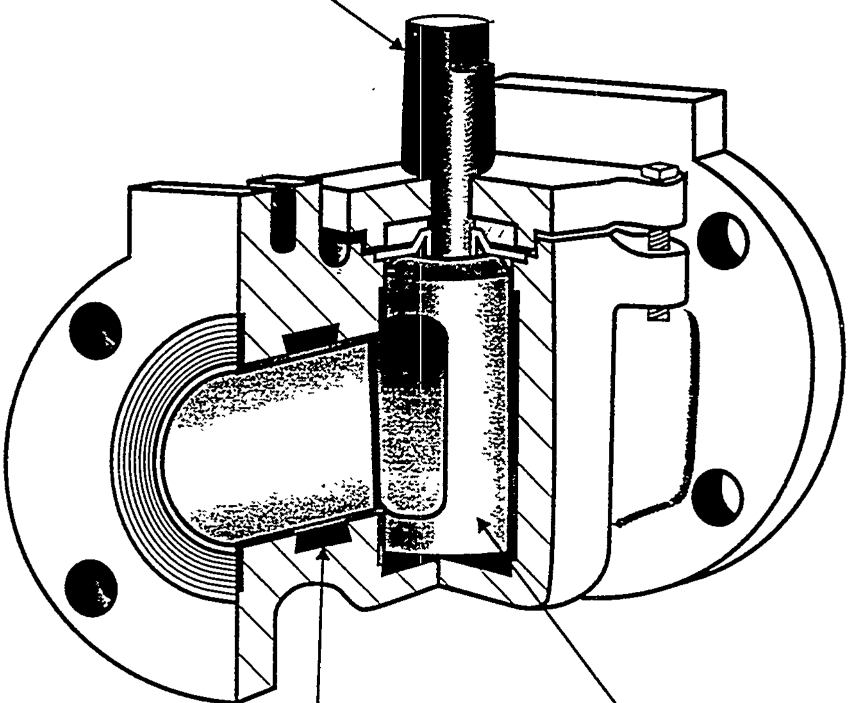


Figure 8-7. Plug Valve

Table 8-1

Valve Operating Characteristics

Valve Type	Service Suitability*							
	Clear Water		Abrasive		Corrosive		Scaling	
	Isolation	Control	Isolation	Control	Isolation	Control	Isolation	Control
Knifegate	3	0	3	0	0-3	0	3	0
Pinch								
Pinch	2	1	2	1	2	1	2	1
Diaphragm	3	2	2	1	3	3	2	2
Concentric-orifice	0	3	1	3	0	2-3	0	3
Butterfly	3	3	0-2	0	3	3	2	1
Ball/Plug	3	3	1-2	1-2	3	3	1	1

* Service suitability scale:
0 = unsuitable
1 = limited suitability
2 = suitable
3 = very suitable

ratings is indicated for a valve type, the appropriate rating depends on the specific service conditions. For example, a butterfly valve may be suitable for isolation service in the moderately abrasive conditions presented by the 10 to 15% solids slurry in the absorber module recirculation lines, but would be unsuitable for the same service in a limestone reagent slurry line handling an extremely abrasive, 30 to 40% solids slurry.

Knifegate valves are full-port valves that offer no restriction to the fluid when in the open position. These valves are very suitable for process isolation for any of the FGD process flows, but should not be used for modulating flow control.

All three pinch valve types are full-port valves that offer limited restriction to the fluid when in the open position. With the exception of the concentric-orifice type pinch valve, pinch valves are capable of tight shutoff, even on entrapped solids, and are suitable for isolation service. However, because the closure force must be maintained at greater than the process fluid pressure at all times, these valves have a lower service-suitability rating for isolation than knifegate valves. If the closure force is lost, due to low service air pressure for example, leakage past the valve is possible.

As noted in Table 8-1, pinch valves vary widely in their suitability to isolation and flow control service. Standard pinch valves are not frequently used for flow control in FGD systems because the high fluid velocities experienced when the valve throttles the flow can erode the elastic valve liner. However, the diaphragm-type pinch valve provides good flow control for clear process water and mildly abrasive slurries. The concentric-orifice valve was designed specifically for throttling service in abrasive slurries but cannot provide isolation service. The orifice of this valve contracts concentrically as the valve closes. The minimum flow through this valve at the smallest orifice diameter is approximately 20% of its maximum flow. When flow control and isolation are both required, a concentric-orifice valve must be coupled with a valve suitable for isolation valve service.

Butterfly valves and plug/ball valves can be used for both isolation and flow control services depending on the fluid characteristics, as discussed below. Both valve types have their highest suitability ratings for clear water and corrosive service.

Fluid Characteristics

Table 8-1 rates the suitability of the four valve types in relation to four types of FGD system process fluids: clear water, abrasive fluids, corrosive fluids, and scaling fluids. Examples of each of these process fluids were presented in Section 7.0--Piping. In general, all of the valve types are well suited to clear water service. Even standard knifegate valves with packing will perform satisfactorily in this service.

The suitability to abrasive fluids for these valves is related to the degree of abrasion present and the design of the valve. Any internal valve structures, locations of abrupt changes in fluid direction, and areas of high liquid velocity are likely to experience abrasive wear in proportion to the solids content of the fluid. As discussed in the section on piping, the most abrasive fluid handled in an FGD system is the limestone reagent slurry. Full-port valves such as knifegate valves are most suitable to isolation service with abrasive slurries. Some FGD vendors have experienced good performance from lined butterfly valves in absorber recirculation pump isolation service and in other moderately abrasive areas.

A valve's suitability to corrosive fluid service depends on the chemical characteristics of the fluid being handled. If the corrosive fluid being handled is a chemical additive such as DBA or formic acid, then a packingless knifegate valve would be unsuitable to the service because these valves leak when opening and closing, and such leaks would produce hazardous working conditions. However, if the corrosivity results from high chloride levels, as in a thickener overflow line, then packingless knifegate valves would be suitable. From chemical additive lines and other corrosive fluid lines where leaking cannot be tolerated, diaphragm, butterfly, and plug/ball valves are suitable for both isolation and flow control services.

No one specifically designs an FGD system to produce scaling fluids; in fact, considerable effort is expended in preventing scaling conditions from developing. Nevertheless, some FGD process fluids can become scaling under certain conditions. For example, the solubility of calcium sulfate decreases as the fluid temperature decreases. During the winter, the decant water from a gypsum stacking operation (which would be saturated with calcium sulfate and contain very few solids) may experience a temperature drop if the return pipe is located above grade and exposed to the wind. Under these conditions, the decant water can become scaling.

Suitability to scaling fluid service depends primarily on the method of sealing the valve. If the buildup of scale in the valve could prevent the valve from sealing, that valve would not be suitable for isolation service. Butterfly valves suffer from this problem. If scale could build up between the valve body and internal moving parts, the valve might not be able to open or close when needed. Both butterfly and plug/ball valves are susceptible to this mode of failure.

Operational Frequency

Operational frequency refers to how often the valve opens or closes. This process characteristic varies widely in the FGD system. For example, the absorber module recirculation pump isolation valves may remain in the open or closed position for several months or longer without being actuated. On the opposite end of the spectrum, each ME wash water valve opens and closes several times each hour. In flow control service, such as reagent slurry feed rate control, the valve position may be constantly changing or may change every few minutes. Frequent cycling reduces the potential for valve failure by scaling or solids deposition, but increases valve wear.

Knifegate valves are not designed for frequent cycling. The movement of the blade in and out of the mating body seals is the principal source of wear. Also, the small amount of leakage that occurs during opening and closing could become a maintenance nuisance if the valve is cycled frequently. For these reasons, knifegate valves are most often used in services where they do not cycle frequently. These services include pump isolation and tank drains.

Pinch valves are very suitable to frequent cycling but can also be used in normally open/normally closed service. The flexible linings used in this type of valve are the major wear part and are capable of several thousand cycles between failures. Diaphragm valves are often used in ME wash water lines because of their long life in cycling service and ease of repair. The flexible liner is relatively inexpensive and can be replaced in less than one hour. There is a concern regarding the use of pinch valves in normally closed service when the valves operate very infrequently. The elastic lining is normally in tension when the valve is closed. The lining, therefore, is much more prone to failure due to tears or stretching when left in the closed position. For this reason, pinch valves are not recommended for tank drain valves and similar, normally closed services.

Butterfly and plug/ball valves are well suited to frequent cycling. However, if left in the open or closed position for long periods of time (especially in scaling-fluid service), the internal valve parts may become frozen in position and actuation may become difficult or impossible.

8.2.2 Mechanical Considerations

The actual design of the valves used in an FGD system is the responsibility of the valve manufacturer and the FGD system vendor. However, when specifying valves for FGD service, the utility engineer must frequently set the maximum fluid velocity through the valve and the type of actuators that will be used.

Maximum Fluid Velocity

The maximum fluid velocity through the valves should consider the same ranges used in the sizing of FGD system process piping. Therefore, the valve size normally matches the size of the pipe in which it is installed. In some cases, however, smaller valves (with resulting higher fluid velocities) are used. This is most often seen in flow control valves, where a smaller valve may be used to obtain the correct flow control characteristics.

Type of Valve Actuators

Valve actuators can be manual, electric, pneumatic, or hydraulic. The type selected depends on factors such as the valve design, frequency of actuation, required actuation time, and actuation force required, as well as utility and vendor preferences.

Manually operated actuators are available for all four types of valves, but are limited to applications where the valve is infrequently actuated and actuation can be delayed until operating personnel can reach the valve. Examples of manually actuated valves are tank drain valves and maintenance isolation/bypass valves ahead of control valves or instruments. Even for infrequently operated valves, the valve type and size can preclude the use of manual actuators. Large knifegate valves in particular are very difficult to close manually. Even with mechanical gear drives to reduce actuation effort, it may take more than five minutes of concentrated effort to close a 305-mm (12-inch) valve.

Electric actuators are frequently applied to valves of all types in locations with poor accessibility and to valves that must be actuated remotely. Electric actuators may be either solenoids or electric motors. Solenoid actuators are limited to small valves such as those used for automatic drain and flush lines in slurry piping. Solenoid actuators do not have enough power to operate the knifegate valves used in the FGD system. Electric motor actuators are used for larger valves when the actuation force exceeds the capability of a solenoid. They are especially useful when the actuation force also exceeds the capability of a pneumatic actuator or when station air is not available at the valve location.

The majority of the FGD system process valves equipped with actuators use pneumatic actuators. Compared to electric motor actuators, pneumatic actuators are less costly and relatively more easily maintained. Pneumatic cylinders and electric solenoids are the preferred methods of actuating frequently operated valves such as the ME wash water valves. Pneumatic operators are also commonly applied to less frequently operated valves such as pump isolation valves, and piping flush and drain line valves.

The use of hydraulic valve actuators is generally limited to the very large absorber recirculation pump suction isolation knifegate valves. These valves may be 1 m (39 in.) in diameter or larger. The actuation force requirements of these valves may exceed the capability of pneumatic actuators. A hydraulic actuation system is typically lower in cost and less complicated than a comparable electric motor actuator. Although these valves are not frequently operated, they are commonly opened and closed remotely as part of an automatic pump startup/shutdown control logic. At facilities where more than three to five of these large valves are used, a dedicated, centralized hydraulic system is typically provided for these valve operators. Where fewer than three valves are used, it may be more economical to use individual hydraulic systems for each valve or to use a portable hydraulic system to actuate these valves.

8.2.3 Other Considerations

Another major consideration in the selection of a valve is its frequency of operation and ease of maintenance, repair, and replacement. A valve that will be frequently operated, such as an ME wash water control valve, should be easily accessible to maintenance personnel, and the valve type used should permit quick inspection and replacement of the parts most likely to fail. This is especially true for any valve that is used to control the flow of reagent feed slurry to the absorber modules because, regardless of valve type, these valves will require frequent maintenance.

Some valves and valve components can be very large and heavy (e.g., the knifegate blades on absorber module isolation valves). Accessways and room for temporary hoists are necessary at these locations.

At times it may be necessary to use a cleaning rod on a valve to break free or remove solids deposits that may have formed in the valve and associated piping. This maintenance activity is most commonly applied to slurry tank drain valves. Full-port valves such as knifegate and plug/ball valves are preferred for this service because the rodding operation is less likely to damage valve internals.

As discussed in the Section 7.0--Piping, some pipelines may be designated for periodic "pigging" to remove accumulated deposits. Valves used in such lines must be true full-port valves presenting no reduction at all in the pipe internal diameter. Not even all knifegate valves meet this requirement.

8.3 Material Selection

The materials used in FGD system valves depend on the characteristics of the process fluids to which they will be exposed. Most valves used in FGD systems are rubber-lined to withstand either abrasive or corrosive conditions in the reagent feed lines, absorber recirculation lines, and thickener/hydrocyclone underflow slurry lines.

The blades of knifegate valves are typically fabricated of stainless steel, although corrosion-resistant nickel alloys could also be used. In some knifegate valve designs, it is relatively easy to replace the valve blade with the valve still in service. In such cases, it may be more cost-effective to periodically replace the valve blade than to use a more corrosion-resistant and expensive material.

The flexible internal linings of pinch, diaphragm, and concentric orifice valves are available in rubber and a variety of other materials. The valve manufacturer should be consulted for a recommendation on the best material for the specific operating conditions. In erosive service, the body of a diaphragm valve typically is rubber-lined.

The disk of a butterfly valve can be fabricated from stainless steel or another corrosion-resistant alloy, or it can be lined with rubber or another corrosion/abrasion-resistant material. Stainless steels and corrosion-resistant alloys should not be used as disks in valves subjected to abrasive fluids. The reduced passage diameter of the butterfly valve increases the fluid velocity in the valve relative to the velocity in the connecting piping. The abrasion by the slurry solids can remove the protective oxide coating that protects the alloy from corrosion. Because the disk shaft is not typically exposed to erosive conditions, it can be fabricated from stainless steel or a corrosion-resistant alloy.

Plug/ball valves fabricated from stainless steel or nonmetallic materials are used in chemical additive lines where resistance to corrosion is the most significant concern. When used elsewhere in the FGD system, these valves typically have rubber-lined bodies with plugs that are encapsulated with a corrosion/erosion-resistant lining material.

As stated several times in this section, the control of the reagent feed slurry into the absorber modules is an especially difficult service. Some valve manufactures have developed special plug/ball valves for this service. These valves use special ceramic materials for the plugs to withstand the very high abrasive wear experienced by these valves.

8.4 Recommendations

- "Packingless" knifegate valves are preferred for equipment isolation service in abrasive and scaling conditions where the valve is infrequently operated.
- Pinch, butterfly, and plug/ball valves are preferred for flow control and frequently operated valves.

- If possible, flow control of abrasive slurries, such as the reagent feed slurry, should be avoided by on/off valve operation, variable speed pumps, or similar measures. When such slurry flow must be regulated, valves specifically designed for extremely abrasive service should be used.

- When used in slurry service, butterfly valves should be installed with the blade shaft in the horizontal position to avoid binding the blade in solids that may deposit on the bottom of the piping. The bottom of the valve disk should rotate in the downstream direction.

- True full-port valves must be used in pipelines that will be "pigged" to remove accumulated solids.

8.5 References

1. O'Keefe, William. "Valves and Actuators for Severe Service." Power. 135(8):13-22, 1991.

2. O'Keefe, William. "Pumps, Valves and Piping for Pollution Control Retrofits." Power. 136(3):19-42, 1992.

9.0 SPRAY NOZZLES

Spray nozzles are used to break up an FGD process liquid into small droplets to promote gas/liquid mass transfer, to wash deposits from absorber surfaces, to wash vacuum filter cake, or to cool the flue gas. The recommended nozzle type and materials of construction vary with the location in the FGD process and the characteristics of the fluid handled. In most cases, the type of spray nozzle used in each FGD application is selected by the FGD system vendors on the basis of their experience and the specific requirements of their systems.

9.1 Types Available

Three types of spray nozzles have been used in FGD systems: tangential nozzles, axial nozzles, and spiral nozzles. Examples of these nozzles and their spray patterns are shown in Figure 9-1.

9.1.1 Tangential Nozzles

Tangential nozzles usually produce a hollow-cone spray pattern where the majority of the spray forms a ring pattern downstream of the nozzle. The fluid is introduced tangentially to a swirl chamber and discharged through an orifice that is at right angles to the inlet. There are no internal parts in these nozzles, resulting in a free-passage diameter* approximately equal to the nozzle inlet diameter.

Tangential nozzles can produce a full-cone spray pattern if they have vanes in the closed end of the whirl chamber that deflect some of the spray into the center of a hollow-cone spray pattern. The free-passage diameter of these modified nozzles is equal to that of the hollow-cone tangential nozzle, but the spray droplets produced are larger.

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* "Free-passage diameter" corresponds to the largest diameter solid particle that can pass through the nozzle.

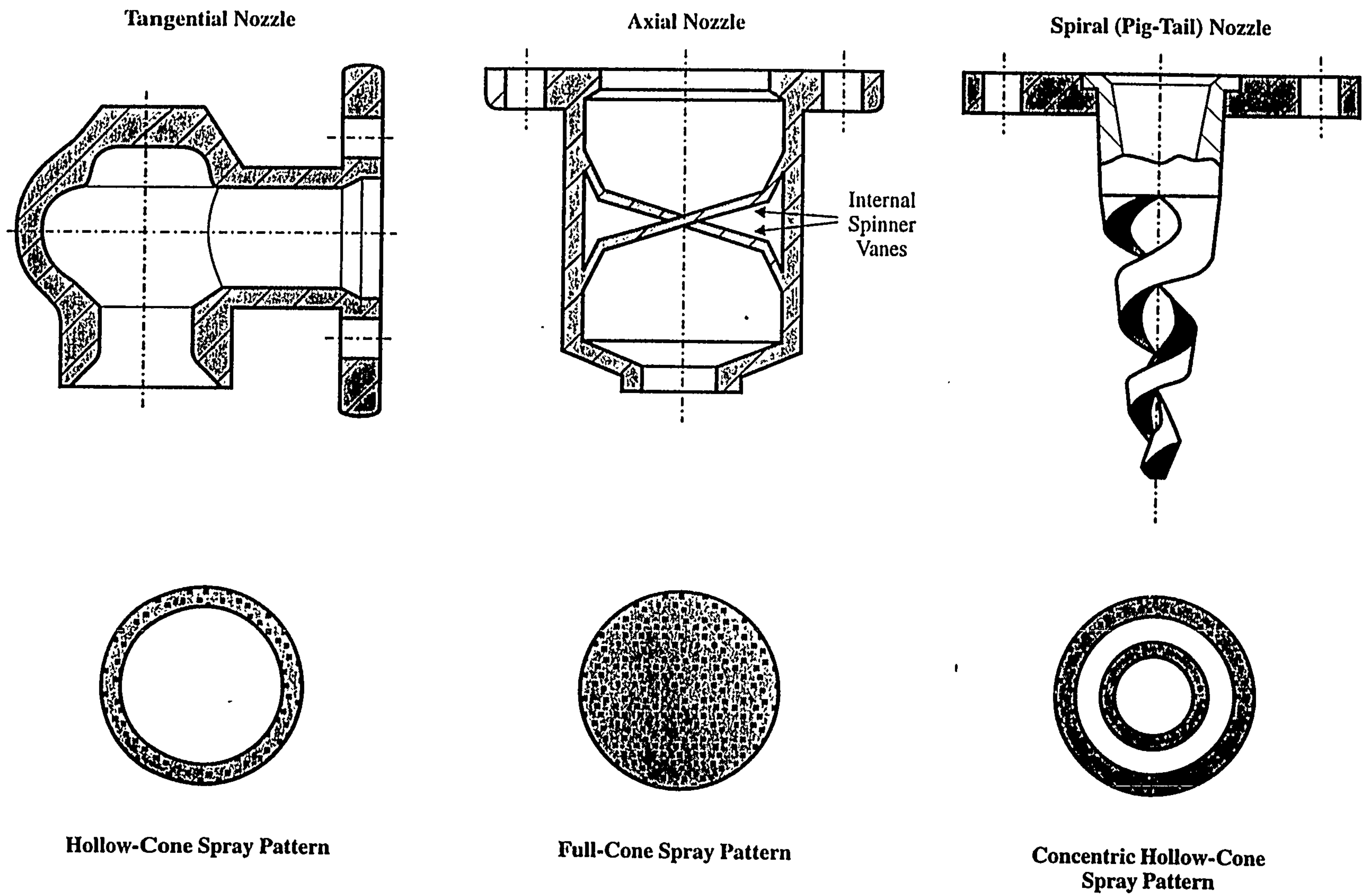

Figure 9-1. Spray Nozzle Types

9.1.2 Axial Nozzles

Axial nozzles produce a full-cone spray pattern. Internal spinner vanes impart a swirl to the slurry, which exits the orifice axially in line with the nozzle inlet. The free-passage diameter is usually significantly smaller than the nozzle inlet diameter, but approximately equal to the orifice diameter. An axial nozzle requires a lower pressure drop across the nozzle to produce the same droplet size as a hollow-cone tangential nozzle. At equal pressure drops, an axial nozzle produces a smaller droplet size than a tangential nozzle.

Filter cake wash nozzles are typically axial nozzles without internal spinners. Instead, these nozzles use specially designed nozzle tips and orifices to concentrate the spray in a full-cone, flat spray pattern. A typical spray pattern for these nozzles might be 50 mm (2 in.) wide by 305 mm (12 in.) long.

9.1.3 Spiral Nozzles

Spiral nozzles (also called "pig-tail" nozzles because of their shape) produce a series of concentric hollow-cone spray patterns. As in the axial nozzle, the fluid inlet and outlet of a spiral nozzle are on the centerline of the nozzle; however, the nozzle contains no internal spinner vanes. Instead, the body of the nozzle is formed into a decreasing-diameter spiral that shears the fluid into two or more concentric spray rings. In some spiral nozzles, the concentric rings are close enough to form an essentially full-cone spray pattern. The orifice diameter is the free-passage diameter and is typically less than the nozzle inlet diameter. A spiral nozzle produces approximately the same droplet size distribution as a hollow-cone tangential nozzle, but at a lower pressure drop. Higher flow rates are possible with a spiral nozzle than with an axial flow nozzle at the same pressure, but the spiral nozzle may be structurally weaker and more prone to breakage during absorber maintenance.

An extra-passage type spiral nozzle provides greater free-passage diameter than a standard spiral nozzle because it has fewer spiral turns. However, because of the fewer spiral turns, an extra-passage nozzle produces larger droplets.

9.2 Design Considerations

9.2.1 Process Considerations

Five categories of spray nozzles are used in FGD systems:

- Absorber slurry spray nozzles;
- Absorber slurry flooding nozzles;
- Mist eliminator (ME) wash nozzles;
- Vacuum filter cake wash nozzles; and
- Flue gas quench spray nozzles.

These spray nozzles can be further categorized by their spray patterns, as shown in Table 9-1.

High-pressure, absorber slurry spray nozzles are installed in the open spray section of countercurrent absorber modules (See Part I, Section 4.2.1--Absorber Design Alternatives for descriptions of the different absorber module types). These nozzles must generate large numbers of very fine droplets in order to produce the required liquid surface area for gas/liquid mass transfer. Typically, droplet diameters for the slurry spray nozzles are

Table 9-1

Spray Nozzle Types and Service Conditions

Service	Fluid	Pressure, kPa (psi)	Spray Pattern
Absorber spray	Slurry	48-103+ (7-15+)	Full-cone or hollow- cone
Absorber packing flooding	Slurry	7-70 (1-10)	Full-cone
Mist eliminator wash	Clear water	275 (40)	Full-cone
Vacuum filter cake wash	Clear water	138-275 (20-40)	Full-cone (flat spray pattern)
Flue gas quench	Clear water	275 (40)	Full-cone or hollow-cone

in the range of 2500 to 3000 μm Sauter mean diameter.* Both full-cone and hollow-cone spray patterns are used in this service.

Low-pressure (flooding) slurry spray nozzles are installed in absorber modules that use packing for gas/liquid contact, such as cocurrent absorbers, tray absorbers, and dual-loop absorbers. It is not necessary to produce fine droplets above packing sections because the packing provides a majority of the surface area for gas/liquid mass transfer. The Sauter mean diameter for flooding nozzles can be as high as 5000 μm. Full-cone nozzles are required for this service in order to ensure full coverage of the packing material.

ME wash nozzles are utilized to remove entrained slurry from the ME blades as discussed in Part I, Section 4.4.6--Wash System Design Issues. Full-cone nozzles are used in this service in order to wash all ME surfaces. The production of fine droplets is not desirable for ME wash nozzles because fine droplets (less than 1700 μm in diameter) are more likely to be carried through the ME by the flue gas. ME deposits are removed either by the direct impact of the sprays or by the washing action of the water collected on the ME blades, and coarser droplets are suitable for both of these purposes.

Vacuum filter cake wash nozzles are used to spray fresh wash water that is low in dissolved solids onto the byproduct solids filter cake during secondary dewatering by a vacuum filter (see Part I, Section 4.8.2--Secondary Dewatering and Part II, Section 13--Vacuum Filters). The wash water displaces the process liquor from the filter cake reducing the filter cake's soluble salts content. In most cases, commercial-quality gypsum byproduct solids must be washed in order to meet the quality specification for soluble salts. The production of fine droplets is not required since the principal purpose of the nozzles is to evenly distribute the wash water across the entire width of the vacuum filter cloth.

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* There are many different droplet diameter characterization methods, each serving a specific process need. Sauter mean diameter is the most frequently used in FGD system design since it is based on surface area. The Sauter mean diameter is the diameter of a droplet having the same volume-to-surface area ratio as the total volume of all of the droplets produced to the total surface area of all droplets.

Flue gas quench spray nozzles are located in the inlet duct of each absorber module and are used only in emergency situations. If the absorber module slurry spray system fails (such as during a failure of the electrical power supply to the absorber recycle pumps), then water from the plant fire protection system will be provided to the quench nozzles to cool and saturate the hot [150°C (300°F)] absorber inlet flue gas. Quenching of absorber inlet flue gas is required to avoid damage to temperature-sensitive absorber internals such as absorber organic linings and ME blades. Either a hollow-cone or full-cone spray pattern is acceptable in this service.

9.2.2 Mechanical Considerations

The following mechanical considerations influence the design of spray nozzles:

- Number of nozzles/flow rate per nozzle;
- Droplet size;
- Spray angle;
- Spray coverage; and
- Nozzle attachment method.

Number of Nozzles/Flow Rate Per Nozzle

The number of spray nozzles and flow rate per nozzle are influenced by the quantity of flue gas to be treated and the desired SO_2 removal efficiency. The slurry flow rate to the absorber spray headers is based on the liquid-to-gas ratio (L/G) necessary to maintain the required SO_2 removal efficiency. The required L/G is determined on the basis of several factors, including the total droplet surface area available for gas/liquid mass transfer. This surface area is, in turn, dependent on nozzle type, fluid pressure, and flow rate per nozzle. Nozzles with larger flow rates reduce the numbers of nozzles required and provide larger free-passage diameters, but also produce larger droplets, reducing the total surface area and increasing the required L/G. Conversely, a large number of low flow rate nozzles reduces the required L/G, with the penalty of increased capital cost and reduced free-passage diameter. As stated earlier, most FGD system vendors have established their designs on the basis of operating experience, and the flow rate per nozzle used in their designs has been optimized using these considerations.

Droplet Size

As discussed above, the size of the droplets produced by absorber spray nozzles has a direct impact on gas/liquid surface area and, therefore, the required L/G ratio. The smaller the droplet, the larger the surface area provided by a given volume of slurry and the lower the L/G required to achieve a given total surface area. Droplet size is determined by nozzle design, nozzle flow capacity, spray angle, and pressure drop across the nozzle. As stated above, nozzles with higher flow rates produce larger droplets at a given pressure drop. Wider spray angles and increasing pressure drop across the nozzles produce smaller droplets. Test date are required to determine actual nozzle performance (i.e., droplet size) for specific operating conditions.

Nozzle Spray Angle

Nozzle spray angle is the angle formed by the spray cone leaving the nozzle. The spray angle may vary with nozzle design, but for most FGD system applications it should be between 90° and 120°. Wider spray angles reduce the number of nozzles required to attain the desired spray coverage. Typically, the selection of the best nozzle spray angle for a specific application is determined by the FGD system vendor on the basis of actual operating experience; however, for the ME wash nozzles, the spray angle should be 90° or less. If nozzles with spray angles of over 90° are used, then the angle of incidence of the wash spray with the ME blades may be too shallow to permit adequate penetration of the wash water along the full depth of the blade, and ME wash efficiency will suffer.

Spray Coverage

Spray coverage is estimated at a given distance from the nozzle outlets on the basis of the angle of the spray from the nozzle and the layout of spray nozzles on the spray header. In the absorber module, full spray coverage of the absorber slurry across the absorber cross section or over the packing is necessary to avoid maldistribution of absorber flue gas and areas of unwetted packing. Maldistribution of absorber flue gas and unwetted packing decreases the SO_2 removal efficiency of the absorber. Similarly, unwashed areas of an ME section result in pluggage of the unwashed area, excessive flue gas velocity in the remaining ME area, and high liquid carryover rates.

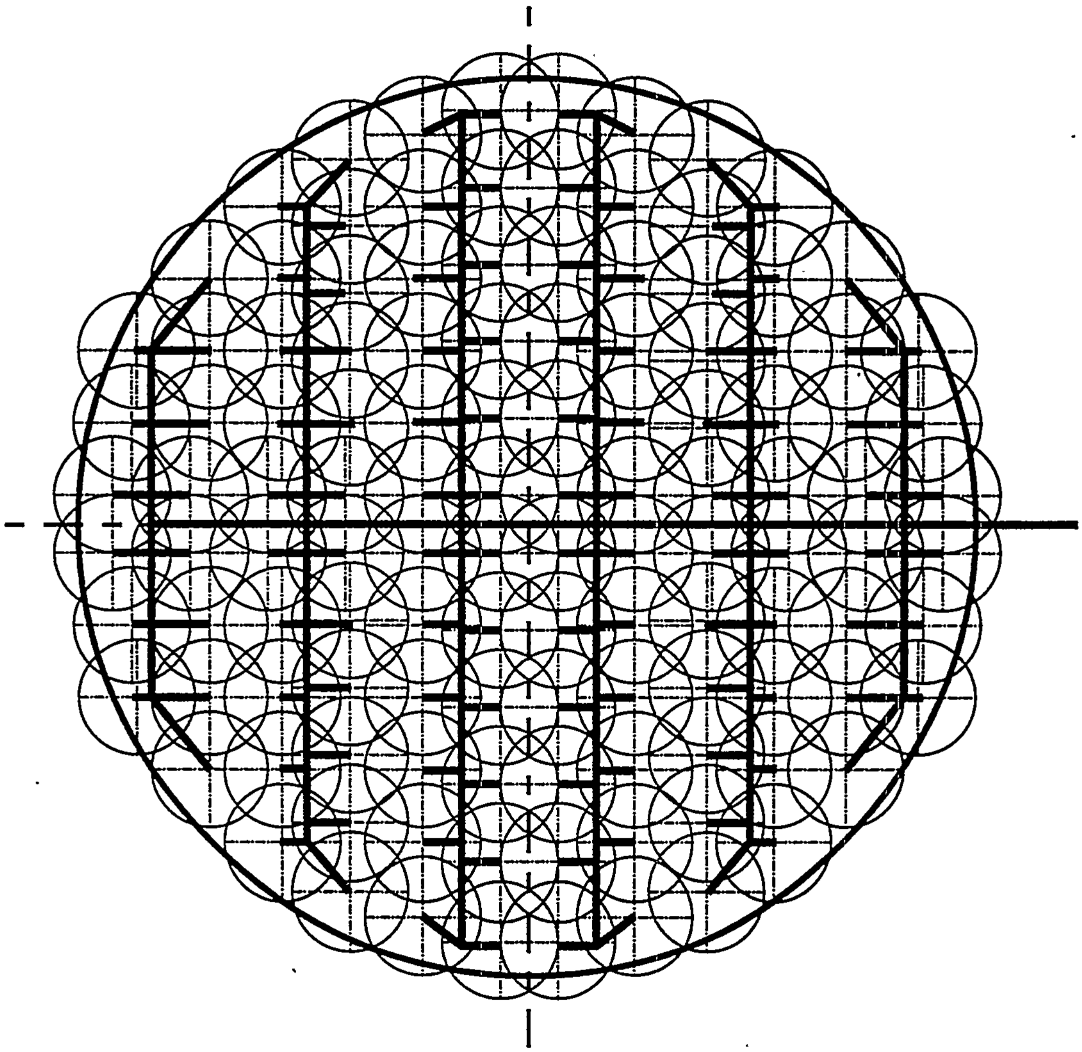
An example of a typical spray pattern coverage measured 1 m (3 ft) below the nozzle outlet is presented in Figure 9-2. As shown in this figure, a significant degree of overlap of the spray patterns was achieved at this distance. This overlap is designed into the system by the FGD system vendor through the selection of spray nozzle type and the nozzle positioning. The degree of coverage overlap is calculated by the following equation:

$$\text{Coverage} = \frac{N_{nozzle} \times A_{nozzle}}{A_{absorber}} \times 100\% \qquad (9\text{-}1)$$

where:

Coverage = Spray coverage overlap, %;
N_{nozzle} = Number of nozzles at a spray level;
A_{nozzle} = Spray area of a nozzle measured at a distance below the nozzle outlet, m^2; and
$A_{absorber}$ = Absorber module area measured at a distance below the nozzle outlet, m^2.

For absorber spray nozzles, the overlap is typically calculated at a distance of 1 m (3 ft) below the nozzle. For packing flooding nozzles and ME wash nozzles, the overlap is calculated at the packing/ME surface. In all of these cases, coverage overlap values of 200 to 300% are usually provided.



Coverage measured 1 m (3 ft) below spray header.

Figure 9-2. Example Absorber Spray Nozzle Coverage Overlap

Nozzle Attachment Method

There are four methods typically used to attach the spray nozzle to the header:

- Screwed attachment;
- Flanged attachment;
- Mechanical coupling attachment; and
- Bonded attachment.

Screwed Attachments--Screwed attachments are commonly used for the small ME wash nozzles, vacuum filter cake wash nozzles, and flue gas quench nozzles, but are seldom used for the larger absorber slurry spray nozzles. Typically the nozzles contain the male threads and the spray header contains the female threads.

Flanged Attachments--A flanged attachment uses bolted flanges on the spray header and nozzle, and is the most frequently used attachment method for absorber spray nozzles. The nozzles that were shown in Figure 9-1 use flanged connections. Typically, each flange uses four bolts with nuts and washers. Because the bolting will be subjected to the corrosive environment inside the absorber module, nickel alloy bolts, washers, and nuts are required.

Although flanged nozzle attachments are used by most FGD system vendors for absorber spray nozzles, this method has several problems. First, a large utility FGD system may have over 1000 absorber spray nozzles, which would require the use of 4000 alloy flange bolts. In addition to the high capital cost of this bolting, the numerous small parts are easily dropped during installation of the nozzles and can become a source of tramp material that damages the nozzles. Second, the flanges of ceramic nozzles may be damaged during installation of the nozzle if the bolts are over-tightened. Often this is the most common cause of nozzle damage. Third, if each nozzle's bolting is not tightened uniformly, a leak from the flange joint may result, producing a high-velocity jet of abrasive slurry that can damage adjacent equipment. It is very difficult to detect such leaks in advance. finally, even when alloy bolting materials are used, it can be difficult to loosen nozzle flange bolt nuts that have been in service for a prolonged period of time. Removing frozen nuts is another common cause of nozzle damage.

Mechanical Coupling Attachment--An alternative to flanged nozzle attachments is to replace the flange bolting with a mechanical coupling, such as a Vitaulic™ coupling. This coupling use a mechanical clamp to hold the nozzle to the header and is secured by a single bolt. The use of mechanical couplings requires slight modifications to the nozzle and spray header flanges. Two recent papers on the use of mechanical couplings for nozzle attachment reported that no nozzles were broken during installation at large utility FGD systems (1,2).

Bonded Attachment--In the past, permanent bonding of nozzles to the spray header has generally been avoided because it makes the replacement of nozzles difficult. With recent improvements in nozzle materials and designs, however, nozzle replacement is becoming less frequent. Adhesively bonded spray nozzles have been successfully used at Houston Power & Light Company's Parish Generating Plant since 1980 (2). Although specific repair methods must be implemented, the total cost of bonded nozzles may be significantly lower than the other alternatives (2).

9.2.3 Other Considerations

Spray coverage will decrease if nozzles become plugged with solids; therefore, it is important for spray nozzles to have a sufficiently large free-passage diameter to reduce the potential for pluggage. While most slurry solids are less than 100 μm, larger diameter solids are possible in an FGD system.

One significant source of these large-diameter solids is calcium sulfite or sulfate scale that can form in the absorber module or recirculation piping. When scale deposits break away, they can be carried through the piping to the spray nozzles.

Another source of large-diameter solids is large pieces of rubber from the linings used in the absorber module, piping, and slurry pumps. Delamination of rubber-lined slurry piping is a serious problem, because these pieces can be large enough to plug an entire branch of a spray header as well as individual nozzles.

A third source of large-diameter solids is tramp material left in the absorber module following maintenance. Tools, welding rods, nuts, bolts, and other debris have been removed from plugged spray nozzles in operating FGD systems.

Of the three nozzle types, tangential nozzles have the largest free-passage diameter for a given fluid flow and axial nozzles have the smallest. Tangential and spiral nozzles are also more likely to clear a partially plugged condition by themselves than are axial nozzles.

9.3 Material Selection

Spray nozzles are subjected to extremely high local fluid velocities and may be subject to severely erosive conditions. The available materials of construction depend on the nozzle location and service. The most frequently applied materials include selected metal alloys, ceramics, and other nonmetallic materials.

9.3.1 Metal Alloys

Metal alloy nozzles are generally suitable for spraying clear process liquids such as ME wash water and inlet emergency quench water. The alloy specified should be at least as corrosion-resistant as the alloy that would be specified for fabrication of the absorber in this same location. Type 300 series stainless steels are generally suitable for ME wash applications. Corrosion-resistant nickel alloy nozzles are required for the quenching nozzles. Alloy selection is discussed in detail in Part I, Section 5.6.1--Alloy Products and Corrosion Resistance.

Less frequently, alloy materials have also been used for slurry nozzles. However, experience has shown that the life expectancy of alloy nozzles decreases rapidly with increasing slurry particulate size and slurry solids level. For example, increasing slurry limestone reagent particulate size from 90% less than 44 μm (325 mesh) to 90% less than 149 μm (100 mesh) can result in about a 10-fold decrease in nozzle life (3).

Stellite 6B, a cobalt-based, wear-resistant alloy, has been widely used for FGD spiral slurry nozzle applications. This alloy is extremely resistant to erosion and moderately resistant to corrosion, but it is very brittle. Stellite 6B nozzles may break if dropped. The alloy can be machined only by grinding. Stellite 6B nozzle bodies are typically either flanged or welded to threaded necks of another alloy.

While Stellite 6B is extremely wear-resistant, it is not particularly resistant to chlorides, and severe external pitting has occurred in relatively low-chloride (less than 10,000 mg/L Cl^-) environments. Another cobalt-based alloy, Ultimet™, offers high abrasion resistance along with high chloride resistance, although at considerably greater cost.

9.3.2 Ceramics

Ceramic nozzles of either sintered silicon carbide or sintered alumina are essentially immune to erosion, abrasion, and corrosion by the slurries used in an FGD system, and currently are the type most frequently used for absorber spray nozzles. However, these nozzles are extremely brittle, and often break during removal to clear pluggages. A fall of only a few feet will shatter them. These nozzles can be fabricated entirely of ceramic materials, including the flanges. Since the flanges are often broken by over-tightening the flange bolts during installation, the nozzles are also frequently fabricated with a ceramic nozzle body with an alloy or fiber-reinforced plastic (FRP) flange. Ceramic axial nozzles, fabricated with cast ceramic threads, have been used in the past, but should be avoided. These nozzles are very prone to breaking during installation and removal.

9.3.3 Other Nonmetallic Materials

Other nonmetallic materials that are used for spray nozzles include polyurethane, polypropylene, and FRP.

Absorber slurry spray nozzles fabricated from erosion-resistant polyurethane have been used in a few FGD systems. These nozzles are much less prone to breakage than ceramic nozzles, but are less erosion-resistant and can be damaged by high flue gas temperatures. FRP or a corrosion-resistant alloy can be used for the nozzle flange.

Polypropylene and FRP nozzles do not have sufficient erosion resistance for use as absorber slurry spray nozzles, but have been applied as ME wash nozzles.

9.4 Recommendations

In a new FGD system, the types of nozzles and the materials of construction are typically selected by the FGD vendors on the basis of their specific designs and experience. In reviewing vendor proposals or evaluating replacement nozzles, the following factors should be considered:

- Any of the three nozzle types can be used effectively in absorbers with high-pressure spray nozzles. Tangential hollow-cone spray nozzles provide large free-passage diameters and no internal parts. Axial and extra-passage spiral nozzles provide greater spray coverage and smaller droplets at a constant operating pressure.
- Pressure drop across the absorber spray nozzles should be in the range of 48 to 103 kPa (7 to 15 psig) at nozzle capacities between 10 and 12.5 L/s (150 and 200 gpm).

- For absorber spray nozzles, droplet Sauter mean diameter should fall between 2500 and 2800 μm. For all nozzles used in the FGD system, the percentage of droplets less than 2000 μm in diameter should be minimized because these droplets can carried up into the ME section by the flue gas.

- The absorber spray nozzle spray angle should be 90° to 120°.

- Absorber spray nozzles and ME wash nozzles should provide at least 200% spray coverage. For high-pressure absorber spray nozzles, the coverage should be calculate at a distance of 1 m (3 ft) from the nozzle orifice. For low-pressure flooding nozzles and ME wash nozzles, the coverage should be calculated at the packing or ME surface.

- Axial nozzles are typically preferred for low-pressure (flooding) spray nozzles designed for full spray coverage directly above packing. Only 7 to 70 kPa (1 to 10 psig) pressure drop is required for low-pressure flooding operation. Large-capacity [19 L/s (300 gpm) and greater] nozzles can be used with small spray angles. Droplets can reach up to 5000 μm in size.

- Mist eliminator wash and emergency quench nozzles require full-cone spray patterns at 90° spray angles. Pressure drop across the nozzle can be as high as 275 kPa (40 psig).

- Vacuum filter wash nozzle spray angles can be 120° or greater provided that even wash water coverage of the cake is produced.

9.5 References

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2. Boucher, E.J. "New Methods of Nozzle Attachment to FRP Spray Headers." Presented at the EPRI/EPA/DOE 1995 SO_2 Control Symposium. Miami, Florida, 1995.

3. Ellis, P.F., D.M. Anliker, G.D. Jones, and D.A. Stewart. "FGD System Failure Analyses: Metallic Components." Presented at Corrosion/85. Boston, Massachusetts, 1985.

10.0 REAGENT BALL MILLS

Most FGD systems use either lime or limestone as a source of alkalinity to neutralize the SO_2 removed from boiler flue gas. Both lime and limestone are typically delivered to the plant in forms that are the most economical for purchase and delivery; however, both reagents must be processed further before they can be used in the FGD system. The term "reagent preparation" refers to the total process of converting the reagent from its as-received form into a slurry that can be added to the absorber reaction tank.

The basic design considerations regarding reagent receiving, storage, preparation, and slurry storage are presented in Part I, Section 4.7--Reagent/Additive Preparation Equipment. This section of the manual emphasizes the characteristics of wet ball mills used for reagent grinding or slaking, while other sections of Part II discuss associated reagent preparation equipment. This associated equipment includes slurry pumps (Section 5.0), tank agitators (Section 6.0), hydrocyclones (Section 12.0), and process tanks (Section 16.0).

Limestone for FGD system reagent is usually delivered to the power plant as crushed rock in a size range of up to about 19 mm (3/4 inch) in diameter. It must then be ground to a fine size to increase the surface area and reactivity (see Part I, Section 4.7.2--Limestone Reagent Preparation Equipment).

Limestone can be ground either wet or dry. Wet grinding of the limestone in a ball mill produces a pumpable slurry that can be metered into the absorber reaction tanks. Consistent grinding is essential to maintaining efficient reagent utilization and to meeting the byproduct quality specifications for commercial-quality gypsum. Dry grinding of limestone in a roller mill (similar to the mills used to produce pulverized coal) is an option that utilities may wish to consider; however, because there are no utility installations currently conducting on-site dry grinding, this option is not covered in this manual. It should be noted that at least one U.S. utility is purchasing dry-ground limestone powder from a supplier for use in their

FGD system, and several FGD vendors are promoting on-site dry grinding of limestone reagent for future FGD systems.

Pebble quicklime (CaO) for lime-based FGD systems must be slaked to hydrated lime [$Ca(OH)_2$] to make a slurry that is easily pumped and metered into the reaction tanks. The three basic types of slakers have been used to produce hydrated lime for FGD systems: paste slakers, detention slakers, and ball mill slakers. Commercially available paste slakers are limited to a slaking capacity of approximately 3.6 tonnes/hr (4 tons per hour), which is much less than the typical reagent requirements of a large FGD system. As a result, a large number of paste slakers would be required. Large-capacity detention slakers could be used, but these slakers are less efficient* than either paste or ball mill slakers, and reagent costs would be greater. As a result, most recent lime-based FGD systems have selected large-capacity ball mill slakers for reagent preparation. For this reason, this section will be limited to a discussion of the ball mill slaker.

10.1 Types Available

Ball mills used for grinding limestone or slaking lime can be of either the horizontal or vertical type. Both types are available in capacities of greater than 90 tonnes per hour (100 tons/hr). The differences, advantages, and disadvantages of these two mill types are discussed below.

10.1.1 Horizontal Ball Mills

Historically, horizontal ball mills have been the predominant choice for producing limestone reagent slurries in FGD systems. They have been much less commonly used for slaking lime. The horizontal ball mill, Figure 10-1, is a cylinder that rotates at 15 to

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* Slaker efficiency is a measurement of the percentage of the CaO feed that is converted to $Ca(OH)_2$. CaO can not react with dissolved SO_2 in the absorber slurry and is lost from the process in the byproduct solids.

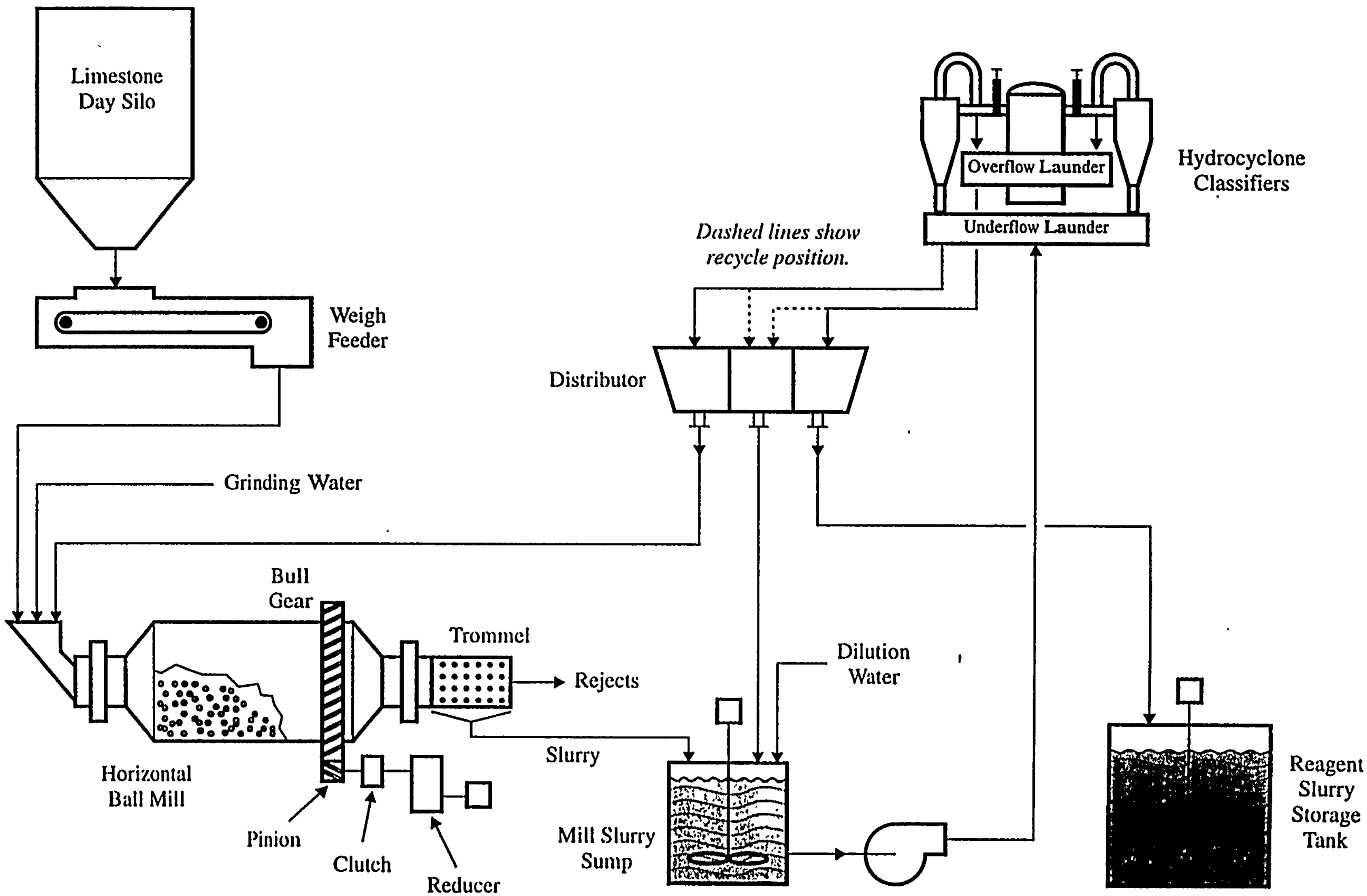

Figure 10-1. Horizontal Mill Grinding System

20 rpm and is partially filled with steel balls. Reagent and water enter at one end of the cylinder and leave the other end through a trommel screen discharge. As the cylinder rotates, the balls are lifted by ridges on the mill's internal liner and then tumble back onto the reagent and other balls. In a limestone ball mill, this action grinds the coarse reagent feed to a very small particle size; in a lime slaking ball mill, it mixes the lime and water, promoting the slaking reaction. The grinding action also improves the slaking rate and efficiency by continuously removing the outer layer of $Ca(OH)_2$ coating the unslaked CaO particles. Any unreactive material in the lime (also called grit) is ground to a small particle size and leaves the mill with the lime slurry. The outlet of the mill has a set of reversing spiral flights that push the balls back into the mill as it turns.

The discharge trommel is a cylindrical screen with relatively small openings that allow the reagent slurry to discharge into the mill slurry sump but that retain any grinding balls and large particles of tramp material (such as nuts, bolts, and pieces of wood). Any unground stone, tramp material, and grinding ball fragments that get past the outlet spiral flights, but do not pass through the trommel, are discharged through a chute to a waste rejects hopper.

When producing a limestone slurry, the horizontal ball mills are operated as wet, closed-circuit systems, where "closed circuit" refers to oversized particles being separated from the slurry and returned to the feed end of the mill for additional processing. When used as a lime slaker, horizontal ball mills typically operate in an "open circuit," with no separation or recirculation of oversized material.

A considerable amount of associated equipment is needed in order for a horizontal mill to produce a consistent slurry product. Belt-type weigh feeders are used to meter dry reagent from the day silo into the mill inlet. The mill discharges into an agitated tank called the mill slurry sump. In closed-circuit limestone slurry preparation systems, the slurry pumps transfer the limestone slurry to hydrocyclones, which split the feed into streams of relatively coarse and fine particles. A device called a distributor is often used to direct the hydrocyclone overflow (containing the finer limestone particles) and underflow (containing the coarser limestone particles). Under normal closed-circuit operating conditions, the hydrocyclone overflow is directed to the reagent slurry storage tank(s), and the hydrocyclone underflow is directed to the feed end of the mill for reprocessing. When sufficient reagent slurry has been produced, the weigh feeder stops, the mill's drive clutch disengages, and both the hydrocyclone overflow and underflow are routed back to the mill slurry sump.

In open-circuit lime slaking systems, the slurry pump transfers the lime slurry directly from the mill slurry sump to the reagent slurry storage tank(s). A few lime slaking ball mills use closed-circuit systems to improve slaking efficiency and ensure maximum size reduction of grit. The determination of whether the additional equipment required for closed-circuit operation is cost-effective is dependent on the cost and quality of lime, with closed-circuit operation being favored in instances of high-cost or low-quality lime.

At initial startup, a horizontal ball mill is charged with an assortment of ball sizes, ranging from 19 mm (3/4 in.) up to 750 mm (3 in.) in diameter. Limestone grinding mills are usually 40 to 50% filled with ball charge; somewhat less grinding media is required for lime slaking. During operation, attrition of the balls occurs and their diameters gradually diminish.

Periodically, additional balls of the largest diameter are added to the mill to maintain the correct ball charge size distribution. Most commonly, balls are added when the electrical current drawn by the mill's drive motor decreases by a specified amount. The drive motor current decreases as the total weight of the ball mill contents decreases. Because the weights of reagent and water are relatively constant, the decrease is attributable to reduced ball charge.

10.1.2 Vertical Ball Mills

Vertical ball mills (also called tower mills or stirred mills) are a relatively new grinding option and are currently offered by only two ball mill vendors worldwide. Although their experience base is much smaller than that of horizontal mills, vertical mills offer several advantages. The main advantages relate to simplicity of design, smaller equipment footprint, and reduced power consumption. Tests by one vendor, who supplies both vertical and horizontal ball mills, concluded that the vertical mill produces a higher slaking efficiency (1).

Unlike horizontal mills, which can accept feed sizes up to 500 mm (2 in.), the vertical mill requires a relatively finer feed size. Limestone feed must be crushed to less than 6 mm (1/4 in.) in diameter prior to the mill. For lime slaking, the maximum size of pebble quicklime is 16 mm (5/8 in.). Unless the reagent can be purchased to these size specifications (often at additional cost), a crusher must be installed ahead of the mill. Some installations have large-capacity crushers that operate at reduced frequency (e.g., 8 hours/day), and the ground reagent is stored until fed to the mills. However, it is usually more economical to size the crusher system to match the grinding system and operate both simultaneously.

Vertical ball mills, Figure 10-2, are significantly lighter in weight than horizontal mills because the shell is stationary while an internal helix (screw) turns at 28 to 85 rpm to lift the balls in the center of the mill from the bottom of the mill to the top. (Larger diameter mills operate at a lower speed.) The balls then slowly progress to the bottom of the mill inside the perimeter of the shell. The screw is suspended from above to avoid the need for support bearings in the grinding media. Vertical alignment of the screw is maintained by the weight of the ball charge.

The limestone or quicklime feed enters the top of the mill with overflow slurry exiting near the top. The recycle pump is sized to provide an optimal upward velocity of slurry in the grinding chamber, which carries fine particles out of the mill and allows the larger ones to settle back into the grinding media. An integral classifier separates the mill

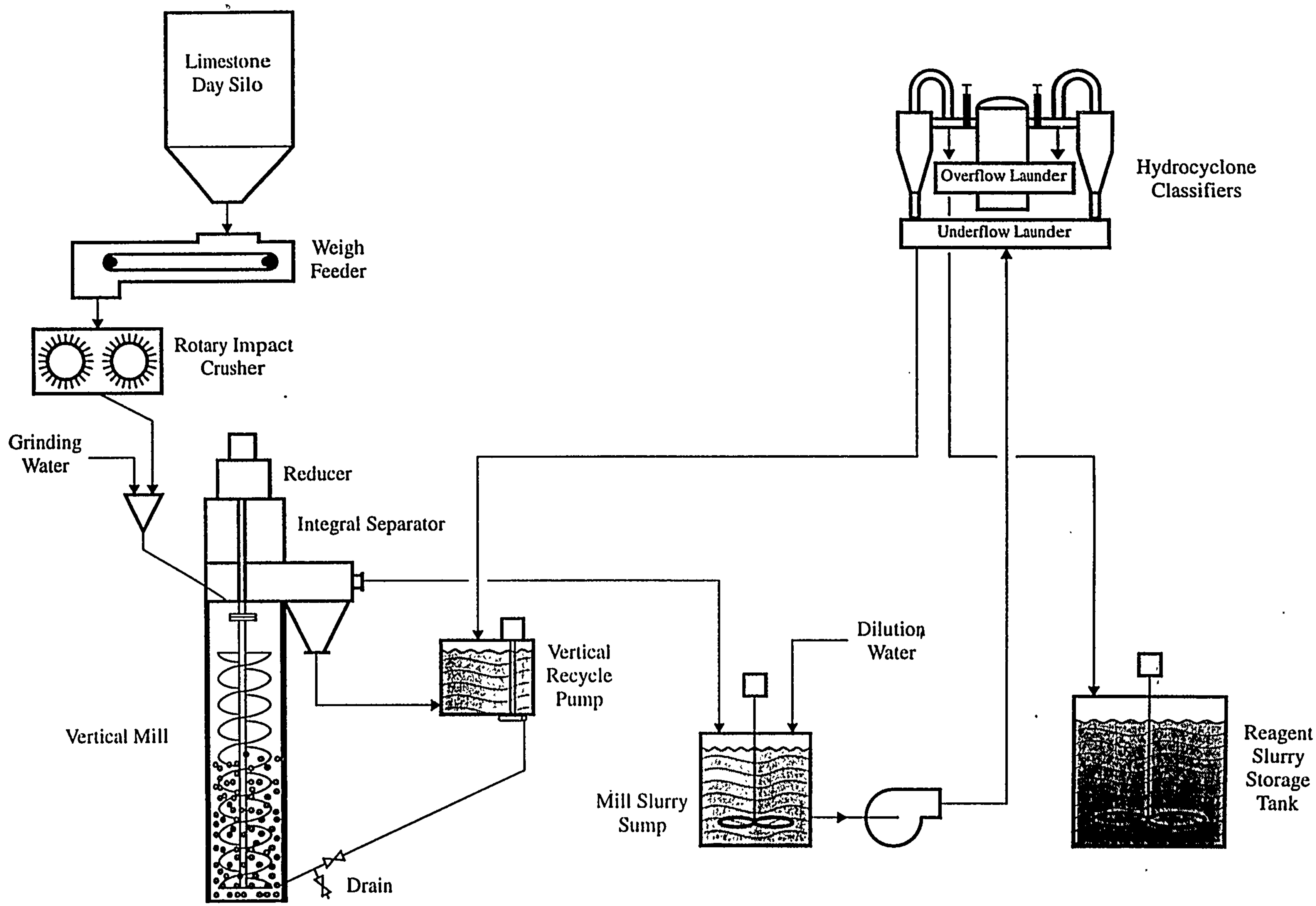

Figure 10-2. Vertical Mill Grinding System

overflow into a recycle stream, which is returned to the bottom of the mill by the recycle pump, and a product stream. A vertical mill used in limestone grinding service would be expected to operate with hydrocyclone classifiers and a distributor similar to those described for closed-circuit horizontal mills. Vertical mill slakers do not require the hydrocyclones, although the recycle pump and integral classifier are still used.

Operating grinding equipment requires a certain amount of energy. Most of the energy goes into breaking the rock, but a large amount is wasted as heat and noise. The vertical mill creates less heat and noise, and consequently is more energy-efficient. Based on mill power requirements presented by an equipment manufacturer, vertical mills (including crushers) require about 70% of the power of a horizontal mill to produce the same limestone slurry fineness (2). The finer the grind required, the greater the power savings with a vertical mill.

Erosion of the mill internals is minimized through equipment design and material selection. The inner surface has several vertical protection bars, where grinding media and limestone accumulate and serve as a wear surface. The normal replacement schedule for the wear parts on the screw is 12 to 18 months. The replacement schedule for the protection bars is typically half as often as the screw parts.

Vertical mills use smaller balls than horizontal mills [2.5 cm (1 in.) maximum], and the ball wear rates are about half as great. As with horizontal mills, balls are added when the drive motor current decreases. The typical depth of grinding media is 1.8 to 2.4 m (6 to 8 ft) for limestone grinding and 1.2 to 1.5 m (4 to 5 ft) for lime slaking.

10.2 Design Considerations

10.2.1 Process Considerations

Four important process considerations related to the selection of limestone grinding equipment are:

- Product particle size;
- Lime/limestone characteristics;
- Water requirements; and
- Reagent processing rate turndown ratio.

Product Particle Size

The rate of limestone dissolution depends largely on its surface area, which is a function of the particle size distribution (PSD). Limestone fineness affects both the reaction tank pH and the limestone utilization. These factors are discussed in detail in Part I, Section 8.4.1--Effect of Limestone Particle Size on FGD System Performance. Recent FGD system designs have specified a PSD of 90 to 95% of ground limestone passing a 44 μm (325-mesh) screen.

Lime/Limestone Characteristics

Limestone grinding systems are designed for a specific limestone hardness, which is most commonly measured in terms of Bond Work Index (BWI). Limestone hardness is discussed in Part I, Section 8.4.3--Limestone Hardness; however, this section provides some additional details describing the effects of hardness on grinding equipment design.

Bond Work Index is determined using a laboratory-scale ball mill to measure the amount of energy required to reduce the size of a given limestone from 3.36 mm to 80% passing 100 μm. Changes in BWI affect the product fineness and/or the grinding system capacity, as shown in Figures 10-3 and 10-4 (2). The following relationship is used for estimating grinding power in a wet closed-circuit ball mill (2):

$$W = \left(\frac{11\ BWI}{\sqrt{P}} - \frac{11\ BWI}{\sqrt{F}} \right) x\ CF \qquad (10\text{-}1)$$

where:
- W = Grinding power, kilowatt-hour/tonne;
- BWI = Bond Work Index;
- P = Screen opening through which 80% of the product will pass, μm;
- F = Screen opening through which 80% of the feed will pass, μm; and
- CF = Correction factor, unitless.

An empirical correction factor (CF) can be applied in many different grinding situations. For example, a correction factor is used with wet, closed-circuit limestone grinding when the product size is very small (2). If P is less than 75 μm (as it is in most FGD system applications), then (2):

$$CF = \frac{P + 10.3}{1.145\ P} \qquad (10\text{-}2)$$

The limestone reagent feed is typically expressed as a range of particle sizes [e.g., 19 x 0 mm (3/4 x 0 in.)], which does not address the particle size information needed to apply Equation 10-1. Table 10-1 provides a list of some common feed and product sizes and the corresponding typical 80% passing sizes (the size of a screen opening that will pass 80 weight percent of the particles) (2).

Figure 10-5 shows the theoretical grinding power required for a wet closed-circuit ball mill system as a function of limestone hardness (BWI) and product size. Although

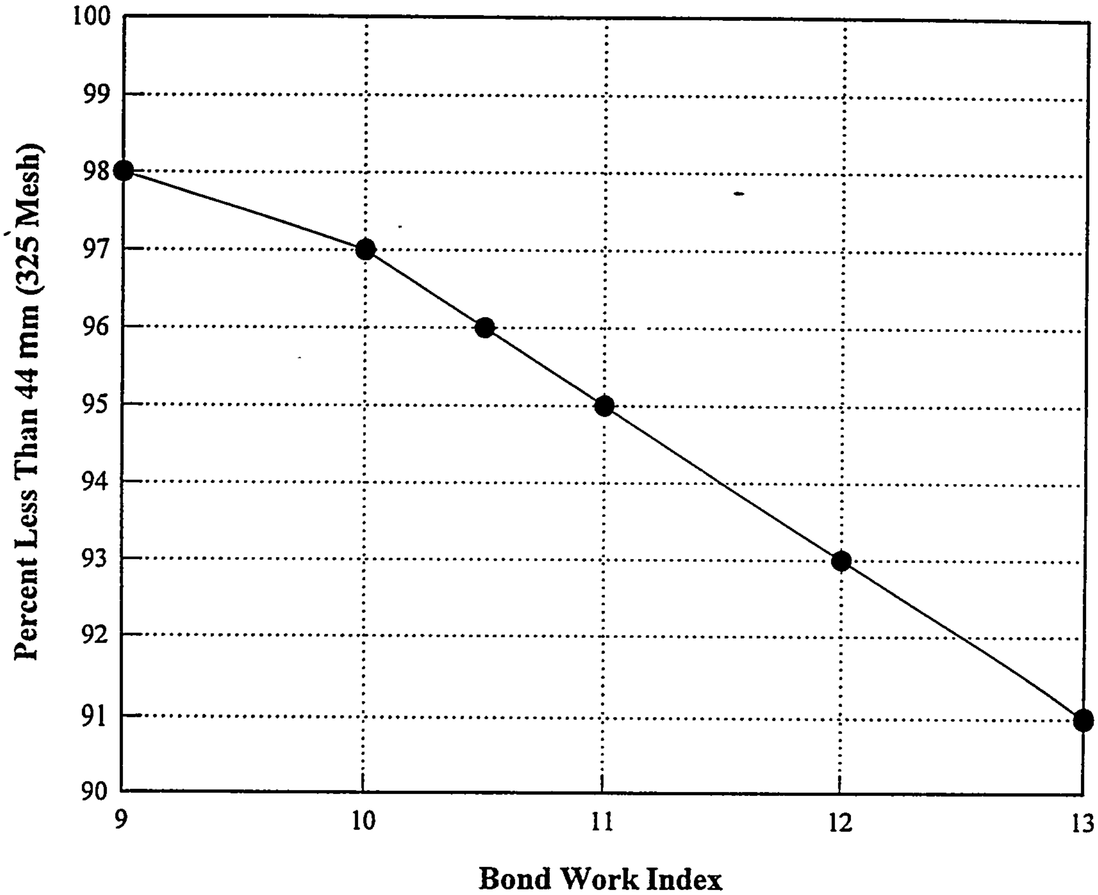

Figure 10-3. Typical Limestone Grinding: Ball Mill Product Size vs. Bond Work Index

Source: Svedala Industries, Inc. (1)

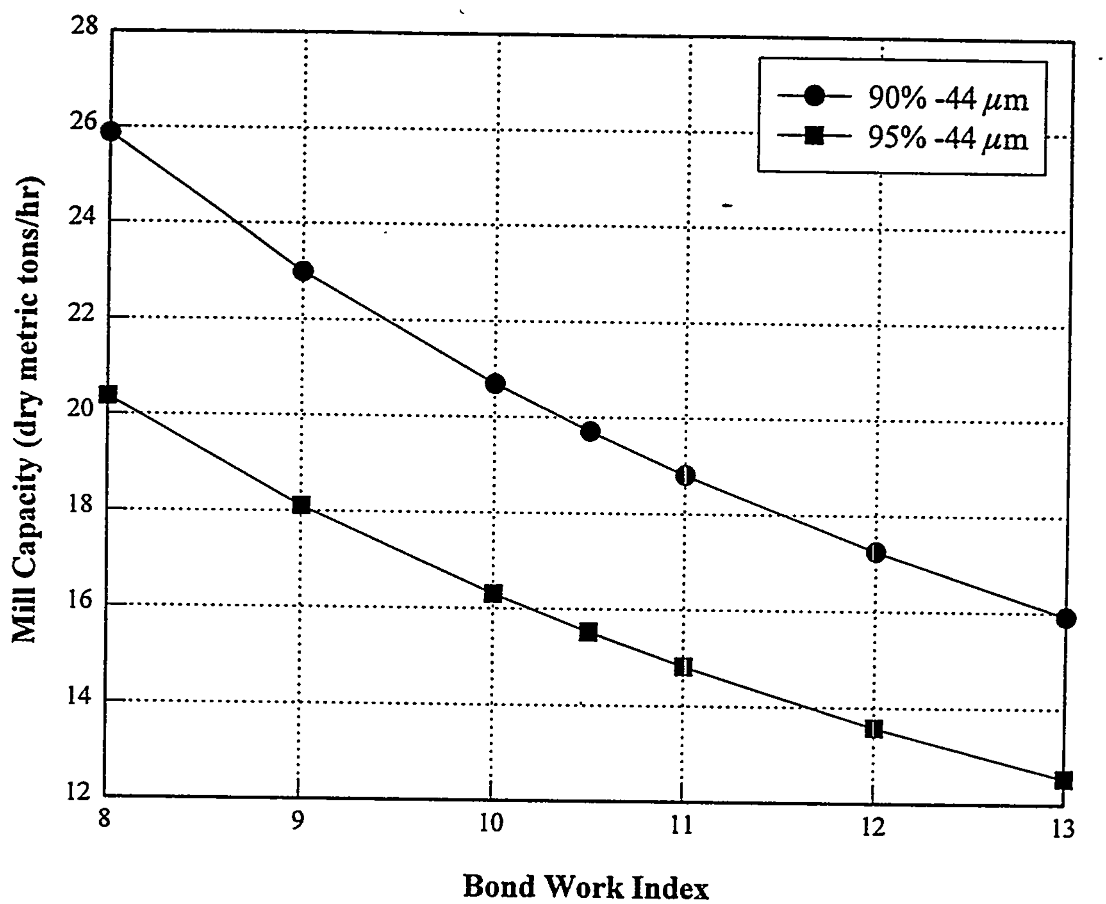

Figure 10-4. Typical Limestone Grinding Ball Mill Capacity vs. Bond Work Index

Source: Svedala Industries, Inc. (1)

Table 10-1

Typical Limestone Feed and Ball Mill Product Particle Size Correlations

Feed Size			Product Size			
Size Specification		F_{80}*	% Passing	Screen Opening		P_{80}*
(mm)	(in)	(μm)		(μm)	Mesh	(μm)
25 x 3	1 x 1/8	19,000	80	74	200	74
19 x 12	3/4 x 1/2	15,000	80	44	325	44
19 x 0	3/4 x 0	14,000	85	44	325	37
12.7 x 0	1/2 x 0	9,400	90	44	325	31
9.5 x 0	3/8 x 0	6,400	95	44	325	23

* F_{80} and P_{80} are defined as the size of a screen opening through which 80 weight percent of the feed and product will pass, respectively.

Source: Svedala Industries, Inc. (2)

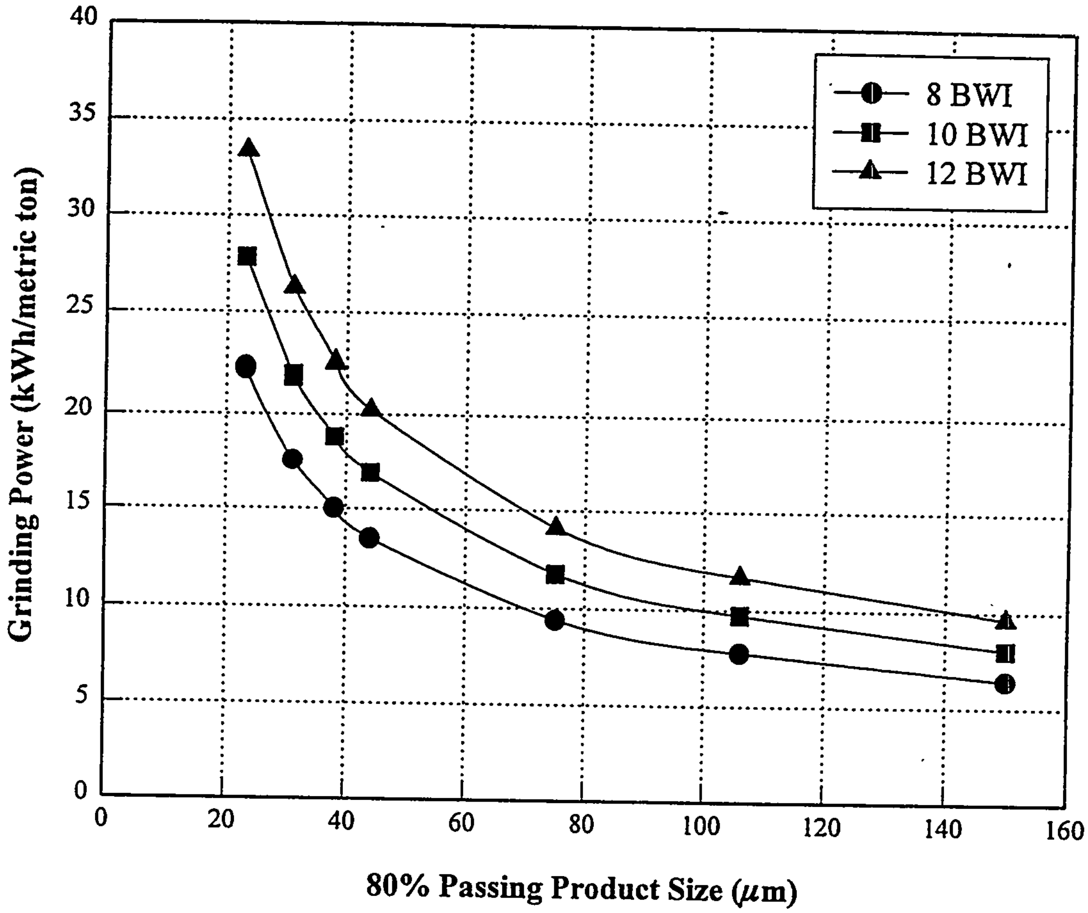

Figure 10-5. Theoretical Ball Mill Power Requirement as a Function of Product Size and Bond Work Index

Source: Svedala Industries, Inc. (1)

the theoretical data are for a horizontal mill, similar curves would be produced by a vertical mill. As indicated by this figure, grinding power is proportional to the BWI. Grinding power is also dependent on the product fineness, since it takes more power to produce a finer grind. And similarly, though not indicated by this figure, grinding power increases with increasing feed size.

A closed-circuit system, in which hydrocyclones separate the large particles and return them to the mill, is more energy-efficient than an open-circuit system that produces the same average fineness. In order to minimize the size of the largest particle leaving the mill, an open-circuit system must over-grind the remainder of the particles, with much higher energy costs. For this reason, limestone FGD grinding systems are operated as a closed-circuit process. Empirical correction factors can be applied to Equation 10-1 to account for dry grinding, open circuits, rod grinding media (as opposed to ball media), abnormal feed size distributions, and other differences. The utility engineer can use Equation 10-1 for estimating purposes, but equipment vendors will design the grinding systems based on their experience. In some cases, vendors may wish to perform additional tests on the proposed limestone.

Limestone often contains a small amount of harder stone, such as flint and shale, some of which is not ground as it passes through a horizontal ball mill. Such material is termed "rejects" and is discharged from the horizontal ball mill through the reject chute for disposal. If the volume of rejected limestone is small, a waste drum set at the discharge chute can collect the rock. However, some utilities have had to install equipment such as small conveyors to take away their large volumes of rejects. In a horizontal ball mill, a significant increase in limestone hardness will cause an increase in the amount of limestone that is discharged with the rejects.

Vertical ball mills do not have trommels and reject chutes. Rejects and tramp materials either remain in the mill until they are ground to a sufficiently small size to enable their leaving the mill in the product stream, or they accumulate in the mill and act as additional grinding media. A significant increase in limestone hardness would reduce the capacity of the mill.

Pebble lime contains a fraction of unreactive material (grit) that is composed of uncalcined limestone, unreacted calcium oxide, and acid-inert material. Grit is typically 1% to 2% of the lime feed. An advantage of slaking with a horizontal or vertical mill is that grits are ground along with the lime and do not produce a separate waste stream.

Water Requirements

The grinding or slaking operation is a significant water consumer in the FGD system. Depending on SO_2 removal rates, the reagent slurry will likely provide 10 to 30% of the total makeup water to the reaction tank. Limestone slurry can be made using relatively low-quality water; in fact, thickener/hydrocyclone overflow water is typically used as the primary makeup water source in limestone grinding. However, in systems with high levels of dissolved chloride, some designers or operators have used fresh water to avoid corrosion problems. As discussed below in the section entitled Slurry Density Control, the amount of water used for grinding (as opposed to slurry dilution) is small. Therefore, using fresh water for grinding would have little effect on the overall FGD water balance.

Potable water is recommended for slaking because dissolved sulfites and sulfates can retard the slaking process, preventing some lime from hydrating. Although potable water is usually used in the slaking step, recycled water can be added after slaking to dilute the slurry to the desired consistency (3).

Both types of mills require a reliable source of cooling water: for cooling the mill support bearings in horizontal ball mills, and for cooling the drive speed reducer in vertical mills.

Other water requirements relate to shutdown and emergency conditions. On system shutdown, the mill should be flushed with water to remove ground material and prevent it from solidifying. A solidified ball charge can seriously damage the drive gears, support bearings, and mill internals. In slaking operations, it is especially important to have an adequate amount of water present at all times. Lime hydration is an exothermic reaction and an ample amount of water is needed to control temperatures to prevent rubber liner damage or steam explosions. In case of a power failure to the slaking system, a horizontal ball mill should be quickly flooded, while a vertical ball mill should be drained through a drain valve.

Reagent Processing Rate Turndown Ratio

A horizontal ball mill is designed for a specific throughput (tons of feed per hour). At lower feed flows, the wear rates of balls and mill shell liners increase as balls are hitting each other and the shell instead of grinding the reagent. Although vertical ball mills are also designed for a specific feed rate, they also perform well at lower feed rates. When slaking lime, the vertical mill has been shown to have a turndown ratio* of up to 10:1 (2). Operation of either type of mill at a higher-than-designed limestone feed rate reduces the product fineness. A higher-than-design lime feed rate results in incomplete slaking.

Limestone preparation systems are seldom run at reduced capacity because of the problems noted above related to increased attrition of grinding media. Instead, when less slurry is needed, the equipment is operated at full capacity for fewer hours per day. Therefore, the ability of grinding equipment to perform at a high turndown ratio is not very important.

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* Turndown ratio is the ratio between the equipment's highest and lowest continuous processing rates. A system with a higher turndown ratio is capable of continuous operation at a lower fraction of its maximum capacity.

10.2.2 Mechanical Considerations

Grinding mills are heavy-duty pieces of equipment with a long history of use in other industries. Generally, mills operate with high reliability, but FGD systems are highly dependent on having a continuous supply of reagent slurry. Therefore, spare equipment is typically provided. Although the mills themselves are usually purchased as the vendor's standard design, the utility engineer should be aware of some of the associated equipment. Slurry density control, mill lubrication, and the ball charging hopper are discussed below.

Equipment Redundancy

Both horizontal and vertical ball mill systems are usually provided as a train of equipment consisting of a weigh feeder, ball mill, mill slurry sump, and classifier system. Typically, a single train is sized to provide the full requirements for a generating unit's FGD system, with a duplicate train as a spare. A single day silo can supply both trains, or a separate day silo can be provided for each train. Where the reagent preparation system supplies more than one generating unit, there is typically one ball mill train for each unit, with a common spare.

Slurry Density Control

Grinding or slaking water is added to the feed end of the mill based on a feed rate signal from the reagent weigh feeder. The water addition rate is typically set at the optimum value for grinding or slaking. A density monitor is installed on the piping between the mill slurry sump pump discharge and the hydrocyclones. The density monitor controls dilution water addition to the sump to maintain the desired density in the reagent slurry storage tank. Since slurry density in a limestone mill is usually about 65% solids, about one-fourth of the water used in the limestone preparation area is added at the mill inlet and the remainder goes into the mill sump. Table 10-2 shows typical ranges for percent solids in the various reagent preparation streams.

Table 10-2

Typical Reagent Slurry Solids Content

Application	% Solids in Mill		% Solids in Reagent Slurry Storage Tank
	Horizontal	Vertical	
Limestone grinding	65-70	50-60	25-40
Lime slaking	30-35	25-28	20-25

Each makeup water stream should have a flow monitor to facilitate making adjustments to the grinding circuit and troubleshooting problems. Density and other instrumentation is discussed in detail in Part I, Section 4.10--Process Controls and Instrumentation.

Mill Lubrication

Horizontal ball mills require special lubrication systems; separate oil pumps provide high-lift lubrication and flooding lubrication. Prior to startup, the high-lift oil pump (also called the jacking pump) pumps oil into the bottom of the two mill-supporting sleeve bearings to lift the mill and eliminate metal-to-metal contact. This reduces the starting torque and prevents bearing damage during startup. The flooding oil pump provides a flow of oil to the top of each bearing during mill operation. While horizontal ball mills in the United States have traditionally used sleeve bearings, the use of roller bearings is common in Europe (4). Roller bearings are less expensive and do not use bearing oil pumps.

Horizontal mills are driven by an electric motor with an air-operated clutch, a pinion gear, and a bull gear that encircles the mill. Lubricating grease is sprayed onto the bull gear. The oil and grease systems must be heat-traced to ensure proper operation in cold weather.

Vertical mills are driven by an electric motor with a gear-type speed reducer. The bearings that support the screw are periodically greased. Also, the speed reducer has a circulated oil lubrication system.

Ball Charging Hopper

Replacement balls must be added to the mills on a regular basis; therefore, equipment should be provided to facilitate this manual procedure. This equipment usually includes a hoist and a ball charging hopper that can dump to the limestone feed chute.

10.2.3 Other Considerations

Other considerations include foundation (space) requirements, noise levels, and dust control.

Foundation Requirements

Space requirements can be a concern at many power plants, particularly if the FGD system is a retrofit. Grinding systems typically elevate much of the equipment, including day silos, weigh feeders, and hydrocyclones, which allows some space conservation. However, the mills and mill slurry sumps are located at grade. A vertical mill occupies only about one-third of the floor space of a horizontal mill of similar capacity (1). The crusher required with the vertical mill is typically located above grade.

Horizontal ball mills require much larger foundations than vertical mills, since the latter develop very little dynamic force. The horizontal mill's rotating mill cylinder, drive mechanism, and foundations must all withstand tremendous forces from the moving parts. In most cases, a horizontal ball mill is mounted on massive concrete piers that are an integral part of a reinforced concrete floor. A vertical mill, on the other hand, can be bolted to a concrete floor. Installation costs and time are consequently higher for the horizontal ball mill.

Noise Levels

The sound pressure (noise) level can be a particular concern if the ball mills are located in an enclosed building. However, hearing protection is normally required in the vicinity of an operating mill, even if the mill is located outdoors. Occupational noise exposure limits in the United States allow workers to be exposed to 90 dBA for up to 8 hours per day, but a hearing monitoring program is required if the daily average sound level is 85 dBA or greater. The typical sound levels near horizontal and vertical mills are 90 to 95 dBA and 85 dBA, respectively (4). Noise levels from vertical ball mills are typically lower than from horizontal mills because the vertical mill's moving parts are mostly inside a stationary liquid-filled vessel.

Dust Control

Dust emissions are not usually a significant problem in limestone operations, because the limestone is contained in enclosed equipment from the point at which it enters the day silo. The transfer conveyor discharge point typically has a dust collection device, such as a baghouse.

Lime slaking operations produce dust and water vapor, which must be controlled for reasons of both health and housekeeping. One solution is to install a hood on the inlet chute. A more effective but complex solution is to maintain a negative pressure at the inlet and vent through a dust collector. Although the dust collector must be kept at a temperature above the vapor dew point, this procedure keeps moisture away from the dry lime feed chute.

10.3 Material Selection

Although abrasion is the greatest concern in the reagent preparation area, corrosion can be a problem, particularly with the use of high-chloride reclaim water to grind limestone. (Lime slaking must use a higher quality water.) Horizontal mills are typically rubber-lined, with cast iron feed and discharge sleeves. The grinding media (balls) are usually made of cast iron with a Rockwell "C" hardness of 62 to 65 on the surface and 60 to 64 inside. Some utilities have used stainless steel balls to gain a longer ball life in high-chloride environments. This is a significant expense that can be avoided by using a lower-chloride water for grinding.

Most of the interior of vertical mills is rubber-covered, including the shell, protection bars, and parts of the screw. The screw parts that receive the most wear are abrasion-resistant cast iron. A recent development is to use a magnetic liner in place of the protection bars. The magnetic tiles hold the steel grinding medium, which then serves as a wearing surface.

Although materials for most of the other reagent preparation system equipment are discussed in other sections, some discussion about piping is presented here. Piping in the limestone preparation circuit is subject to extreme abrasion, and erosive failures have been common. Some of the materials that have been successfully used include rubber hose (especially at pump connections for ease of pump maintenance), extra-high-density polyethylene (EHDPE), and cast basalt-lined steel. Some utilities have opted for thick-walled carbon steel, and regularly rotate or replace the worn sections.

10.4 Recommendations

- Both horizontal and vertical mills are suitable for limestone grinding and lime slaking. A purchase specification should allow the FGD system vendor to make the most economical selection for the particular application based on initial equipment cost and on installation, operating, and maintenance costs.
- Particular attention should be given to the specification of abrasion- and corrosion-resistant materials of construction.

- The ball mill equipment arrangement should provide maintenance access corridors to the mill drives and other components. This should include a corridor for periodically removing contents of the reject waste hopper from the reagent preparation area.

- Access platforms should be provided around all aboveground equipment, particularly weigh feeders and hydrocyclones.

10.5 References

1. Dharmarajan, M.N. and R.D. Forbus. "Lime Slaking Using Stirred Mills." Presented at the Ninth Symposium on Flue Gas Desulfurization, Cincinnati, Ohio, 1985.

2. Svedala Industries, Inc. "Product Catalog." York, Pennsylvania, 1991.

3. National Lime Association. <u>Lime Handling, Application and Storage</u>. Arlington, Virginia, 1982.

4. Telephone conversation with Mr. Randy Will of Svedala Industries, Inc., York, Pennsylvania, July 21 and August 30, 1995.

11.0 THICKENERS

Thickeners are commonly used as a primary dewatering device in lime- and limestone-based FGD service (see Part I, Section 4.8.1--Primary Dewatering). The thickener is a gravity sedimentation vessel in which the FGD slurry is concentrated from the typical 6 to 17% solids content in the reaction tank to about 25 to 50% solids content for feed to the secondary dewatering equipment (e.g., filter or centrifuge).

11.1 Types Available

Figure 11-1 is a simplified sketch of a conventional thickener configuration used for FGD service. The thickener is essentially an open, circular tank designed to promote settling of solids. Feed slurry from the absorbers is pumped to the feedwell at the center of the thickener. The feedwell extends below the surface of the thickener and serves to distribute the feed slurry. As the feed slurry flows downward and outward from the feedwell toward the perimeter of the vessel, the solid particles settle toward the bottom and the process liquor flows toward the surface-mounted overflow weir along the perimeter of the thickener. In continuous operation, the feed slurry is partitioned between the overflow liquor, which is nearly free of solids, and the underflow slurry, which contains from two to five times the solids content of the feed slurry. A rotating rake mechanism is provided to sweep the settled solids into the central underflow discharge area.

Thickener types are distinguished by various arrangements of the rake drive and rake supports, and by different underflow slurry discharge conditions. In smaller thickeners, the central rake drive and rake mechanism are supported by a bridge truss that extends across the entire tank diameter and is supported by the tank walls. In larger thickeners, the bridge truss is replaced by a center column support for the rake and rake drive. The choice of bridge versus center-column support is an economic choice that depends mainly on the tank diameter.

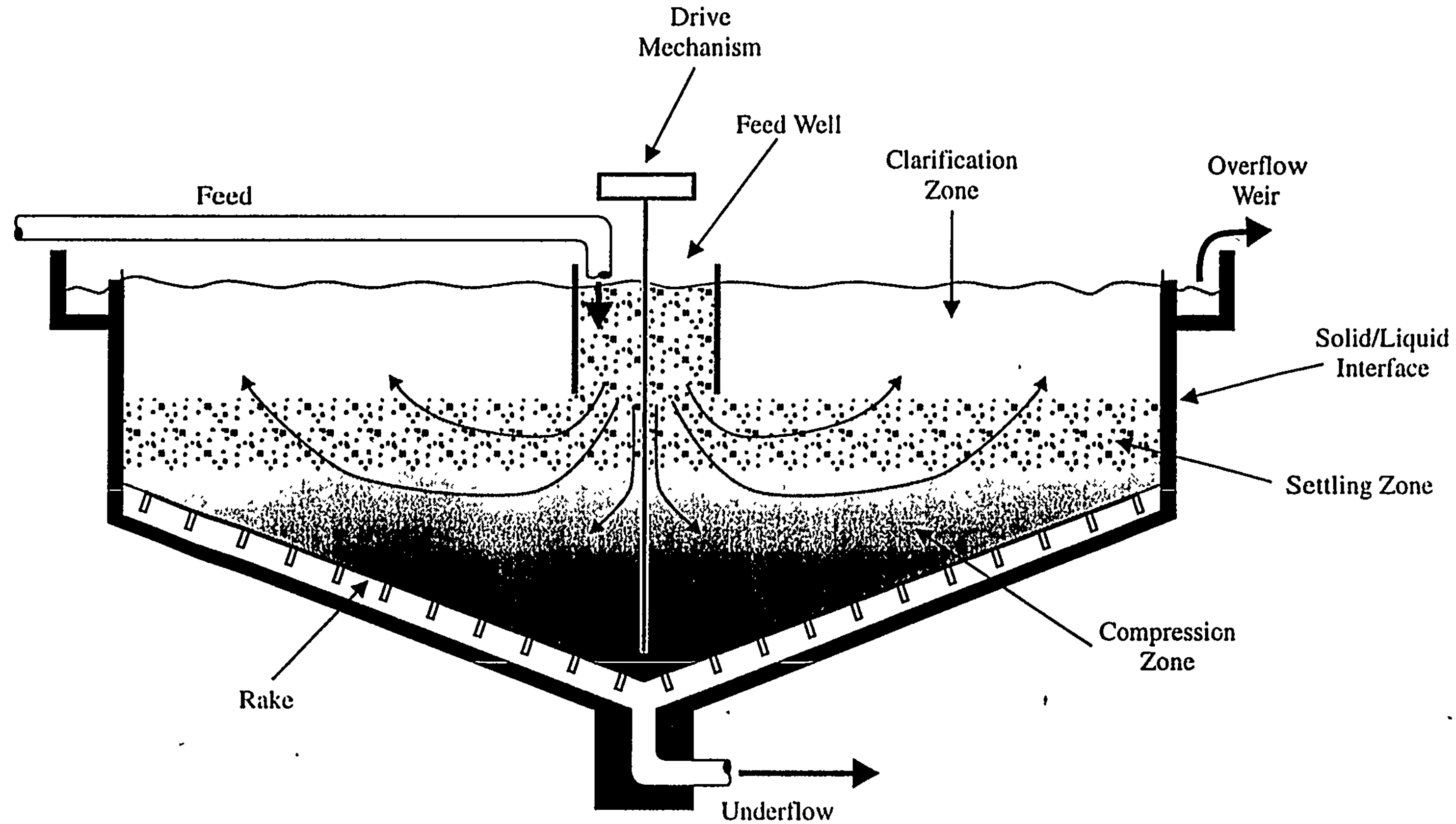


Figure 11-1. Diagram of a Conventional Thickener

The rake itself must be either self-supporting or supported along its length and also must be designed so that it can be lifted from its normal operating position during occasional conditions when the torque exerted on the rotating rake by the resistance of the settled solids exceeds the design torque capacity. The two basic rake options are the rigid-truss rake and the cable-supported rake. The rigid rake structure is self-supporting along its length and is fixed to the rotating center drive. The cable-supported rake is lighter in construction but requires a number of support cables along its length. Figures 11-2a, b, and cillustrate various rake support and lift arrangements. The cable-supported rakes generally pivot at the center attachment and are lifted by the torque arm from which the cables are suspended. The truss-type rake arm is attached to the center rake drive and is lifted along its entire length as the center drive is lifted.

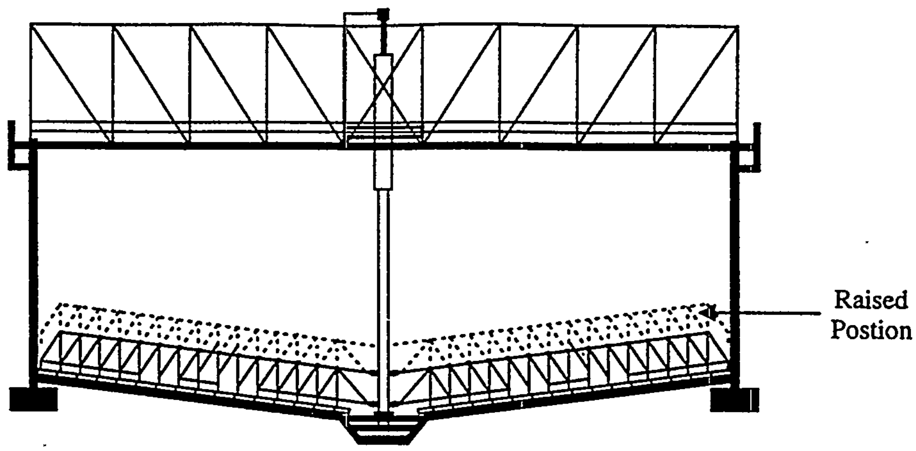
11.2 Design Considerations

11.2.1 Process Design Considerations

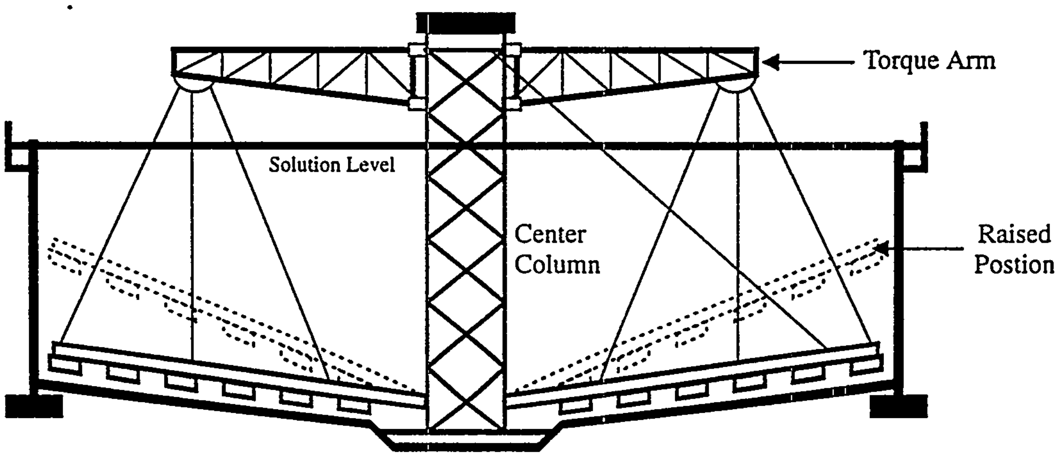
Thickener Sizing

Thickener process design consists of choosing the correct thickener size (diameter and depth) to provide the desired underflow and overflow solids content based on an expected range of feed slurry flow rate, solids content, and particle settling properties. The feed slurry flow rate and solids content are fixed by the process material balance and the absorber/reaction tank design and control approach. Generally, as the boiler load and fuel sulfur content vary, the feed slurry solids content and/or the flow rate to the thickener vary. The solids properties may also vary substantially with process operating conditions. The thickener is usually designed for "worst-case" conditions (i.e., highest feed flow rate with lowest solids content), and other conditions are accommodated by operating flexibility.

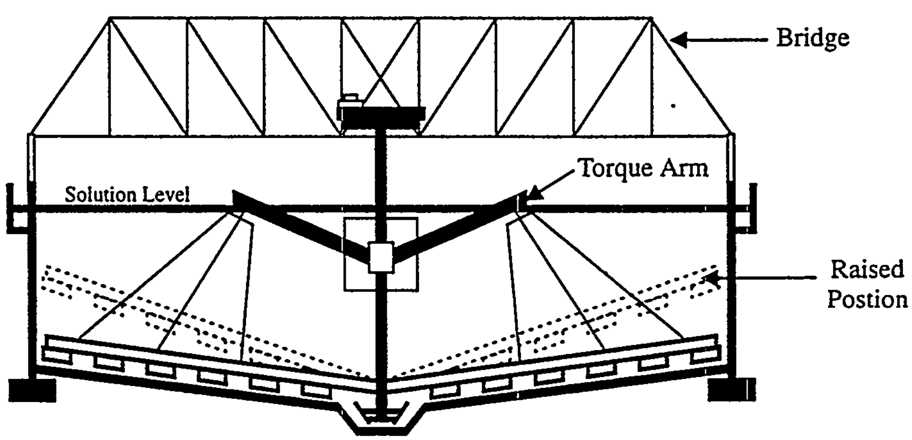
In FGD service, the underflow solids concentration is usually the design-limiting criterion. That is, a thickener that is properly sized to obtain a desirable underflow



a. **Bridge-Supported Rake and Drive with Truss-Type Rake Arms**



b. **Column-Supported Cable Torque Thickener (Dorr-Oliver, Inc.)**



c. **Bridge-Supported Swing Lift Thickener (EIMCO)**

Figure 11-2. Thickener Rake Support Types

solids content will usually result in an acceptable overflow solids content. The thickener is sized according to the appropriate design value for the "unit area." The unit area [m^2-day/tonne (ft^2-day/ton)] is an expression of the surface area required to obtain a given underflow solids content with a given feed slurry solids content and total solids throughput.

For new systems, the design value for unit area is usually selected by the thickener vendor based on their experience with similar applications. For an application where actual slurry is available, a laboratory or pilot scale settling test may be used to evaluate the required unit area. In a laboratory batch settling-test, a mixed slurry is poured into a graduated cylinder and the height of the solid-liquid interface is recorded versus time. The unit area is calculated from the settling curve by:

$$UA = K \times \frac{T}{H_0 \times C_0} \tag{11-1}$$

where:

- UA = Unit area, m^2-day/tonne (ft^2-day/ton);
- K = Unit conversion factor;
- T = Settling time to reach a given interface height, minutes;
- H_0 = Initial column height, mm (in.); and
- C_0 = Initial slurry solids content, kg/m^3 (lb/ft^3).

The corresponding underflow solids content at any given time (and unit area) is calculated by:

$$C_u = K \times \frac{W}{H \times A} \tag{11-2}$$

where:

- C_u = Underflow concentration at a given interface height, tonne(s)/m^3 (ton/ft^3);
- K = Unit conversion factor;
- W = Total weight of solids in the cylinder, kg (lb);
- H = Interface height at any given time, mm (in.); and
- A = Cylinder cross sectional area, mm^2 ($in.^2$).

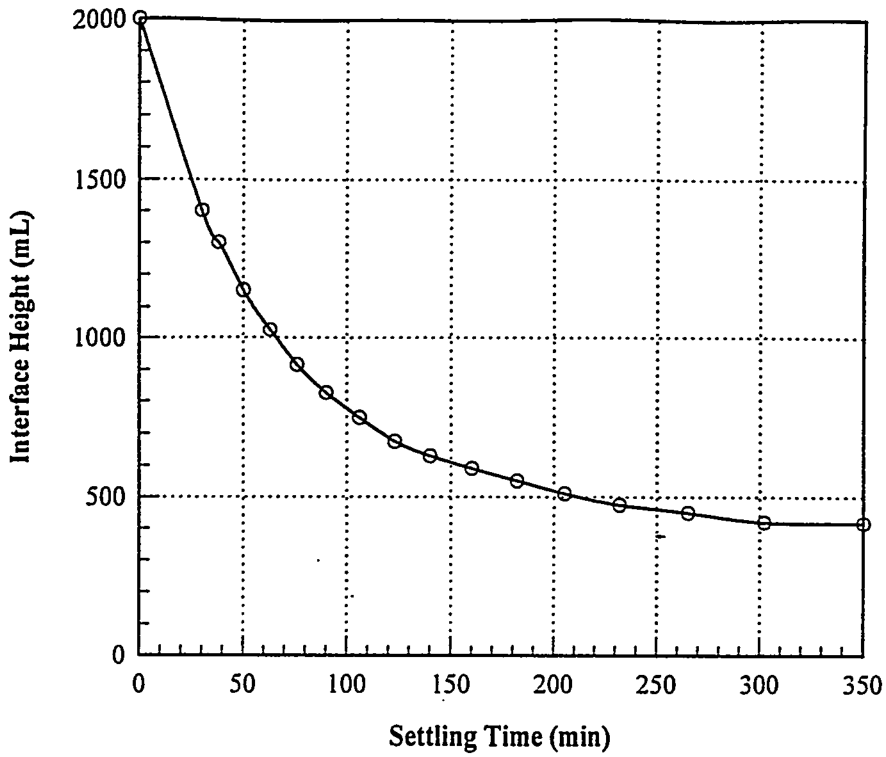
Figures 11-3a and b show a typical laboratory settling test curve and calculated unit area as a function of underflow solids content.

Settling properties of FGD slurries determined by laboratory settling tests have recently been reported for a variety of full-scale FGD systems. Table 11-1 summarizes some of these test data. Site 1 was a limestone-based forced-oxidation process. Gypsum crystals formed in the forced-oxidation process usually have the most favorable settling properties of wet FGD process byproduct solids. In this process, the solids were at least 99% oxidized to sulfate, and the feed slurry solids content was 17 percent. The measured unit area required to obtain a 30%-solids underflow ranged from about 0.1 to 0.4 m^2-day/tonne (1 to 4 ft^2-day/ton). The maximum settled solids content in the test cylinder was 65 percent.

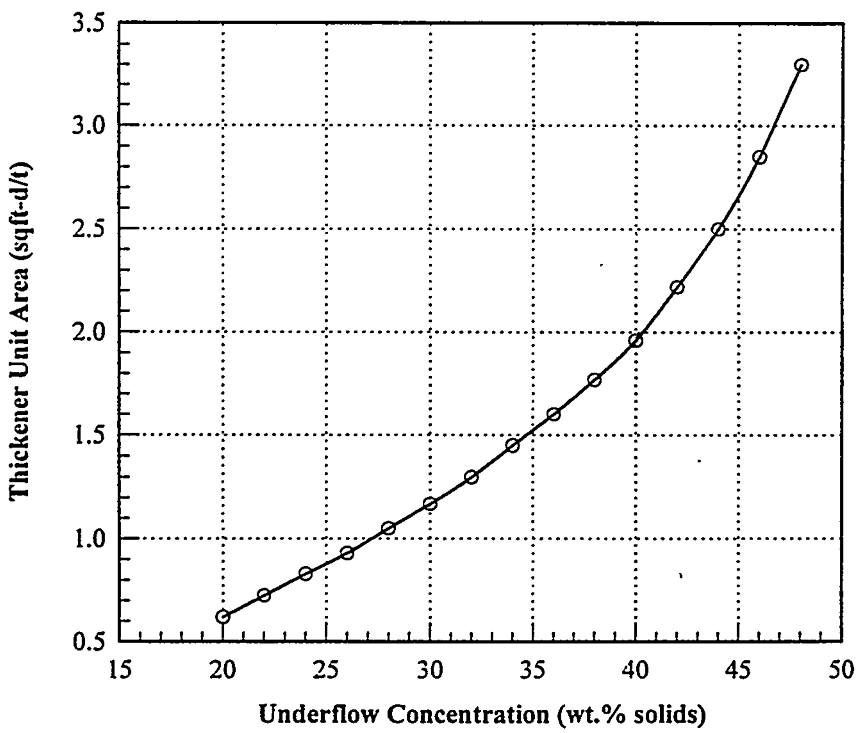
Sites 2, 3, and 4 were limestone-based inhibited-oxidation processes. Settling rates in the inhibited-oxidation processes are known to be a strong function of oxidation fraction. At Site 2, the oxidation fraction was 4%, and the measured settling rate and maximum settled solids content for this calcium sulfite slurry were in the same range as for the gypsum slurry at Site 1. Settling rates of sulfite slurry generally approach those of gypsum slurry only when the sulfite oxidation fraction is less than about 5 percent.

Site 3 had an oxidation fraction of 13% and showed a calculated unit area in the range of 1 to 3 m^2-day/tonne (10 to 30 ft^2-day/ton) for a 30%-solids underflow. The maximum settled solids content ranged from 40 to 44 percent. These results are more typical of inhibited-oxidation limestone processes. The variation in settling rates by a factor of three at this site is also typical for full-scale FGD systems where changes in process operation, especially due to boiler load swings, can have significant effects on solids dewatering properties.

Site 4 was an inhibited-oxidation process that often operated with oxidation fractions greater than the intended 15% target. The observed 19% oxidation fraction is more typical of "natural" or uncontrolled oxidation, although very few FGD systems are



a. **Typical Settling Curve for FGD Limestone Scrubbing Sludge , Natural Oxidation**



b. **Typical Thickener Operating Curve Predicted from 2-L Settling Test for FGD Limestone Scrubbing Sludge**

Figure 11-3. Typical Settling and Unit Area Curves for FGD Byproduct Solids

Table 11-1

Settling Rates at Full-Scale FGD Systems Expressed as Thickener Unit Area

Site	Process Type	Solids Oxidation, mole %	Typical Feed Slurry Solids, wt%	Calculated Unit Area for 30% Solids in Underflow, m^2-day/tonne	Maximum Settled Solids Content, %
1	Limestone-based Forced-oxidation	99+	17	0.1-0.4	65
2	Limestone-based Inhibited-oxidation	4	10	0.2	63
3	Limestone-based Inhibited-oxidation	13	17	1-3	40-44
4	Limestone-based Inhibited-oxidation	19	13	2.5	33
5	Lime-based Inhibited-oxidation (magnesium-enhanced)	9	9	2-3 (for 15% solids in underflow)	24

intentionally operated under these conditions. The calculated unit area (for a 30%-solids underflow) for slurry from this system was within the range seen at Site 3, but the maximum settled solids content was much less, at only 33 percent. Solids from limestone-based processes that operate with oxidation fractions in the 15 to 40% range are typically more difficult to dewater than those from processes operated at lower oxidation fractions.

Site 5 was a magnesium-enhanced lime-based FGD process operated with 9% oxidation. Settling tests for this slurry failed to obtain a 30%-solids underflow, and the unit area required to obtain only a 15%-solids underflow was similar to the high end of the observed range for the limestone-based processes with a 30%-solids underflow. The final settled solids content for this slurry was only 24%, which is also the lowest observed for all five of the sites. In general, slurry from magnesium-enhanced lime-based FGD processes is the most difficult to dewater of any wet FGD slurry. However, more recent process designs for magnesium-enhanced lime-based systems have taken advantage of research showing that operation with lower slurry solids content in the reaction tank produces byproduct solids with greatly improved dewatering properties (1,2).

Table 11-2 summarizes typical recommended design ranges for thickener unit area and underflow solids contents for different lime- and limestone-based FGD process conditions (3). Note that thickener designs for the limestone-based inhibited-oxidation process do not usually extend to the rapid settling conditions and low unit area measured at Site 2 above because it is difficult to predict whether or not oxidation can be maintained below 5% at a given site.

Trade-off with Filter/Centrifuge Size

There is obviously a design and cost trade-off in thickener sizing in that the thickener can be sized larger or smaller to produce a higher or lower underflow solids content. The underflow solids content, in turn, affects the design size and cost of the secondary dewatering equipment--vacuum filters (see Part I, Section II-13) and centrifuges (see Part I,

Table 11-2

Recommended Design Conditions for Thickeners in FGD Service

Process Type	**Thickener Unit Area, m^2-day/tonne**	**Underflow Solids Content, %**
Limestone-based		
Forced-oxidation	0.3-0.8	40-55
Inhibited-oxidation	1-2	30-45
Natural-oxidation	1-3	30-40
Lime-based*		
Inhibited-oxidation	2.5-4	25-35

* Magnesium-enhanced lime.

Section II-14)--that are used for final dewatering of the byproduct solids. Therefore, the optimum thickener size would normally be selected by evaluating the total annualized cost of the integrated primary and secondary dewatering equipment.

Polymer (Flocculent) Use

A flocculent is a chemical additive that is designed to improve the settling properties of the thickener feed slurry by forming agglomerates of fine and coarse particles. Flocculents used in FGD service are typically high-molecular-weight anionic polyelectrolytes that neutralize the surface slurry particles' charge and help form physical (as opposed to chemical) bonds between colliding particles. Polymer dosages are typically in the range of 0 to 2 parts per million by weight of feed slurry. Polymer can be purchased in dry, emulsion, or solution form. It is typically added to the thickener feed slurry as a nominal 1% solution, requiring a low volumetric dose rate of 1/10,000 relative to the feed slurry flow rate. Depending on the properties of a specific slurry, a flocculent can decrease the required thickener unit area by up to a factor of five and will usually improve overflow clarity.

Studies have shown that optimum use of a polymer can reduce the annualized cost of FGD solids dewatering by 0 to 40%, but in practice, thickener designs for utility FGD systems are rarely based on polymer addition as a base case (3,4). Because of the significant uncertainty in slurry dewatering properties and the known variation in properties as a function of boiler operation, the thickener is conservatively sized to yield the desired slurry concentration without polymer, and polymer use is reserved as a backup operating measure in case the actual thickener performance does not meet the design objective.

Thickener Operation

Under ideal steady-state conditions, a thickener will yield constant underflow and overflow solids contents and flow rates at constant feed conditions, and the solid-liquid interface in the thickener will be maintained at a specific elevation. However, utility FGD systems rarely operate at steady conditions. Instead, the volume and solids content of the feed slurry may change with boiler load swings and with fuel sulfur content. To accommodate these changes in feed conditions, the solids inventory and interface height in the thickener are allowed to vary somewhat, and the thickener is operated to maintain a relatively constant underflow solids content. A constant underflow solids content is usually desirable to maintain optimum performance of the secondary dewatering equipment.

The usual means of controlling the underflow solids content is by controlling the rate at which underflow slurry is removed from the thickener. The thickener underflow pumps are normally operated continuously to avoid plugging problems that can occur with high solids concentrations. In some systems, variable-speed pumps are used, and the underflow pumping rate is adjusted to match thickener feed conditions so that the proper underflow solids content is obtained. In other systems, constant volume pumps are used and the slurry is either pumped to the underflow slurry storage tank (for feed to secondary dewatering equipment) or recycled to the thickener feedwell. Some recycle capacity is always provided, even with variable speed pumps, so that the pumps can be run when the slurry storage tank is full. When the underflow is recycled, the thickener solids content increases, providing some surge capacity in the dewatering system.

11.2.2 Mechanical Design Considerations

Rake and Lift Configuration

The different rake and lift configurations described above have inherent advantages and disadvantages. The bridge-supported mechanism is usually less expensive for smaller thickeners [less than about 40 m (130 ft) in diameter] and the center column-supported mechanism is preferred for larger diameters. The bridge-supported mechanism also has the advantage of a less obstructed underflow discharge cone and a simpler, more accessible lift mechanism.

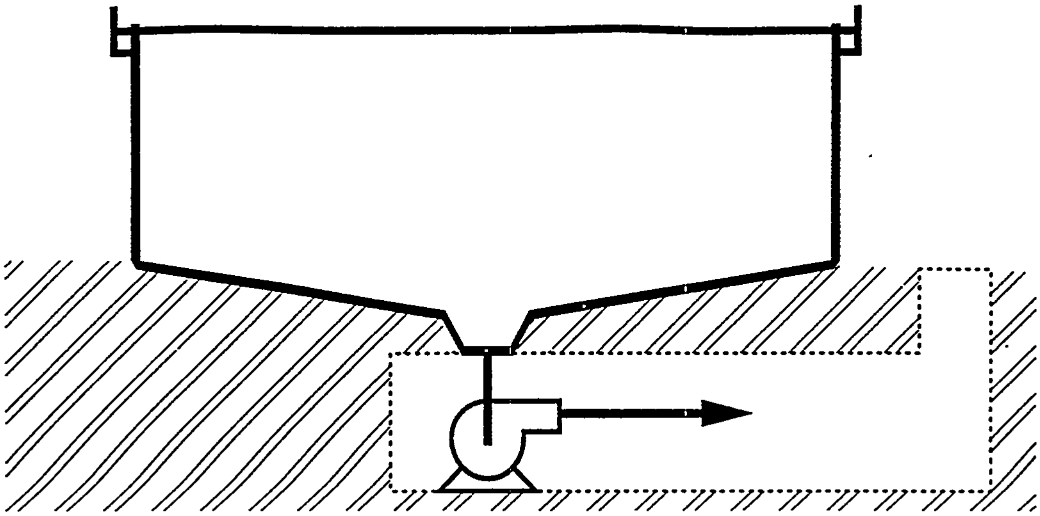
Cable-supported rakes are less expensive than truss-style rakes, but the cable-supported rake does not provide positive control of rake height, permitting the rake to "ride up" on thickened slurry or other deposits on the thickener bottom. The cable-supported rakes also use the center-pivot style lift mechanism, where the center end of the rake is pinned to the drive and the lift clearance increases along the length of the rake (see Figure 11-2b). This type of lift mechanism may not provide sufficient clearance to avoid high-torque problems when upset conditions cause high slurry solids content. Truss-style rakes may also use a center pivot lift, but are usually lifted by lifting the entire drive shaft or cage, providing equal clearance along the length of the rake (see Figure 11-2a).

The cable-supported rake does have the advantage of having less structure exposed to the dense slurry at the thickener bottom, generating less torque on the drive. One type of truss-style rake is designed with rake blades on posts that extend below the rake truss. This "thixo-post™" design permits the truss to move above the densest slurry at the bottom of the thickener, thereby allowing higher solids concentrations to be reached with less torque on the drive and rake.

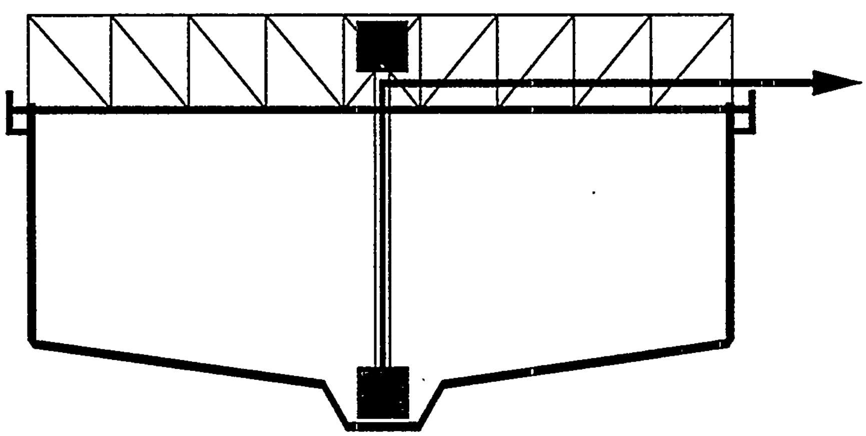
Lift mechanisms may be manually operated or power-operated. In the latter cases, rake lift can be initiated automatically whenever the rake torque (measured by a torque sensor on the drive) exceeds a certain percentage of the maximum allowed. Alternatively, the rake lift can be manually actuated by an operator based on the torque reading. The torque sensor usually actuates a high-torque alarm in the control room.

Underflow Pump Configuration and Type

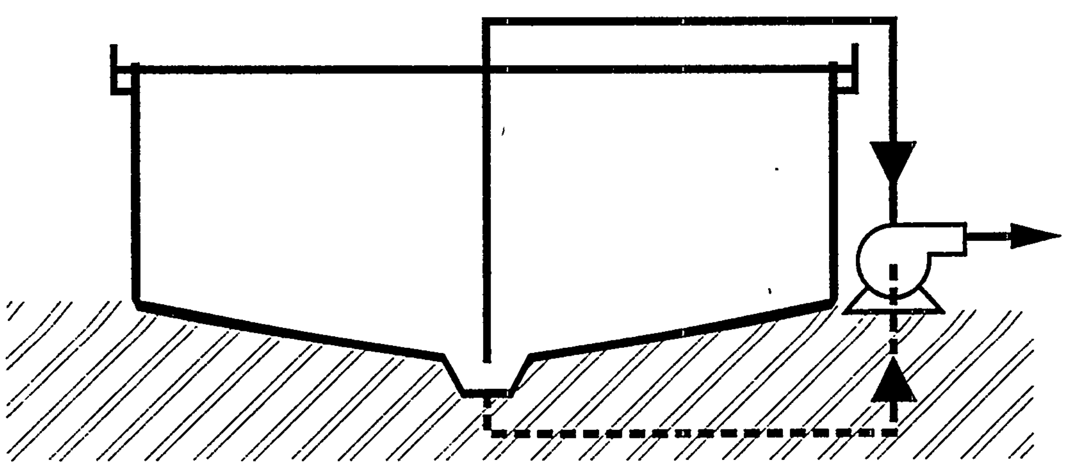
There are several possible underflow pump configurations. Three of these are illustrated in Figures 11-4a, b, and c. The most expensive approach is the underground access tunnel (Figure 11-4a). With this approach, the underflow pumps are located immediately below the discharge cone beneath the thickener. This arrangement provides short pump suction lines with positive suction pressure and complete access to all of the lines and valves.



a)- Underflow Pumps in Tunnel



b) Vertical Underflow Pump on Center Column



c) Underflow Pump on Grade with Overhead or Underground Suction Line

Figure 11-4. Underflow Pump Configurations

It generally results in more trouble-free operation and permits discharge and pumping of the most concentrated slurries.

A vertical pump may be used in the center-column design (Figure 11-4b). This arrangement gives nearly the same slurry pumping capability of the tunnel design without the need for the tunnel. Maintenance access to the pump and impeller is more difficult, however, and lifting the pump for repairs requires a crane or overhead winch.

The underflow pump may also be mounted on-grade outside the thickener perimeter (Figure 11-4c). In this case, the suction lines may be routed either along the access bridge or under the thickener (with or without an access tunnel). Placing the suction lines under the thickener without an access tunnel is the least expensive alternative but presents the most difficulty in clearing suction line plugging problems. Compared to other underflow pump location alternatives, placing the pumps on grade results in longer suction lines and reduces the available pump suction pressure. Relatively minor line pluggage can cause pump cavitation as a result of insufficient net positive suction head, and damage to the pump.*

Centrifugal, progressing-cavity, and diaphragm pumps have been used for thickener underflow slurry. Variable speed pumps are useful for operating over the entire load range that might be experienced without the need for throttling the concentrated slurry.

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* Liquid is not drawn into a pump. A positive liquid pressure must be provided to push the liquid into the pump. The required pressure is termed the "net positive suction head" or NPSH and is a function of the specific pump's design. The available NPSH is a determined by the liquid's static pressure, the suction line's diameter and length, and the liquid flow rate. Flow constrictions, such as suction line deposits, can reduce the NPSH at the pump suction of an otherwise properly designed system and cause pump cavitation. Cavitation is the vaporization of a portion of the fluid due to the liquid pressure falling below the fluid's vaporization pressure at the operating temperature. The bubbles of gas that form then collapse when they reach the higher pressure region of the pump impeller. This collapse causes severe vibration and can damage the pump.

11.2.3 Other Considerations

High-Rate Thickeners

Several manufactures offer "high-rate" thickeners that use more sophisticated internal arrangements and carefully controlled flocculation to substantially increase settling rates and decrease the thickener's space requirements. These thickeners have not generally been used in FGD service where the emphasis is on simplicity and conservative design. However, high-rate thickeners may be considered and evaluated for applications where available site area is restricted.

Sparing Approach

Continuous thickener operation is critical to the reliability of the entire FGD system. Operation of the FGD system without primary dewatering of the byproduct solids will usually be possible for 24 hours or less. If thickener repair involves draining the thickener tank, the repairs may require several days to complete. Therefore, the typical FGD process design includes two thickeners with cross-connected feed slurry piping and a common overflow tank. Underflow pumps are usually dedicated to each thickener and are not cross-connected. Because thickeners are usually conservatively sized and their performance can be upgraded with polymer addition when necessary, the two parallel thickeners are most often designed for 67% of full-load capacity. In this way, the temporary loss of one thickener for maintenance has a relatively minor effect on FGD operations. Full-load operation may be possible with one thickener by using polymers. At low unit load or when burning coal with a sulfur content lower than the design value, one thickener may be sufficient to process all of the byproduct solids produced.

Drain and Fill Requirements

Occasionally, maintenance requirements on submerged thickener mechanisms, such as the rakes, require the thickener tank to be drained. Thickeners can contain a large portion of the total liquid volume in an FGD system. In many cases, a temporary slurry storage pond is provided to contain the entire volume of one or more thickeners so that they can be drained for maintenance. To avoid generating large volumes of wastewater, a means of returning the process liquor from the pond to refill the thickener(s) is also recommended.

11.3 Material Selection

As with other process equipment, thickener materials are selected according to the corrosive environment that is expected. The operating conditions in the thickener are similar to the conditions in the absorber reaction tanks except for pH and slurry solids concentration. The pH of the thickener is in the range of 6 to 8, which is less corrosive than other process areas, but the process liquor chloride content may cause moderately corrosive conditions. The slurry solids concentration on the thickener floor may exceed 50 percent.

The thickener floor is usually sulfate-resistant concrete and may be lined for additional protection. The thickener shell is most often lined carbon steel or concrete. Vitreous ceramic tile has also been successfully used for fabrication thickener tanks. The properties and expected life of coatings for carbon steel are discussed in detail in Part I, Section I--Materials-of-Construction Options.

Thickener mechanical components are fabricated from a variety of materials of construction, depending on their exposure to corrosive and erosive conditions. Drive and rake components that are submerged in the process slurry must resist erosion as well as corrosion and are most often fabricated of rubber-lined carbon steel. The overflow weirs and piping are typically fiber-reinforced plastic (FRP), a corrosion-resistant alloy, or rubber-coated steel. Mechanical components that are not exposed to the process liquor may be carbon steel with typical industrial finishes. Drive components such as gears and bearings are made of appropriately hardened materials for extended service life.

The rake and other submerged components are very difficult to inspect while in operation and cannot be repaired without draining the thickener. Small cuts or seam failures in the rubber-lined components can result in localized corrosion that can progress to extensive liner delamination and even structural failure. For this reason, the quality of the rubber lining applied to submerged parts is critical and the linings should be protected from damage during thickener maintenance.

11.4 Recommendations

- Two parallel thickeners should be specified for a single unit, each with 67% or greater capacity. A common, shared spare can be considered for multiple-unit FGD systems.
- Two 100%-capacity underflow pumps for each thickener should be specified. Variable speed pumps are useful if wide fluctuations in unit load or fuel sulfur content are anticipated. Provision should be made for recycle of underflow slurry to the thickener feed.
- Conservative thickener designs are usually sized without considering the benefits of polymer flocculents, but designs with flocculent should be considered for thickeners in applications with restricted site area.
- If possible, a temporary slurry storage pond should be provided for drainage of a thickener during maintenance. The contents of this pond should be used to refill the thickener(s) when maintenance is complete.

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12.0 HYDROCYCLONES

Hydrocyclones (also commonly called hydroclones) are devices that use centrifugal forces to classify and concentrate FGD system process slurries. In FGD systems, they are most commonly used to control the reagent slurry particulate size in closed-circuit limestone grinding systems (see Part I, Section 4.7.2--Limestone Reagent Preparation Equipment) and to provide primary dewatering of the absorber module bleed stream (see Part I, Section 4.8.1--Primary Dewatering). The same basic principles apply and the same equipment is used in both applications.

12.1 Types Available

A typical hydrocyclone is shown in Figure 12-1. The slurry enters the inlet section of the hydrocyclone tangentially to the centerline, inducing swirling. Centrifugal forces direct the largest and densest slurry particles (those of greatest mass) toward the hydrocyclone's walls. As more fluid enters the hydrocyclone, these large, dense particles migrate downward into the cone section. The finer particles and those with a lower specific gravity (i.e., those with lesser mass) are less affected by the centrifugal forces, and relatively fewer of them move to the hydrocyclone walls (1,2).

Because the large, dense solids are forced to the walls, the solids concentration of the fluid at the walls is greater than in the center of the hydrocyclone. The center, lower-solids stream, containing predominately fine or low-specific-gravity slurry particles, leaves the hydrocyclone through the vortex finder. This stream is termed the hydrocyclone "overflow." The overflow typically leaves the hydrocyclone at atmospheric pressure, but pressurized discharge is also possible. The higher-solids stream at the wall, containing most of the larger or higher-mass particles and a smaller percentage of the fine particles, is carried to the bottom of the hydrocyclone and leaves through the apex finder. This flow is termed the hydrocyclone "underflow." The underflow also typically leaves the hydrocyclone at atmospheric pressure, but again, pressurized discharge is possible.

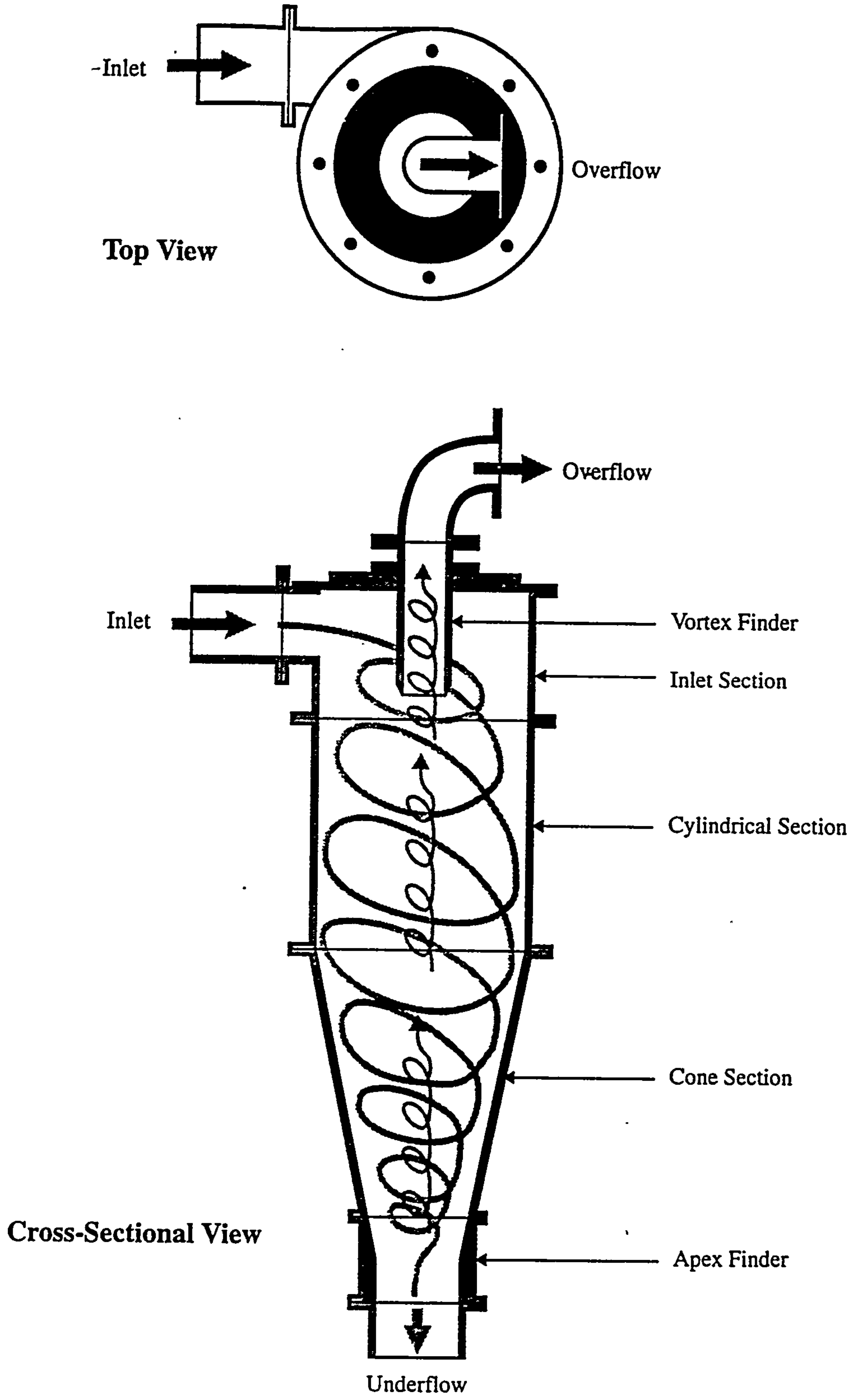

Figure 12-1. Typical Hydrocyclone

As will be discussed in Section 12.2.2--Mechanical Considerations, the performance of a hydrocyclone is determined by many factors, including its diameter, cylinder length, cone angle, and vortex and apex diameters. In order to optimize the performance of the hydrocyclone over a range of process flow rates, the hydrocyclones are usually installed in a cluster, with several identical hydrocyclones operating in parallel. As illustrated in Figure 12-2, the hydrocyclones' inlets are connected to a common cylindrical manifold. Each hydrocyclone is equipped with a knifegate-type inlet isolation valve so that individual hydrocyclones can be removed from service without affecting the operation of the others. The underflow and overflow from each hydrocyclone are collected in common underflow and overflow launders.

In a closed-circuit limestone reagent grinding system, the hydrocyclone equipment is used to remove oversized particles. The underflow, containing relatively coarse limestone particles, is directed to the feed end of the ball mill for an additional pass through the grinding circuit. The overflow, containing the fine limestone particles, is directed to the reagent storage tank.

In a byproduct solids primary dewatering system, the objective is to produce a concentrated underflow. The hydrocyclone feed slurry is typically 10 to 15% solids. Depending on the byproduct particle sizes, the underflow may contain 50% solids or more, and the overflow may contain as little as 4% solids. The underflow is directed to the secondary dewatering equipment; the overflow is either returned to the absorber modules or sent for additional processing to remove the fine solid particles. A secondary effect of using a hydrocyclone for dewatering is that the particles of unreacted limestone in the bleed slurry tend to be smaller and less dense than the byproduct solids, and tend to be retained in the overflow returned to the absorber module. Depleting the bleed slurry of unreacted limestone in this manner allows the solids in the absorber to have a higher level of unreacted reagent than the byproduct solids sent to secondary dewatering. This permits the FGD system to

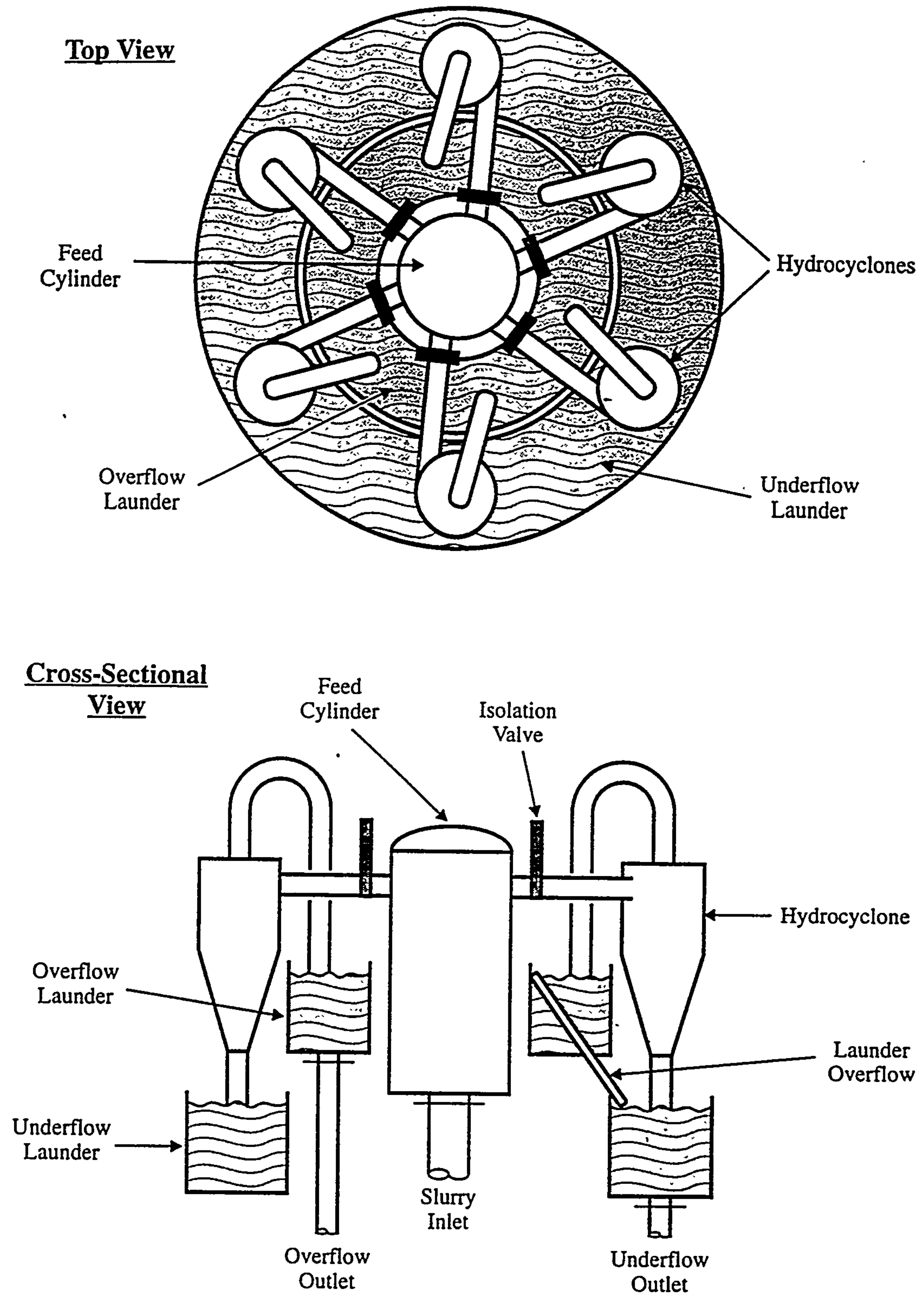

Figure 12-2. Hydrocyclone Cluster

minimize the limestone content of the byproduct solids, maximize limestone utilization, and still achieve high SO_2 removal.*

At some facilities, a second set of hydrocyclones is also used in processing a portion of the overflow from the primary dewatering hydrocyclones. A cluster of higher-efficiency cyclones is used to capture additional very fine particles (such as fly ash) from the overflow stream. The secondary hydrocyclone underflow, containing fine limestone particles, is routed back to the reaction tank. The overflow, containing very fine fly ash particles, is sent to wastewater treatment (see Part I, Section 4.9--Chloride Purge and Wastewater Treatment).

12.2 Design Considerations

12.2.1 Process Considerations

The two principal functions of hydrocyclones, classification and concentration of the slurry particles, are well illustrated by the use of hydrocyclones in the limestone reagent preparation system (classification) and the byproduct primary dewatering system (classification and concentration).

Classification

Because a hydrocyclone uses centrifugal forces to separate slurry solids from the fluid, the particles of greater mass are removed at a higher percentage than particles of lower mass. This classification effect of a hydrocyclone on an absorber module bleed stream

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* In an FGD system operating with a thickener, the unreacted limestone content of the absorber recycle slurry and thickener underflow are the same, and the same reagent ratio (utilization) would be measured in either flow. Because a hydrocyclone depletes the unreacted limestone level in the underflow, the reagent ratio measured in the underflow is lower (and utilization is higher) than measured in the absorber recycle slurry. Thus, compared to a thickener, the use of a hydrocyclone can reduce reagent consumption at the same SO_2 removal efficiency.

slurry is illustrated in Figure 12-3. Figure 12-3a provides typical data on the particle size ranges in the feed slurry, overflow, and underflow of a 150-mm (6-in.) diameter hydrocyclone handling the absorber bleed stream from a limestone-based, forced-oxidation FGD system. Figure 12-3b presents a curve of the recovery percentage (the fraction of the total feed that leaves in the underflow) for each particle size. The particle diameter at which 50% of the slurry particles report to the underflow is termed the D_{50} (1,2).

In this example, the specific gravities of the slurry solids and process fluid were 2.32 and 1.02, respectively. The feed slurry to the hydrocyclone was approximately 9 L/s (140 gpm) and had 15% solids. Both the underflow and overflow discharged at atmospheric pressure, and the pressure drop across the device was 165 kPa (24 psi). As seen in Figure 12-3a, approximately 90% of the feed slurry solids (by weight) were greater than 20 μm in diameter and less than 10% were larger than 60 μm. Approximately 50% (by weight) of the feed slurry solids were greater than 38 μm.

As shown in Figure 12-3b, the recovery percentage is a strong function of slurry particle size in the range of 3 to 45 μm. Below 3 μm, the recovery rate was less than 15%; above 45 μm, the recovery rate was greater than 95 percent.* The D_{50} for these data was 20 μm. This relationship between particle size and recovery percentage is reflected in the particle size distribution curves for the underflow and overflow. The underflow curve is above the feed slurry curve, indicating that it contained a higher percentage of coarse solids. The overflow is below the feed slurry curve, indicating that it contained a lower percentage of coarse material. Less than 15% of the overflow solids were greater than 38 μm.

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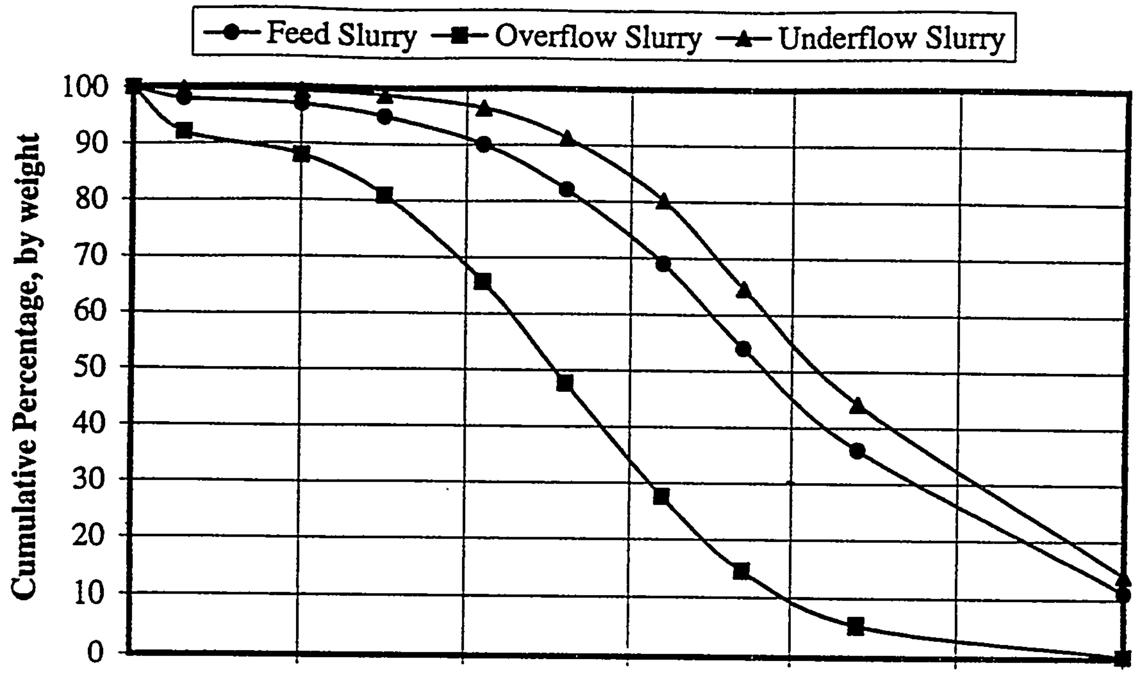
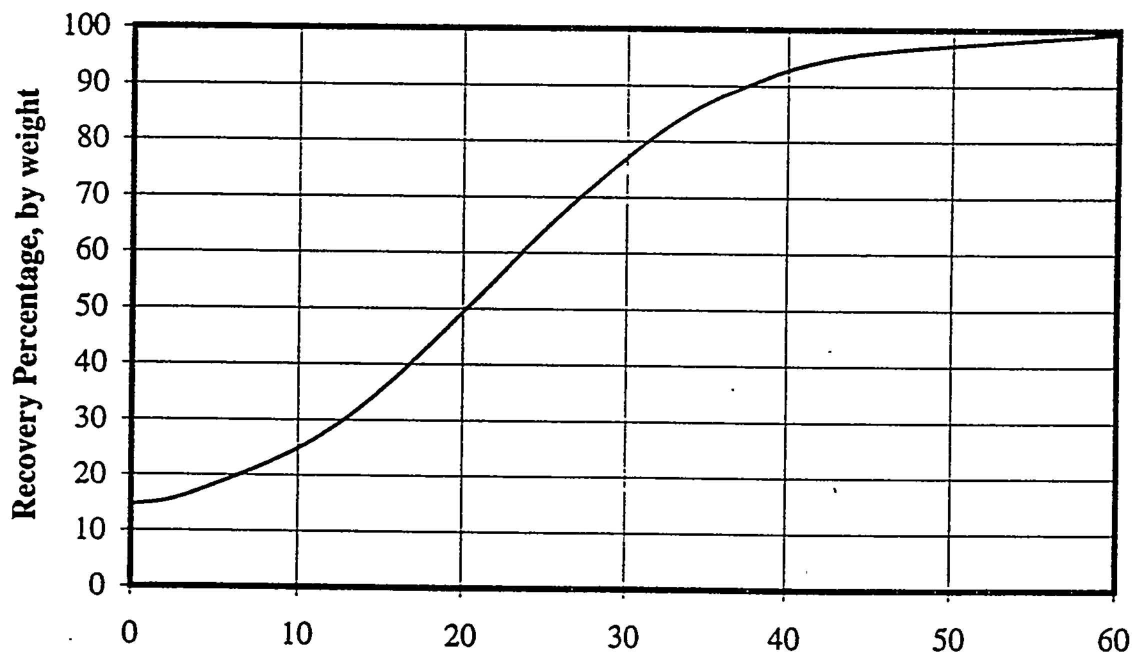
* Hydrocyclone performance is actually based on slurry particle mass rather than particle size. Since the example hydrocyclone performance data are based on a single slurry component (gypsum) it can be assumed that all particles have the same density, and that particle mass is directly proportional to size. When a slurry consists of a variety of components (such as calcium sulfate, calcium sulfite, calcium carbonate, fly ash, and inert material) with different densities, a larger percentage of the smaller-diameter, more-dense particles will be present in the underflow and a larger percentage of the larger-diameter, less-dense particles will be present in the overflow.



a. Particle Size Distribution



b. Particle Recovery Efficiency

Figure 12-3. Hydrocyclone Performance Curves

The example curves are based on a specific flow rate through the 150-mm diameter hydrocyclone. Since the D_{50} is a function of the magnitude of the centrifugal forces applied, at this same flow rate, a higher recovery rate for the finer particles would be experienced in a smaller diameter hydrocyclone, and a lower recovery rate for these particles would be experienced in a larger diameter hydrocyclone.

When the primary purpose of the hydrocyclone is to classify the feed slurry (as in a closed-circuit grinding system), the performance of the hydrocyclone is usually stated in terms of the percentage of the particles that are less than a specified diameter, measured in the overflow stream. In the example absorber module overflow curve, the hydrocyclone's classification performance could be stated as 90% less than 40 μm or as 95% less than 44 μm.

Separation

In Figure 12-3, the feed slurry was 15% solids. Under the test conditions, the underflow and overflow solids contents were 50 and 4%, respectively. Approximately 80% of the slurry feed flow [7.2 L/s (115 gpm)] left the hydrocyclone as overflow. This solid separation performance is comparable to a well-functioning thickener handling a comparable feed slurry. With the use of a polymer, however, a thickener would produce an overflow stream with less than 1% solids, and direct a higher percentage of the fine slurry particles to the underflow.

Separation, like classification, is dependent on a difference in specific gravity between the slurry solids and the fluid. Dense materials such as limestone (specific gravity of 2.93) and calcium sulfate (specific gravity of 2.32) are removed from the overflow better than less dense materials are. Fly ash, for example, may have a specific gravity of less than 2 and has a fine particle size.

The classification effect discussed above may result in differential separation of two components with different specific gravities and similar particle sizes, or similar specific gravities and different particle sizes. Obviously, the best separation occurs between a component that forms large, dense particles and one that forms fine, light particles. As discussed in Section 12.3--Process Considerations, this differential separation can have significant process benefits.

12.2.2 Mechanical Considerations

Hydrocyclones are relatively simple devices with no moving parts. Mechanical considerations include hydrocyclone sizing, process feed rate control, equipment sparing, and the use of easily replaceable components.

Hydrocyclone Sizing Procedures

Hydrocyclones are typically sized by the FGD system vendor or hydrocyclone manufacturer on the basis of their experience and pilot testing. In addition to the classification/separation performance requirements, the designer must consider feed slurry composition, particle size distribution, solids concentration, and flow rate; the particle specific gravity(ies); and available pressure drop. Good overviews of the procedures and correction curves used are provided in References 1 and 2.

The geometry of the hydrocyclone controls the underflow and overflow solids content and the D_{50} point. The aspects of hydrocyclone design that control its performance include the following (2):

- **Inlet Chamber Area.** The inlet chamber area is a factor in controlling the hydrocyclone's D_{50}; smaller inlets increase the inlet pressure and decrease the D_{50}, larger inlets have the opposite results. Typically, inlet areas are 6 to 8% of the total cyclone feed chamber feed area.

- **Cyclone Diameter.** The cyclone diameter controls the centrifugal force applied to the feed slurry. Larger diameters reduce the fraction of fine particles directed to the underflow (larger D_{50}).

- **Vortex Finder Diameter.** The vortex finder is the part most frequently replaced in operating hydrocyclones in order to change their performance. Larger diameter vortex finders reduce the fraction of fine particles directed to the underflow.

- **Cylinder Length.** Increasing the cylinder length increases the time the slurry is in the hydrocyclone and increases the fraction of the fine material directed to the underflow (smaller D_{50}).

- **Cone Angle.** Typical cone angles range from 10 to 20 degrees. Reducing the cone angle has the same effect as increasing the cylinder length.

- **Apex Finder Diameter.** The apex finder diameter controls the underflow solids content. Smaller diameters result in higher underflow solids content. If the diameter is too small, however, the D_{50} will increase as a higher fraction of the large diameter solids is directed to the overflow. The apex finder diameter is typically not less than 25% of the vortex finder diameter.

All of these design aspects depend on slurry feed rate. With the exception of apex diameter, all of these aspects are fixed for a given hydrocyclone, but can be changed, if necessary, by replacing one or more components. The apex finder diameter can be either fixed or can be controlled by the use of a concentric orifice valve (see Part II, Section 8.1.2--Pinch Valves. The control of the apex diameter provides more control of the classification/ dewatering process but increases capital costs and equipment complexity. As a result, most FGD systems rely on a fixed apex finder.

Process Feed Rate Control

The slurry feed flow rate (and specifically, the flow rate per hydrocyclone) is especially important to the selection of the hydrocyclone. As discussed previously, the classification performance varies with feed rate. Therefore, it is desirable that the feed rate either remains constant or has relatively low variability. This requirement offers no problem to the closed-circuit limestone grinding system classifier, since this system typically operates at a constant production rate, with the operating hours adjusted to meet the required daily reagent production requirement. The hydrocyclones for the limestone grinding circuit are typically selected by the limestone grinding equipment supplier. The utility engineer's role is limited to selection or approval of the limestone grind fineness [e.g., 90% less than 44 μm (325 mesh)].

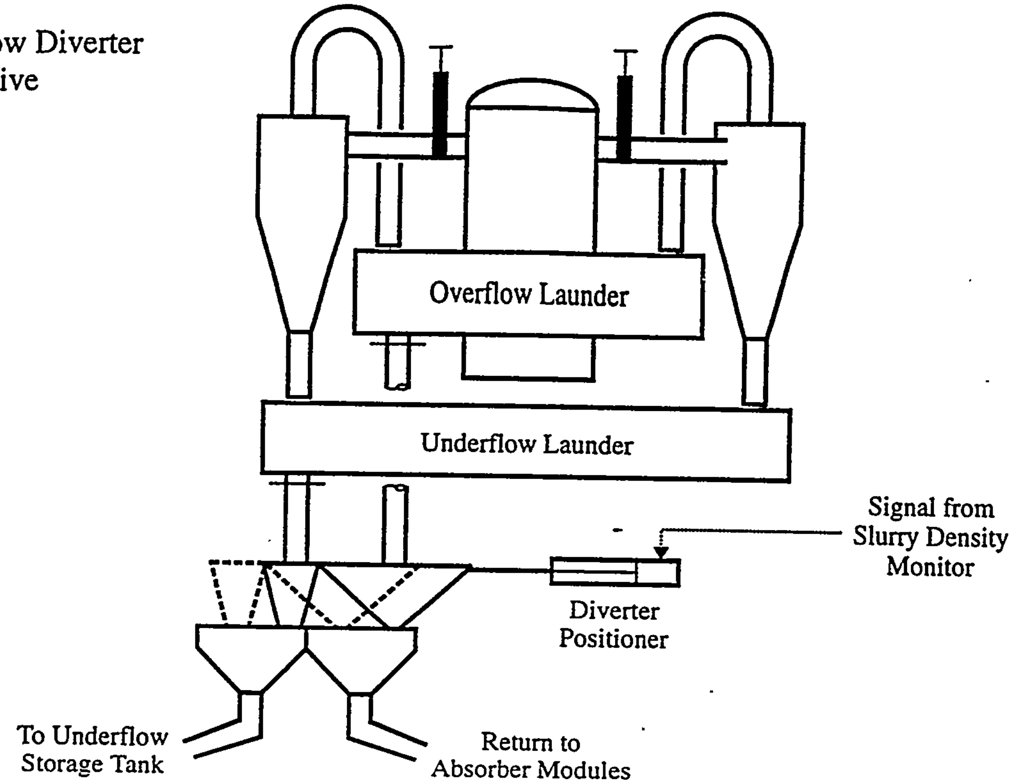
For a primary dewatering hydrocyclone, however, the absorber module bleed stream flow rate varies with unit load, coal sulfur content, SO_2 removal efficiency, and other factors. This flow rate variability can be handled in several ways.

One method used is to direct the bleed stream to the hydrocyclone cluster at a constant rate and to recycle a portion of the underflow back to the absorber modules along with the overflow. A schematic of such a system is shown in Figure 12-4a. In order to avoid additional pumping, the hydrocyclone cluster must be located relatively close to the absorber modules and sufficiently above the reaction tank such that gravity return flow is possible.

Another alternative is to discharge the bleed stream at a variable rate and place individual hydrocyclones in the cluster in and out of service as necessary to maintain relatively constant flow to each hydrocyclone, as shown in Figure 12-4b. This system reduces pumping costs and eliminates the physical hydrocyclone cluster's location limitations; however, it increases the wear on the hydrocyclone isolation valves and requires automatic valve actuators and additional controls.

A third alternative is to discharge the absorber module bleed stream intermittently at a constant flow rate. There are no significant starting or stopping problems with hydrocyclones, and design performance is achieved within a few seconds of startup. This method, however, may require frequent draining and flushing of the absorber module bleed stream lines. Hydrocyclones and their underflow and overflow discharge lines are usually free-draining and do not require flushing on shutdown.

a) Underflow Diverter Alternative



b) Isolation Valve Alternative

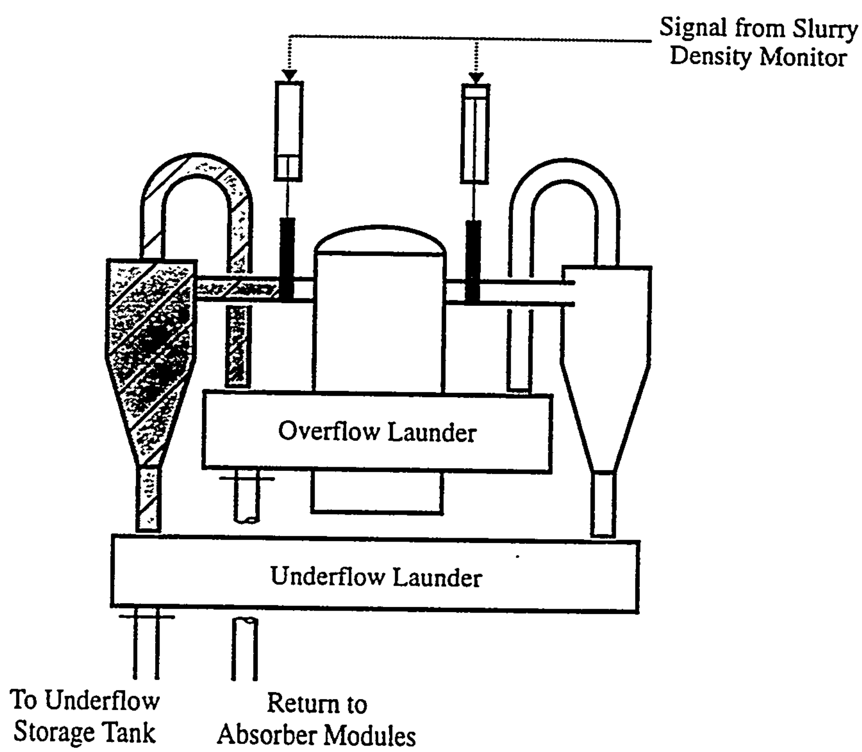


Figure 12-4. Blowdown Flow Variation Control Alternatives

Equipment Sparing

Regardless of the number of operating hydrocyclones in a cluster it is customary to include one or two spares in each cluster. A minimum of 20% spare hydrocyclones is recommended. This permits on-line maintenance of a hydrocyclone without affecting the processing capability of the system.

Use of Easily Replaceable Components

Each individual hydrocyclone can be relatively quickly and easily removed from a cluster for maintenance without disturbing the operation of the other hydrocyclones. It is relatively rare, however, that an entire hydrocyclone must be replaced. As was indicated in Figure 12-1, a hydrocyclone is composed of several individual sections that are bolted together. Each of these sections either uses an abrasion-resistant liner or is fabricated of an abrasion-resistant material, as discussed in Section 12.3. Replacement of individual hydrocyclone sections or liners can typically be completed within a few hours.

12.2.3 Other Considerations

As discussed earlier in this section, the use of a hydrocyclone for byproduct solids primary dewatering can result in differential separation of materials of different sizes and specific gravities. This differential separation effect can be beneficial in limestone-based FGD systems, especially those producing commercial-quality gypsum. Because particles of unreacted limestone reagent, reagent inert material, and fly ash tend to be smaller than the gypsum particles produced by a forced-oxidation FGD process, the overflow has a relatively higher concentration of these components than the underflow.

Differential separation has four important benefits. First, as discussed earlier, the return of unreacted limestone reagent to the FGD system reduces limestone consumption and, therefore, the FGD system's annual operating costs. Second, commercial-quality gypsum specifications contain requirements on the maximum amount of inert material (such as excess limestone reagent and fly ash) that may be present in the dewatered material. Hydrocyclones return a portion of the excess limestone to the absorber modules and direct the very fine fly ash particles to wastewater treatment. Third, commercial-quality gypsum specifications often require that the mean particle size of the dewatered material be 20 μm or greater. The removal of fine material, including small gypsum crystals, from the underflow stream increases the underflow's mean particle size. The hydrocyclone performance curve presented in Figure 12-3b showed that less than 50% recovery percentage was attained at particle sizes less than 20 μm in the example slurry. Finally, the performance of vacuum filters is significantly enhanced if the slurry to be filtered contains a relatively small amount of fine material. Fine particles tend to plug the pores in the filter cake and increase the time required for filter cake formation and drying. The fine particles also are more likely to blind the filter cloth with the same effect on formation and drying times. Increased cake formation and drying times either increase the size of the vacuum filters or reduce their processing rate (see Part II, Section 13.0--Vacuum Filters).

Unfortunately, the separation of fine particles from the underflow can create problems in the FGD system. Unless some mechanism is provided for purging fine, inert solids such as fly ash and limestone reagent inert material from the FGD system, these components can build up to appreciable levels in the absorber spray slurry. Since the FGD system operates at a relatively constant absorber spray slurry density, the buildup of this fine, unreactive material in the slurry displaces an equal weight of byproduct solids and reactive reagent solids. This affects the FGD chemical processes by reducing the concentrations of calcium sulfite and sulfate seed crystals and reagent ratio.

As stated earlier, at least a portion of the overflow from the primary dewatering hydrocyclones must be treated to remove these fine, unreactive particles. Typically, a small clarifier is used, often as the first step in the FGD system blowdown treatment system. As an alternative, a second set of higher efficiency hydrocyclones can be used to recover additional fine particles (primarily limestone) prior to sending the overflow (containing the very fine fly ash particles) to the treatment system.

12.3 Material Selection

Because of the use of abrasion-resistant liners, the body of a hydrocyclone can be selected on the basis of the pressure rating and compatibility with the process liquid. Carbon steel, aluminum, polypropylene, and fiber-reinforced plastic (FRP) have all been used. Nickel-plated or alloy bolting materials are preferred in order to facilitate disassembly.

The hydrocyclone abrasion-resistant liners may be fabricated of a variety of materials, including natural rubber, polyurethane, chromium alloy, and ceramics. Rubber is the least expensive material and is the most frequently used in areas subject to mildly to moderately abrasive conditions. In severely abrasive conditions, such as the lower cone area and the apex finder, ceramic materials are common. Available ceramic materials include silicon carbide, nitride-bonded silicon carbide, and aluminum oxide. Abrasion-resistant chromium alloy is used in severely abrasive areas where brittle, low-strength ceramic material may be unsuitable, such as the vortex finder. Generally, the liners of different materials are interchangeable, and if a material proves to be insufficiently abrasion resistant, it can be replaced with one that is more abrasion resistant.

The feed cylinder, underflow launder, overflow launder, and all piping are typically fabricated of rubber-lined carbon steel. Abrasion-resistant FRP can also be used. In some installations, the lines from the hydrocyclone overflows to the overflow launder are fabricated from rubber hose.

12.4 Recommendations

- Each hydrocyclone cluster should contain one or two spare hydrocyclones (20% spares, minimum).

- Hydrocyclones can initially use less expensive rubber linings. As areas of high wear are identified during operation they can be replaced with more abrasive-resistant materials as needed.

- The control of the buildup of fine particles in the FGD recirculating slurry must be considered in the design of the primary dewatering system and FGD system blowdown treatment system.

12.5 References

1. Arterburn, R.A. The Sizing of Hydrocyclones. Krebbs Engineers, Menlo Park, California, 1976.

2. Warman International, Inc. Warman Hydrocyclones. Madison, Wisconsin, undated.

13.0 VACUUM FILTERS

Vacuum filters are used for final dewatering of byproduct solids from wet lime- and limestone-based FGD systems. Vacuum filters typically process slurry that has been partially dewatered in a thickener or a hydrocyclone. Several filter types are available for this service. Each of these filter types operates on the same general principle. Slurry is fed to the filter, and a vacuum pump is used to draw air and process liquor through a permeable filter medium, while the separated solids are retained on the surface of the medium. The available vacuum filter types differ primarily according to the means by which the filter media are supported, the slurry is fed, and the separated solids are discharged from the unit. Selection and design of vacuum filters for FGD byproduct solids dewatering depends on the amount and physical properties of the feed slurry solids as well as the proposed byproduct solids disposal method or end use.

13.1 Types Available

Filter types that have been widely applied in wet lime- and limestone-based FGD service include the rotary drum filter, the drum/belt filter, and the horizontal belt filter. The rotary drum filter is illustrated in Figure 13-1. With this filter type, the slurry is introduced to a feed tank at the bottom of the unit. The feed tank is provided with a reciprocating paddle-type agitator to keep the feed solids in suspension. The filter medium is a cloth belt that is supported by the surface of a rotating hollow drum. The drum is divided into a number of individual segments, each of which has a shallow pan beneath the drum surface. A vacuum is applied from the drum interior to one or more of the drum segments, causing the slurry in the feed tank to be drawn to the surface of the submerged portion of the drum. The slurry solids are captured on the surface of the cloth, forming a "filter cake," and the liquid portion of the slurry, or "filtrate," is drawn through the cake and cloth and is discharged to a receiver/ separator tank located between the filter and the vacuum pump. Figure 13-2 shows a typical arrangement of the filter, receiver, and vacuum pump.

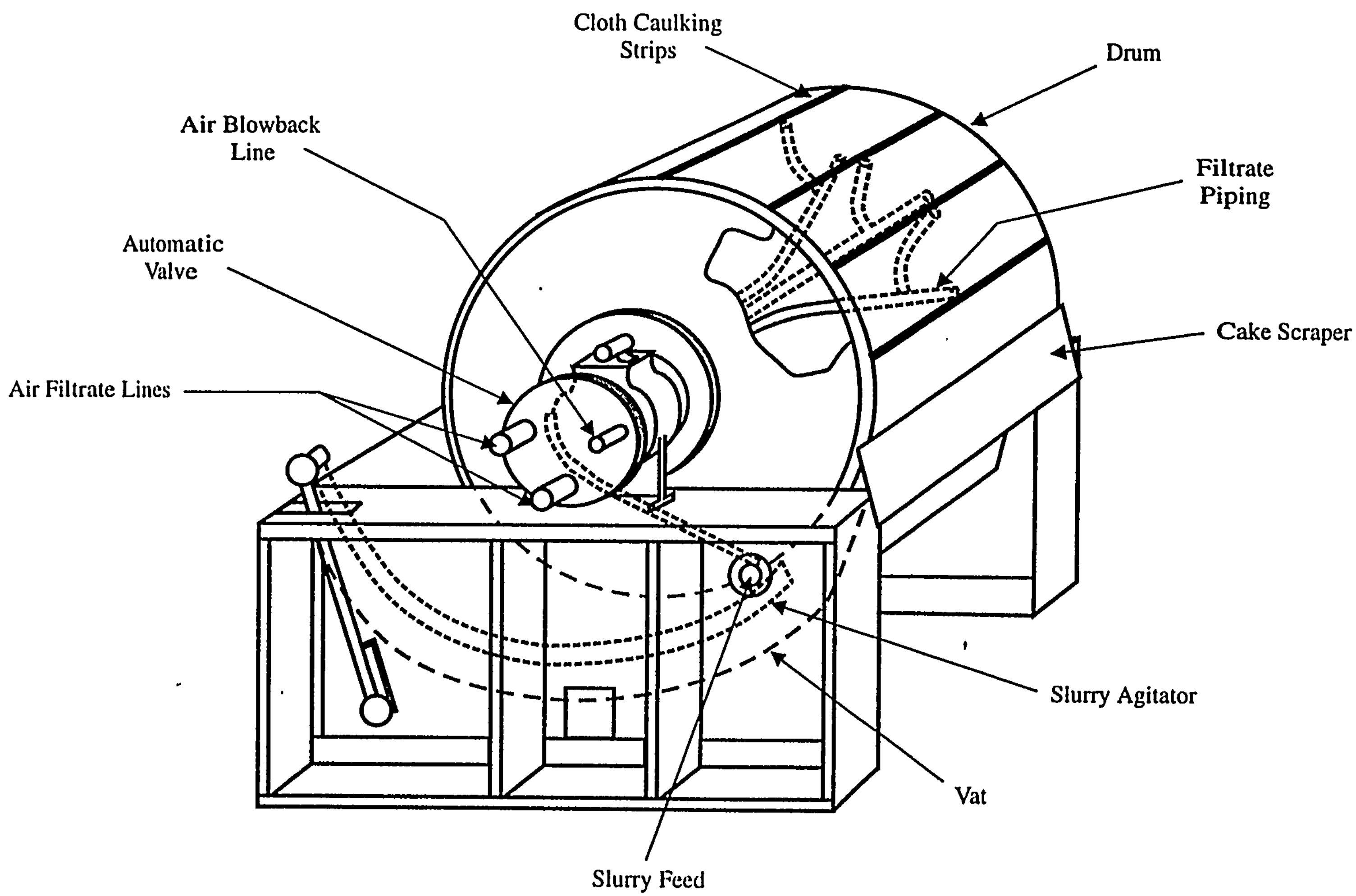


Figure 13-1. Typical Drum Vacuum Filter

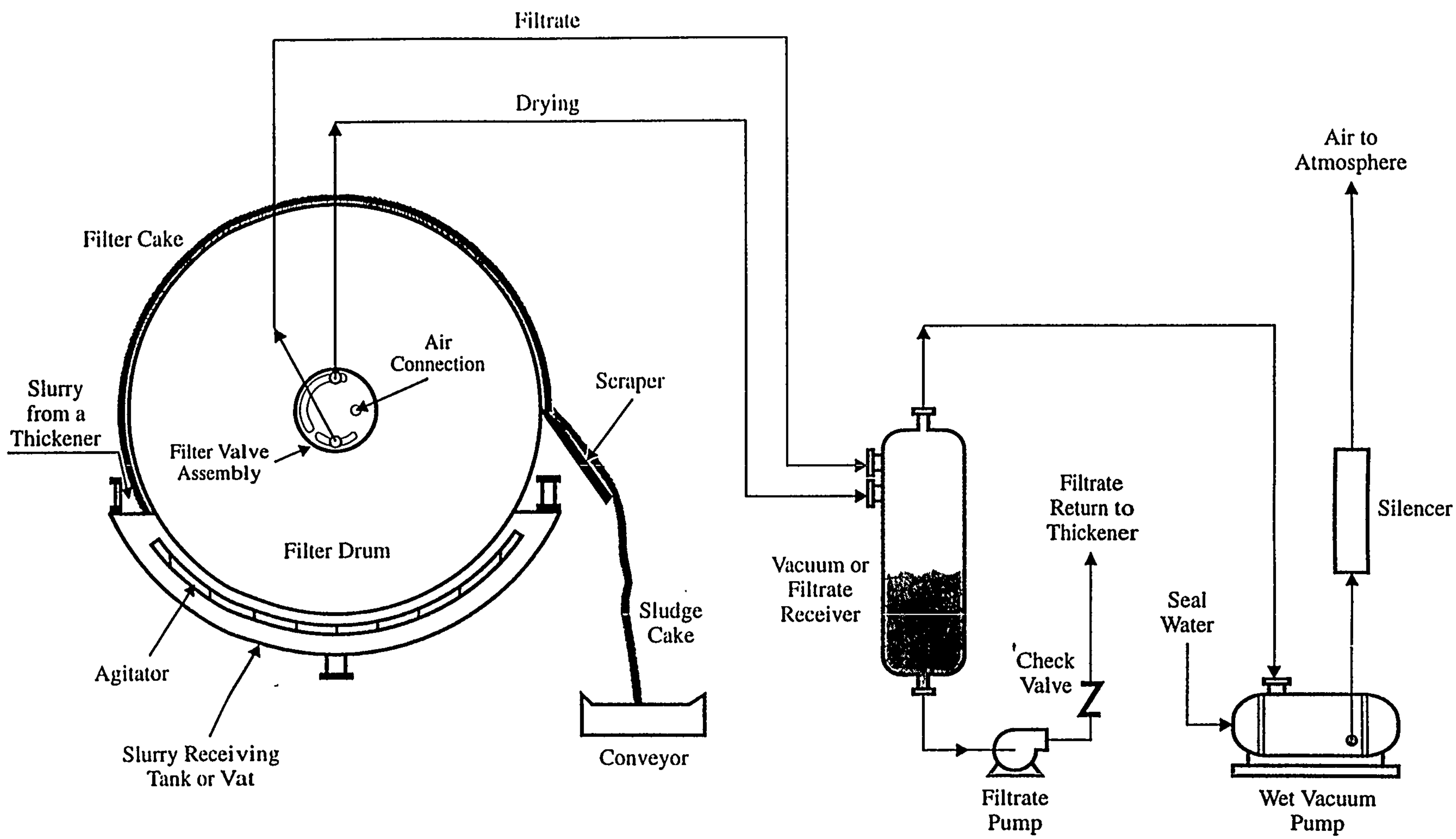


Figure 13-2. Typical Flow Sheet for Continuous Rotary-Drum Vacuum Filtration

The filter cake formed on the submerged portion of the drum is further dewatered as it rotates through the upper portion of the drum cycle, above the level of the feed tank. The dewatered cake may be washed with clean water during the latter part of the cycle to remove residual soluble salts. (Cake washing is usually required in processes that produce a commercial-quality gypsum.) The dewatered cake is removed from the cloth medium of the drum filter at the end of the rotational cycle by a scraper blade mounted close to the drum surface. To avoid wear of the filter cloth, the scraper blade does not actually touch the cloth. Compressed air may also be used to help dislodge the solids from the cloth of drum filters. The solids are removed by conveyor, and the drum and cleaned cloth then rotate through another cycle.

The drum/belt filter, which is illustrated by Figure 13-3, is similar to the drum filter except that the cloth medium is supported by a perforated rubber belt that travels on the surface of the drum. With this arrangement, the belt and cloth are separated from the rotating drum at the end of the rotational cycle and the filter cake is discharged as the belt and cloth bend over a small-diameter discharge roller. The cloth filter medium can then be washed from either side after the cake is discharged and before the filter cycle begins. Washing is an advantage if the slurry contains a large amount of fine particles, which tend to "blind" the pores of the filter medium. Blinding occurs when fine particles adhere to the fibers and clog the open spaces of the fabric structure, causing increased resistance and slowing the filtration rate.

With either type of drum filter, valves between the stationary axis and the rotating drum are used to control the intensity and duration of vacuum (or compressed air) applied to different segments of the drum and to direct filtrate to the receiver. The vacuum valves are designed to control the relative portions of the drum cycle that are devoted to the cake formation, washing, drying, and discharge functions; however, the relative portion of the drum surface that can be used for these different functions is obviously limited by the geometry of the feed tank, drum, and cake discharge mechanism. Typically, a maximum of about 30% of the drum surface can be used for cake formation, while about 20% is required

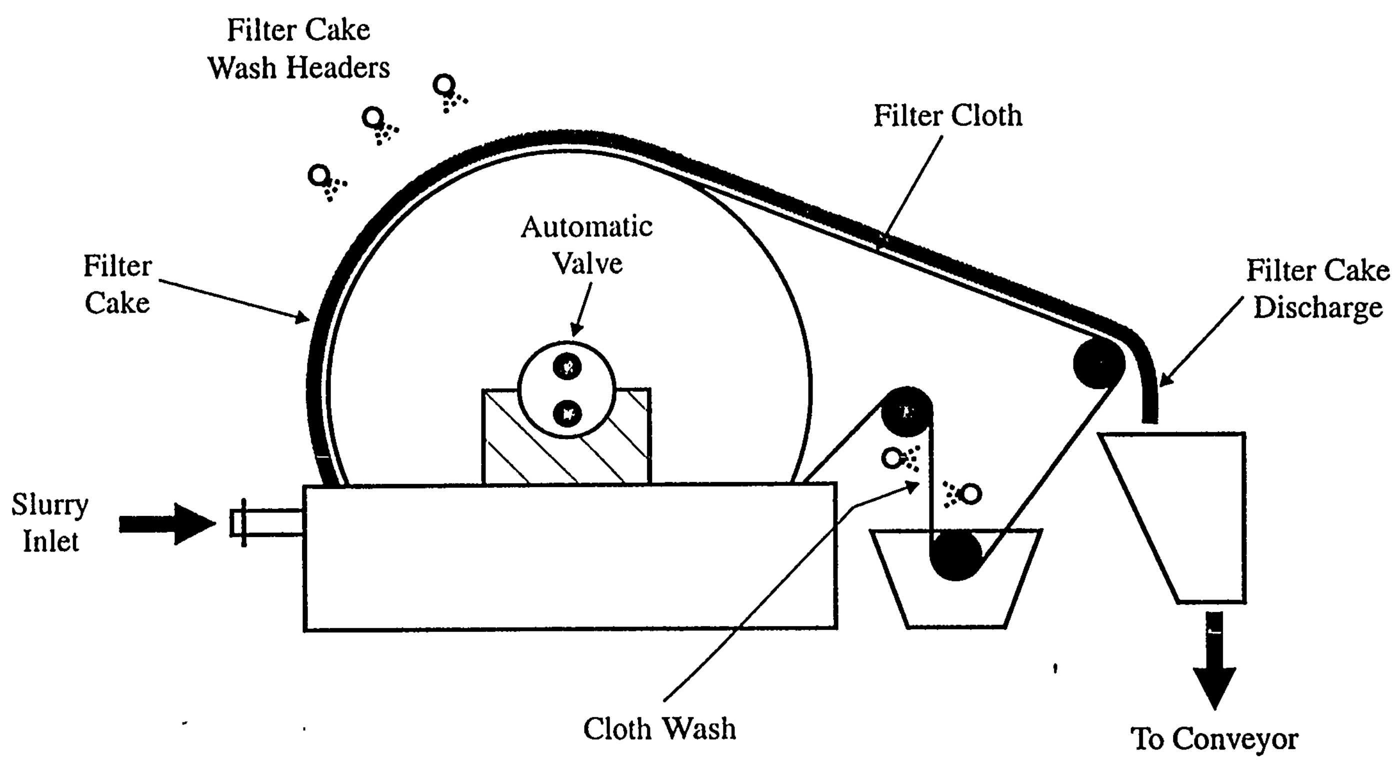


Figure 13-3. Typical Drum/Belt Vacuum Filter

for cake discharge. The remaining surface area can be divided between cake washing and dewatering. The optimal design of the filtration cycle is specific to each application.

The horizontal belt filter is illustrated in Figure 13-4. This filter uses the same general principle as the drum filter; a vacuum is used to draw the filtrate through a cloth medium, leaving the solids on the surface as a filter cake. Like the drum/belt filter, the horizontal belt filter uses a cloth medium that is supported by a perforated rubber belt, but in the horizontal configuration, the belt passes along the top of flat pans to which the vacuum is applied. The slurry is fed to the top of the horizontal belt filter through a distributor box at one end. At the opposite end, the filter cloth and supporting belt are separated. The cake is discharged from the cloth as it rotates around a small-diameter roller. The support belt rotates around a larger roller, and the cloth and belt are joined as they travel beneath the vacuum pans and return to the feed end of the filter. This horizontal configuration requires more floor area for the same filter medium area, but it offers some important advantages over the drum configuration. These advantages are discussed below.

13.2 Design Considerations

In the design procedure for vacuum filtration, the size and operating conditions for the filter are calculated on the basis of the filtration properties of the feed slurry. The filtration properties may be evaluated in bench-scale or pilot-scale equipment if the actual slurry is available for testing. In the case of a new FGD system, the expected slurry properties and filter design basis would be based on experience with slurry from existing FGD systems operating under similar process conditions.

In the following subsections, the vacuum filtration process design approach is first described. This process design discussion shows how filter design and operating conditions affect the three different steps in the filtration cycle: cake formation, cake washing, and cake dewatering. Then, filtration cycle design, filter selection, and important mechanical design options are addressed.

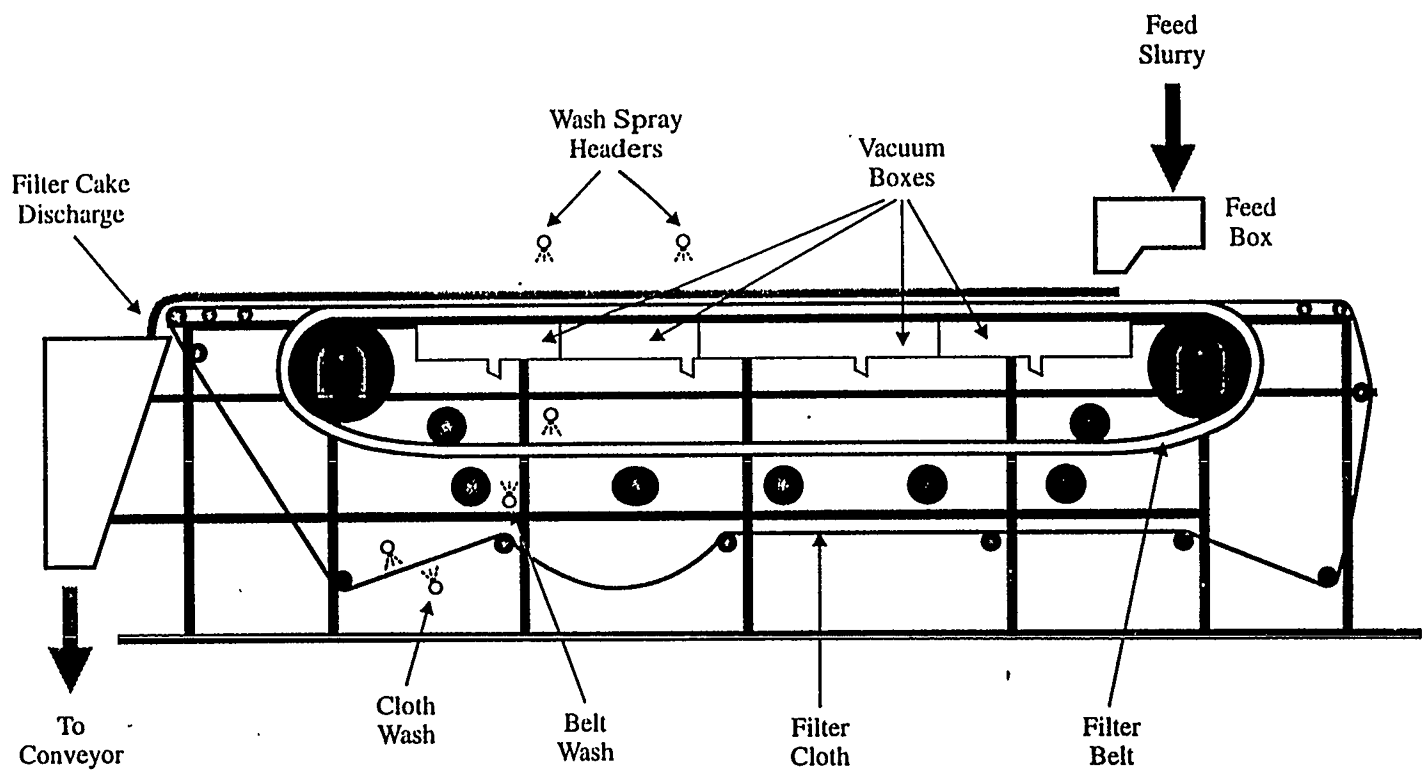


Figure 13-4. Typical Horizontal Belt Filter

In most cases, the utility engineer selects the type and number of vacuum filters to be used, and the actual design of the vacuum filter system is performed by the equipment vendor. The following information on vacuum filter design is presented for the purpose of assisting the utility engineer in understanding the operating principles involved.

13.2.1 The Filtration Cycle

The primary design parameter for vacuum filtration is the specific filtration rate [kg/s-m^2 (lb/hr-ft^2)],* which describes the amount of filter surface area required to process a given amount of solids per unit time. The total filter surface area required is the sum of the areas required for each of the sequential steps in the filtration cycle: cake formation, cake washing, and cake dewatering. The surface areas for each step are inversely proportional to the rates of each step:

- Cake formation rate--the rate at which the solid cake is formed on the filter medium;
- Cake washing rate--the rate at which the residual moisture in the cake can be displaced by clean wash water; and
- Cake dewatering rate--the rate at which the moisture is removed from the cake such that the cake moisture content approaches the minimum moisture content.

In general, the filter area required to process the same slurry will be different for each of the filter types, so that the relative costs and selection of the best filter type also depend on the relative rates of these steps in the filtration cycle. Design relationships for the individual steps in the filtration cycle are described below. The basis for these relationships is discussed in standard chemical engineering texts such as Perry's Chemical Engineers' Handbook (1), and McCabe and Smith, Unit Operations of Chemical Engineering (2). A

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* For simplicity and to improve the clarity of the text, the remainder of this section will use metric units only.

useful review and bibliography of filtration literature is given in Solid-Liquid Separation (3). More specific data and design considerations for FGD applications are given by Wilhelm et al. in Sludge Dewatering for FGD Products (4).

Cake Formation

Cake formation is described by the following equation:

$$W = k \sqrt{\left(\frac{2\ w\ \Delta P\ \theta_f}{\mu\ \alpha}\right)} \qquad \textbf{(13-1)}$$

where:

W	= the weight of solids per unit area of filter medium, kg/m^2;
k	= unit correction factor;
w	= the weight of solids per volume of filtrate, kg/m^3;
ΔP	= the applied vacuum, mm Hg;
θ_f	= the cake formation time of the filter cycle, s;
μ	= the filtrate viscosity, kg/m-s; and
α	= the specific cake resistance, m/kg.

This equation shows that the cake weight per unit area of filter (proportional to cake thickness) increases with increasing solids content of the feed slurry (w), the applied vacuum (ΔP), and the formation time (θ_f), and decreases with increasing viscosity (μ) of the filtrate and resistance (α) of the cake to filtrate flow. The cake resistance is primarily a function of the size and shape of the solids. Equation 13-1 suggests that the time required to obtain a given cake thickness can be decreased by operating with the highest practical slurry solids content that can be obtained by the primary dewatering equipment and maintained in suspension in the filter feed tank.

The first design objective for a given slurry and filter is to set the cake formation time, θ_f, to obtain the desired cake thickness at the end of the formation portion of the cycle. The allowable cake thickness varies with filter type. For drum- or drum/belt-type filters, the minimum cake thickness is usually about 4 to 5 mm. Thinner cakes are difficult to discharge. The maximum cake thickness for these filters is about 20 to 25 mm. Thicker cakes tend to fall from the drum before the discharge point. The horizontal belt filter can operate with a much thicker cake (up to 130 mm) because the cake cannot fall from the horizontal belt.

Cake Washing

For FGD systems that produce commercial-quality gypsum, the filter cake is usually washed with fresh makeup water to displace process liquor that contains dissolved salts. The required cake washing time, θ_w, is a function of the time required for the wash water to pass through the cake, and, therefore, is proportional to the cake thickness or cake formation time. The cake wash time is described by:

$$\theta_w = K \theta_f n \qquad (13\text{-}2)$$

where:

θ_w = cake wash time, s;
K = wash water flow constant, dimensionless;
θ_f = cake formation time, s; and
n = ratio of wash water volume to residual moisture volume in the cake, dimensionless.

The required wash water ratio, n, depends on the ratio of the required final salt content of the filter cake to the initial salt content (R), and on the wash efficiency (E) after a single displacement (n = 1):

$$R = \left(1 - \frac{E}{100}\right)^n \qquad (13\text{-}3)$$

As an example, with a typical wash efficiency of 70%, a tenfold reduction in the soluble salt content of the cake (R = 0.1) would require a wash rate ratio of 1.9.

Cake Dewatering

After the cake forms on the filter medium, additional moisture will be removed from the cake as air is drawn through the cake by the vacuum pump. For each specific filter cake, there will be a residual moisture content that cannot be further reduced without some form of evaporative drying. This residual moisture content is a function of the size, shape, and surface area of the solid particles. The rate of reduction in moisture content will be rapid at the beginning of the dewatering part of the filter cycle, but will slow as the inherent residual moisture content of the cake is approached.

For design purposes, the dewatering rate is described in terms of a correlating factor, θ_d/W, which is the ratio of the drying time of the filter cycle to the filter cake weight per unit area of filter (proportional to cake thickness). Figure 13-5 shows the shape of a typical dewatering correlation in which cake moisture content is plotted as a function of the correlating factor. In lime-or limestone-based FGD applications, it is usually advantageous to reduce the cake moisture to the lowest practical value. Therefore, the cake thickness and drying time are selected so that the design value of the correlating factor is just to the right of the steep part of the correlating curve. The design point can be obtained either with a thinner cake and shorter drying time, or with a thicker cake and longer drying time.

13.2.2 Filter Cycle Design

Once the rate relationships for cake formation, cake washing, and cake drying are established, either from experimental data or from similar full-scale applications, the required size and operating conditions can be calculated for any of the filter types. For the drum-type filters, however, the optimum formation, washing, and dewatering times cannot be independently fixed. This can be explained by examining the geometry of the drum and feed

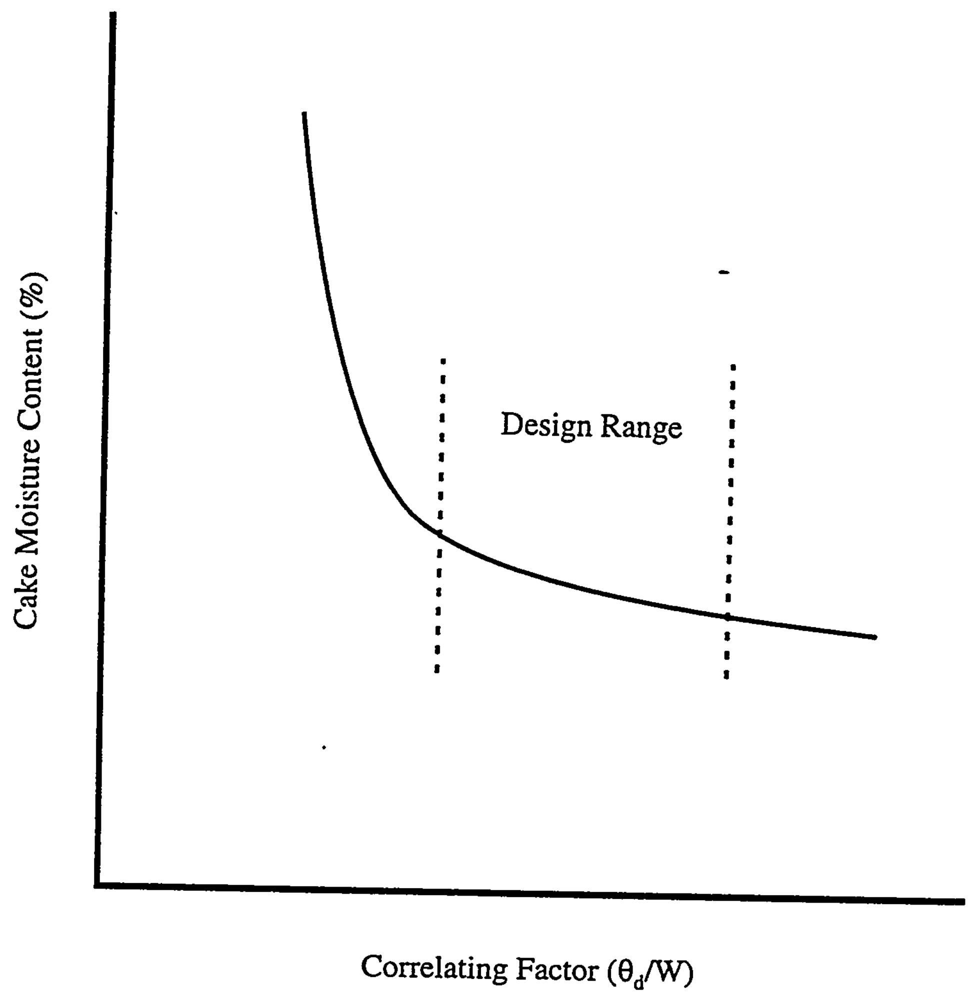

Figure 13-5. Typical Cake Dewatering Correlation

tank illustrated in Figure 13-6. This figure shows how the total portion of the drum filter cycle that is available for cake formation is typically about 30 percent. About 50 to 60% of the cycle is available for dewatering, if the cake is not washed.

Suppose, for example, that the cake density is 800 kg/m^3 and the design cake formation rate is 0.3 kg/m^2-s. Then the required cake formation time (θ_f) to form a 25-mm cake would be: 0.025 m times 800 kg/m^3 divided by 0.3 kg/m^2-s, which equals 67 seconds. Because only 30% of the total filter cycle time is applied to cake formation, the total required filter cycle time based on cake formation rate would be 67 seconds divided by 30%, which is 223 seconds. A typical scale-up factor of 0.8 would be applied to this result, yielding a design cycle time of 279 seconds. Because of the drum geometry, the maximum dewatering time at this filter speed is 60% of 279 seconds, or 167 seconds. If the actual required dewatering time is longer than this, then the cake would not be fully dewatered under conditions where the maximum filter cake thickness is obtained. In this case, the slurry level in the feed tank would need to be lowered or the formation vacuum decreased to obtain a thinner cake and the drum speed slowed to obtain better dewatering. Alternately, the amount of submerged drum surface that is under vacuum could be reduced by changing the vacuum distribution valve setting.

Similarly, the cake formation time might be slow compared to the dewatering time. This would be the case, for example, with cakes that crack during dewatering, preventing efficient dewatering. In that case, the optimum drum speed might be slower, to form a thicker cake, and the vacuum valves would be set to form cake on the entire submerged portion of the drum. Vacuum would be applied to only a portion of the drying area of the cycle. In this case, however, some of the total drum area would be surplus in that it would not contribute either to cake formation or cake dewatering.

If washing is required, the wash rate would also be considered and it might also affect the design drum speed.

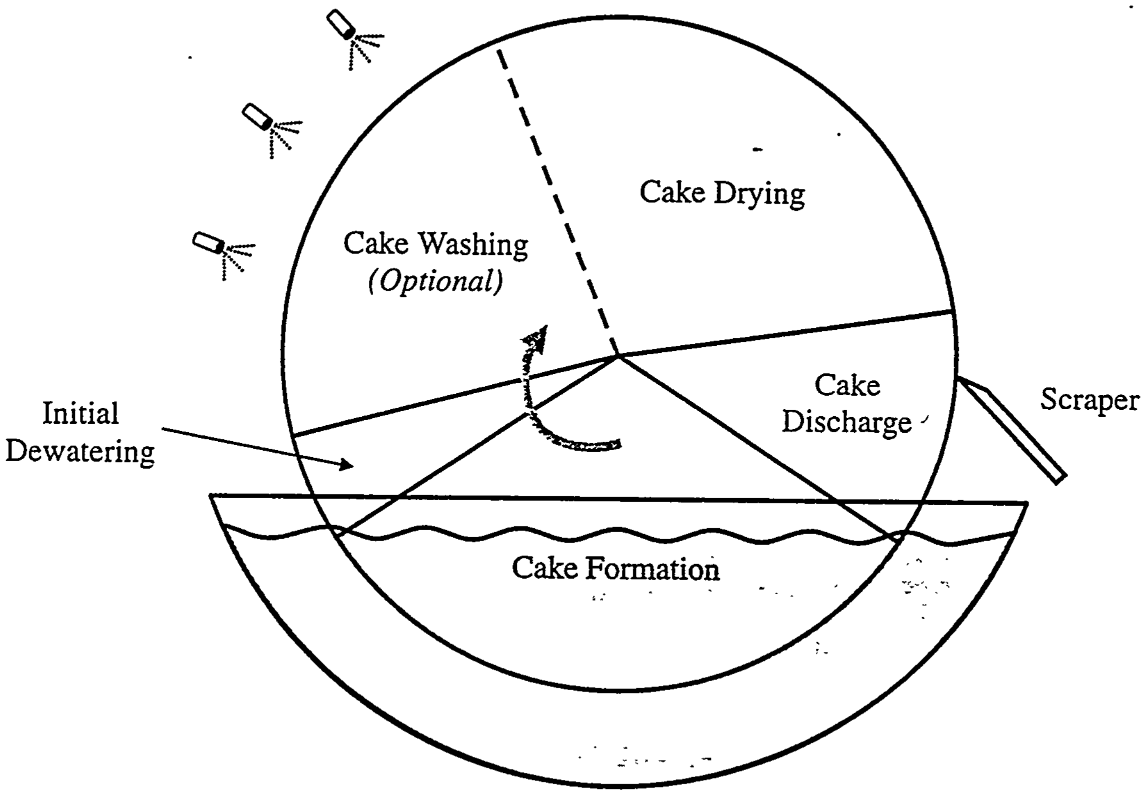

Figure 13-6. Operating Zones of a Rotary Drum-Type Vacuum Filter

The above design limitation for drum and drum/belt filters does not apply to the horizontal belt filter because the vacuum pan arrangement beneath the belt and the belt speed can be "customized" to obtain any required ratio among form time, wash time, and dewatering time. Therefore, all of the belt filter top surface can be used effectively. The ability to optimize the filtration cycle is one advantage of the horizontal belt design. As a result, horizontal belt filtration rates for actual FGD solids range from about 20% to 100% higher than the drum filtration rates.

Laboratory filter-leaf test data were recently reported for slurries from five different full-scale FGD systems that were part of a U.S. Department of Energy-sponsored study of high-efficiency scrubbing (5). Data from four of these systems are summarized in Table 13-1 to illustrate some typical filtration properties of FGD slurries produced under different operating conditions. In all of these tests, a slurry containing 30% solids was filtered under 500 mm Hg of vacuum to form a 12- to 25-mm thick cake. The cake was then dewatered for 120 seconds, which would typically result in the lowest practical moisture content for FGD solids. The filter cake formation rate ($kg/s\text{-}m^2$), cake form time, cake density, and final cake solids content are shown in the table. Also shown is the final vacuum level at the end of the dewatering period.

As expected, the highest cake formation rate and highest final solids content were observed for the slurry from the limestone-based, forced-oxidation process. The gypsum solids produced in this process type are typically more easily dewatered than the calcium sulfite solids produced in the inhibited-oxidation process. With proper filtration cycle design, gypsum solids can usually be dewatered to more than 90% solids. The gypsum solids also produce the highest cake density.

The filtration properties of solids from limestone-based, inhibited-oxidation processes can vary substantially, primarily because of variations in the extent of oxidation. When the oxidation fraction is less than about 0.05, calcium sulfite solids can exhibit

Table 13-1

Filter Leaf Test for Four FGD Systems (30 Wt% Solids in Feed Slurry)

Process Type	Solids Oxidation, %	Cake Formation Rate, $kg/s\text{-}m^2$ at 500 mm Hg Vacuum	Form Time for 25-mm Cake, s	Cake Density, kg/m^3	Solids Content After 120 s Dewatering, % solids	Vacuum at End of Dewatering, mm Hg
Limestone-based forced-oxidation	99+	0.5-1.6	20-50	700-800	78-86	350-500
Limestone-based inhibited-oxidation	3-4	0.3-0.9	20-60	670-760	68-71	400-450
Limestone-based inhibited-oxidation	12-13	0.3-0.5	30-80	560-750	52-58	380-460
Lime-based* inhibited-oxidation	7-10	0.1-0.3	40-80	450-500	39-44	150-200

* Magnesium-enhanced lime.

Source: U.S. Department of Energy (5)

dewatering properties that are nearly as favorable as for gypsum solids. When the oxidation fraction approaches 0.15, the solids are more difficult to dewater.

The first of the two limestone-based, inhibited-oxidation processes listed in Table 13-1 operates with a relatively low sulfite oxidation fraction. The high end of the range for cake formation rate for solids from this process overlaps the range seen for the gypsum solids. The cake is nearly as dense as the gypsum cake, and the final solids content is relatively high, at about 70% solids.

In the second of the two limestone-based, inhibited-oxidation processes, soluble magnesium is added to enhance SO_2 removal efficiency. The presence of high concentrations of magnesium results in solids that have a relatively low cake formation rate and low final solids content compared to processes with lower magnesium content. The cake formation rate, cake density, and cake solids content results from this system are at the low end of the expected range for limestone-based, inhibited-oxidation processes.

The last data set shown in the table is for solids from a magnesium-enhanced, lime-based process. The solids produced in that process type are the most difficult to dewater. Of the four systems shown in the table, these results exhibit the lowest cake formation rate, lowest cake density, and lowest final solids content.

Also shown in Table 13-1 is the final vacuum (at a constant volume of air) that was measured for the filtration tests after the 120-second dewatering period. The magnesium lime process slurry shows the lowest residual vacuum. This result is typical for vacuum filtration of solids from that process type; the filter cake tends to crack so that the air flows through the cracks with little resistance. The result is that more moisture is retained in the cake itself. This cake cracking phenomenon complicates the filtration cycle design for solids from the magnesium-enhanced lime-based process. Longer drying times are of little benefit for those solids.

Perhaps the most important aspect of the test data shown in Table 13-1 is the variability of filtration properties for slurry produced in a single process. Because of the relatively unpredictable effects of boiler load cycling on filtration properties, prudent design practices should allow for sufficient excess filtration capacity to account for changes in solids properties during operation under different conditions. In practice, the filtration equipment is usually designed to operate less than 24 hours per day. Slurry is stored in a surge tank and then processed during part of the operating day. To allow for variation in filtration properties, the filters might be designed to process the entire daily solids production at maximum boiler load and SO_2 removal during a single 8-to 12-hour shift. Variations in filtration properties can then be accommodated by reducing the filter speed and/or operating for longer time periods, as required.

Actual design filtration rates for FGD slurry range from as low as 0.1 kg/m^2-s for difficult-to-dewater solids from a magnesium-enhanced, lime-based process, where thickener underflow solids content is about 25 to 30%, to as high as 1 kg/m^2-s for easily dewatered gypsum solids, where hydrocyclone underflow solids content can be about 50 percent. For forced-oxidation processes, those producing disposal-grade solids require much less filter area than those producing commercial-quality solids because of the much greater washing plus drying time required for the latter product. For the 500-MW design basis used for this manual, the corresponding filter areas range from about 6 m^2 to 40 m^2.

13.2.3 Filter Selection

Based on the above discussion, any of the three filter types described can be used for dewatering FGD solids. The selection would be based primarily on installed cost. In general, drum or drum/belt filters are less expensive than horizontal belt filters with the same filtration area. However, the cost difference is a function of capacity. Costs are much closer for small filters with a total surface area of less than about 10 m^2. Therefore, the horizontal belt filter is often selected for systems producing wallboard-quality gypsum. In this application, the filtration rate is fast, and the added flexibility of the horizontal belt filter for optimum washing and drying cycle design makes that filter type more attractive. Drum or drum/belt filters are more often used for limestone-based, inhibited-oxidation and magnesium-enhanced lime-based processes where larger filters are needed.

Selection of the optimum filter type would normally be based on the experience of the filter vendors. A single supplier usually can provide all three types of vacuum, so they have an incentive to provide the most cost-effective equipment for a given application. It should be noted that the filter selection and design area must also consider the performance of the primary dewatering device because of the strong effect of slurry solids content on the cake formation rate.

13.2.4 Mechanical Design Considerations

Details of the mechanical design of vacuum filters are usually left to the filter vendors, who have considerable experience in processing FGD byproduct solids. Most vacuum filters are typically produced in standard sizes and designs. Some mechanical design options are available to the purchaser, however. Some of the more important mechanical design choices are discussed below.

Number of Individual Filters

The vacuum filters are important equipment items in terms of overall system reliability, but substantial byproduct solids surge capacity (up to two days of production) is usually available before loss of filtration equipment would cause process shutdown. FGD process suppliers typically recommend two 100%-capacity filters, but a less conservative sparing approach could be considered (two 67%-capacity or two 50%-capacity filters), especially if the 100%-capacity size is based on processing one day's production in only one shift. In any case, at least two individual filters should be used to allow for regular maintenance and repairs.

Single- versus Double-Receiver System

The filtration arrangement shown in Figure 13-2 showed a single vacuum receiver. Depending on the filtration properties of a specific slurry, the use of two separate receivers might be preferred. This arrangement permits application of two different vacuum amounts and air flow rates to different portions of the filter apparatus, yielding more flexibility in the overall filtration cycle design.

Variable Speed Drives

Another way to increase the flexibility of filter operation is to provide variable-speed drives for the drums or belts. This option is especially useful for accommodating changes in slurry filtration properties caused by changes in boiler operating conditions.

Filter Cloth Selection

Common materials for filter cloth include polypropylene, polyethylene, nylon, and dacron. The cloth selected should be as open as possible, consistent with the required filtrate solids content. An open cloth is less subject to blinding from fine solids. For dewatering systems that employ a thickener, a more open cloth can sometimes be used because filtrate containing suspended solids can be recycled to the thickener, which can produce a clear overflow. As with many equipment choices, the initial cost of the filter cloth material must be weighed against its projected service life.

Vacuum Pump Design

Vacuum pumps used in filtration applications are usually of the wet centrifugal type with water seals. The air-flow capacity is generally in the range of 20 to 100 m^3/hr per square meter of filter area at a vacuum of 20 to 22 mm Hg.

13.3 Material Selection

Vacuum filters are available in a wide variety of materials. As with other components in the FGD system, the vacuum filters will be exposed to corrosive conditions, and the design chloride content of the process liquor is a critical factor in material selection. For low-chloride applications, the drum and piping materials can be fabricated from an austenitic stainless steel. For high-chloride applications, rubber linings or epoxy-based coatings can be used over carbon steel. Alternately, FRP or high-nickel alloys also can be used. Material choices are discussed in more detail in Part I, Section 5--Materials-of-Construction Options.

13.4 Recommendations

- Either drum-, drum/belt- or horizontal-belt-type vacuum filters can be suitable for dewatering byproduct solids from lime- and limestone-based wet FGD systems. The most economical choice will depend on the expected properties and end use of the FGD byproduct solids. Drum filters tend to be less expensive than horizontal filters in larger sizes such as those required for solids from magnesium-enhanced lime processes. Horizontal filters tend to be best for wallboard-grade gypsum, where short cake formation times and long dewatering times are needed.

- In either case, the filtration system should be conservatively sized to account for wide variability in slurry dewatering properties. Typical designs provide sufficient capacity to dewater the maximum solids production amount in 8 to 12 hours per day of operation.

13.5 References

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14.0 CENTRIFUGES

Centrifuges offer an alternative to vacuum filters for the secondary dewatering of byproduct solids, and typically can produce solids with 5 to 10% lower moisture (see Part I, Section 4.8.2--Secondary Dewatering). Centrifuges have been successfully used for the secondary dewatering of byproduct solids produced by both forced- and inhibited-oxidation FGD systems. Conceptually, centrifuges are similar to gravity settling tanks, but the rate of sedimentation is much greater because of the centrifugal force developed in the spinning slurry. Selection of the appropriate type of centrifuge and its features depends on the FGD slurry characteristics and on the desired properties of the dewatered byproduct solids.

14.1 Types Available

Two general types of centrifuges are used in FGD applications: sedimentation centrifuges, which take advantage of the difference in density between the liquid and solid phases, and centrifugal filters, in which the solids are retained on a permeable membrane through which the liquid passes. Centrifuges may operate in either a batch or continuous process mode. Of the many centrifuge designs available, the two most commonly used to dewater FGD byproducts are the solid-bowl decanter centrifuge and the vertical-basket centrifuge.

14.1.1 Solid-Bowl Decanter Centrifuges

The solid-bowl decanter centrifuge, illustrated in Figure 14-1, is a sedimentation-type centrifuge. This centrifuge has a solid-wall bowl that spins on either a horizontal or vertical axis. In FGD system dewatering applications, the horizontal-axis centrifuge is more common. The bowl may be cylindrical, conical, or, as shown in Figure 14-1, a combination of the two.

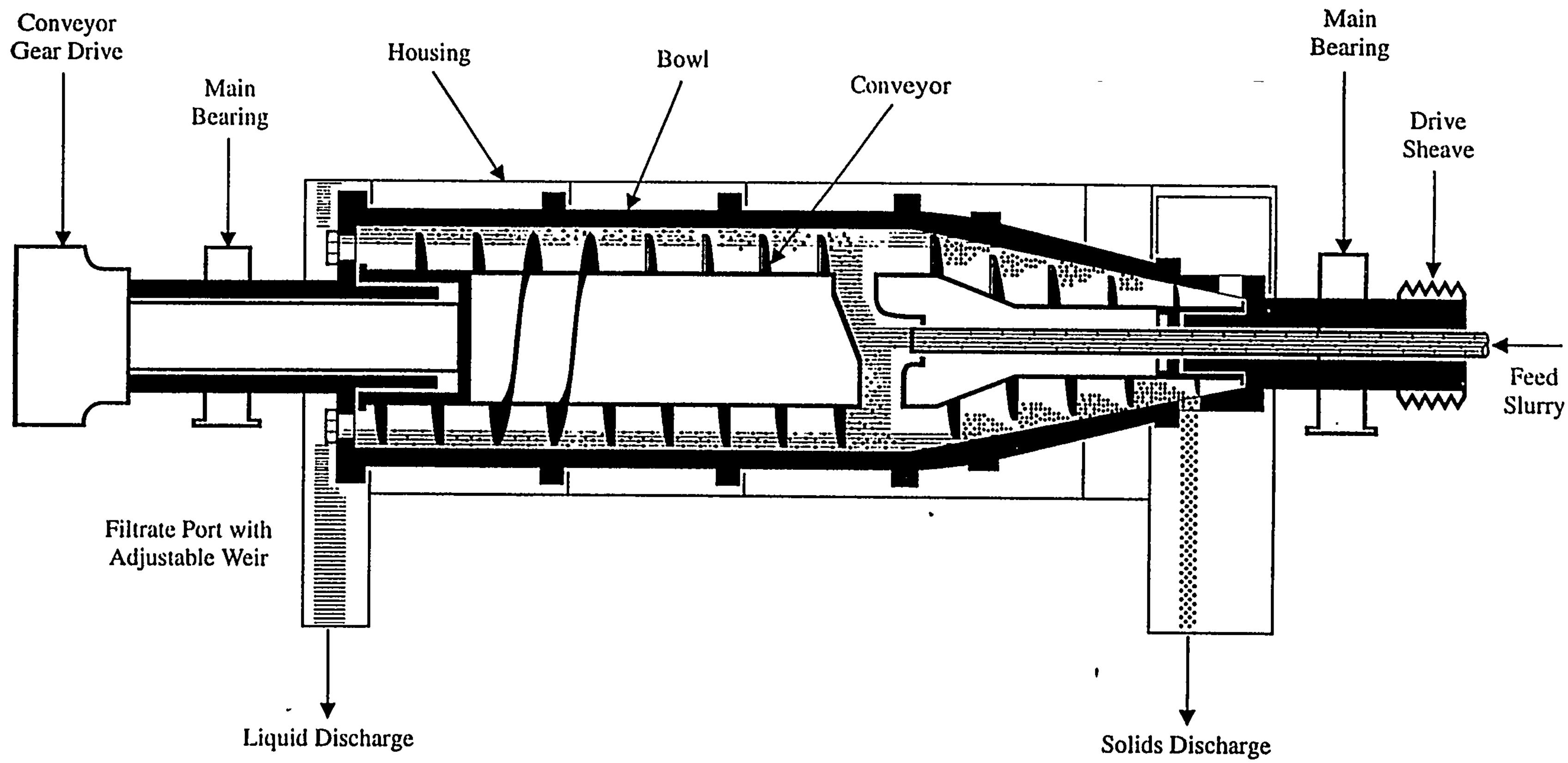

Figure 14-1. Solid-Bowl Decanter Centrifuge

The solid-bowl decanter centrifuge usually operates with a continuous feed of slurry from the primary dewatering system. The slurry feed is introduced at a point inside the centrifuge. As the bowl spins, slurry solids are forced against the bowl's inside wall. A helical-scroll conveyor inside the centrifuge turns at a slightly slower speed than the bowl, pushing the solids up the bowl's conical "beach" section and out of the process liquor. The dewatered byproduct solids leave the centrifuge at the conical end and separated liquid discharges at the opposite end. The depth of liquid in the centrifuge can be altered by adjusting dams at the liquid discharge ports. Reducing the liquid depth reduces both the centrifuge's processing capacity and the dewatered byproduct's moisture content (a result of the cake's spending a longer period of time on the "beach" section).

The bowl rotational speed for the centrifuge sizes most commonly used in FGD system byproduct dewatering applications is typically in the range of 2000 to 2500 revolutions per minute (rpm). A gearbox connected to both the bowl and the helical conveyor turns the conveyor at a speed 20 to 80 rpm lower than the bowl's speed. Wash water can be applied to the dewatered solids in the conical section to reduce the concentration of soluble salts in the dewatered solids. The wash water flows back to the cylindrical section of the centrifuge where it mixes with the process liquor.

14.1.2 Vertical-Basket Centrifuges

A vertical-basket centrifuge, as shown in Figure 14-2, also may be used for dewatering FGD byproduct solids. This is a batch-type machine with a top-suspended cylindrical or conical basket and a variable-speed drive. The basket is lined with a fine wire mesh to retain the byproduct solids. The operation of the vertical-basket centrifuge proceeds in a series of steps. Starting from a low rotational speed, the basket speed is slowly increased as the feed slurry enters the basket through one or two feed pipes. The process liquor passes through the wire mesh, and a solids cake forms on the inside wall. Wash water can be sprayed on the cake to remove chlorides and other soluble salts. The cake is then spun dry at about 800 rpm. When drying is complete, the basket is slowed to about 30 rpm, and solids

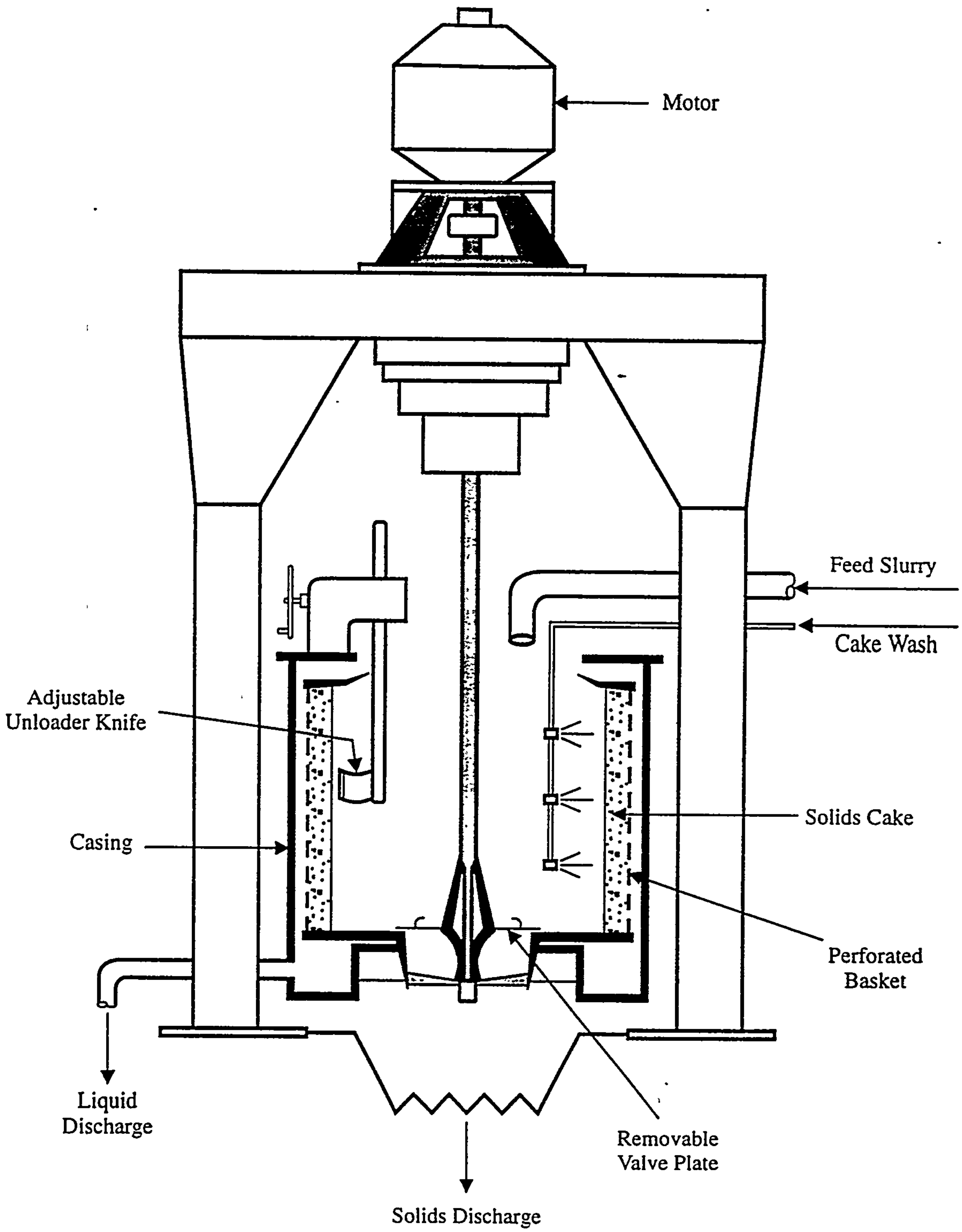

Figure 14-2. Vertical-Basket Centrifuge

are removed by an unloader knife that slowly moves into the cake. A door on the bottom of the basket opens to allow the solids to exit. The filter medium is then rinsed clean and the speed is increased to begin another cycle.

As stated earlier, vertical-basket centrifuges are operated in a batch sequence; however, most dewatering systems use several centrifuges operating in parallel, each at a different stage of the centrifuging process. As a result, the flows of feed slurry, centrate (the recovered process liquor), and byproduct solids from such systems are practically continuous.

14.2 Design Considerations

The type of centrifuge selected for a particular application is based on factors such as the FGD process type (inhibited- or forced-oxidation), existence and type of primary dewatering equipment, final byproduct solids disposition (commercial sale or disposal), and FGD system vendor experience. Detailed design of the centrifuge is handled by the centrifuge vendor and is beyond the scope of the manual. For a new application, the centrifuge vendor works with the FGD vendor to gather as much information as possible on the proposed system's desired byproduct solids' characteristics and the byproduct handling system's requirements. For a retrofit application of centrifuges, normal procedure is to test a slurry sample at the vendor's facility on a small machine. Test results are then scaled up to design the utility-size centrifuge.

Although detailed centrifuge design is the responsibility of the centrifuge vendor, the utility engineer should understand how the equipment operates, what its advantages and disadvantages are, and which features should be specified. The theory behind centrifuge operation and descriptions of the various types of centrifuges can be found in chemical engineering textbooks (1,2).

14.2.1 Centrifugal Separation Theory

As the name indicates, centrifuges use centrifugation to separate the FGD system byproduct solids slurry into liquid and solid streams. In a thickener (Part II, Section 11.0), the force of gravity acts on suspended particles, causing those denser than the liquid to settle. In a rotating centrifuge, the gravitational force is insignificant compared to the force of centrifugal acceleration, which is defined in Equation 14-1. Consequently, the separation in a centrifuge may occur more than one thousand times as fast as in a thickener.

$$a_c = \frac{v^2}{r} = \omega^2 r \qquad (14\text{-}1)$$

where:
a_c = centrifugal acceleration, m/s^2 (ft/s^2);
v = scaler velocity, m/s (ft/s);
r = radius of the circular path, m (ft); and
ω = angular velocity, s^{-1}.

In centrifuges, the magnitude of centrifugal force (or the centrifugal field) is typically measured in terms of multiples of the standard acceleration of gravity, or G's.

$$F_c = \frac{\omega^2 r}{g} \qquad (14\text{-}2)$$

where:
F_c = centrifugal field, unitless or G's; and
g = standard acceleration of gravity, m/s^2 (ft/s^2).

The centrifugal field can also be calculated for a given centrifuge using standard terms, as shown in Equation 14-3.

$$F_c = 3.6 \times 10^{-6}\, n^2\, D_b \qquad (14\text{-}3)$$

where:
n = bowl speed, rpm; and
D_b = bowl inside diameter, mm.

Although some industrial centrifuges can attain over 100,000 G's, the forces attained by those used in FGD dewatering are lower. Typical solid-bowl decanters operate at about 3000 G's, and vertical-basket centrifuges operate at 570 G's.

14.2.2 Process Considerations

A potential advantage of using centrifuges is that it may be possible to eliminate primary dewatering of the byproduct solids by thickeners or hydrocyclones. A disadvantage, on the other hand, is that the centrate typically contains more solids than the filtrate from a vacuum filter. These two considerations and the use of polymer flocculents are discussed below.

Single-Stage Dewatering

Under some circumstances, the primary dewatering step can be avoided by using centrifuges. For example, one existing limestone-based forced-oxidation FGD system in the United States sends a 20 to 25% slurry directly from the absorber reaction tank to the centrifuge feed tank. Eight operating vertical-basket centrifuges (with 1 spare) produce a washed gypsum product containing 92 to 94% solids.

Although eliminating the primary dewatering equipment may appear to be appealing, it does present some problems. As stated in Part I, Section 4.8.1--Primary Dewatering, the principal purpose of the primary dewatering equipment is to reduce the volume of the byproduct solids bleed slurry stream, thus reducing the number and capacity of the secondary dewatering components. Although centrifuges can process an FGD system bleed stream without primary dewatering, the higher slurry volume requires a greater number of centrifuges and increases the capital and operating costs of the secondary dewatering stage. An engineering study typically is required to determine whether elimination of the primary dewatering equipment is cost-effective at a specific site.

Centrate Handling

The centrate stream from a vertical-basket centrifuge typically contains up to 2% solids. Although some of the small-diameter solids pass through the basket medium during the spin cycle, solids also reach the centrate from feed slurry that overflows the basket during the initial filling step. The centrate stream may be returned to the absorber reaction tanks, returned to the thickener (if used), or treated in a separate clarifier. If the solids in the centrate are small sulfite or sulfate crystals, they may be returned to the reaction tank for further growth. If the solids are predominately fly ash or other inerts they should be returned to the thickener or centrifuge feed.

Polymer (Flocculent) Use

Flocculents are often used in liquid-solid separation processes as discussed in Part II, Section 11.0--Thickeners. The same polymers used in thickeners can also reduce the centrate solids concentration by increasing the collection rate of the fine solids. However, polymer use may result in wetter dewatered byproduct solids because it is more difficult to remove water from around the small particles than it is from larger ones. Because of this adverse effect on product solids content and the annual costs of the polymer, polymers are seldom used with centrifuges.

14.2.3 Centrifuge Selection

Selection of the best type of equipment for a particular site mainly depends on the FGD process and the desired characteristics of the byproduct solids. Selection of equipment for secondary dewatering should evaluate both vacuum filters and centrifuges and compare them on a technical and economic basis. Part I, Section 4.8.2--Secondary Dewatering provides a discussion of these choices.

Between the two centrifuge types, the solid-bowl decanter centrifuge is best suited for small solids, such as those produced by lime-based or inhibited-oxidation limestone-based FGD processes. This is because the fine sulfite crystals tend to plug or pass through the screens of centrifugal filters. In the United States, almost all of the recent inhibited-oxidation FGD systems use solid-bowl decanter centrifuges for secondary dewatering.

The vertical-basket centrifuge is more suited to gypsum dewatering because the relatively large calcium sulfate crystals do not readily plug or pass through the filter media and washing is more easily accomplished. Recent U.S. installations of forced-oxidation FGD systems producing commercial gypsum are using either vertical-basket centrifuges or horizontal-belt vacuum filters (see Part II, Section 13.0--Vacuum Filters). Neither alternative dominates the market at this time.

14.2.4 Mechanical Considerations

The utility engineer should be aware of the effects of rotational speed and rotor diameter on material stress and gravitational forces. Also, equipment redundancy is an important design criterion.

Stress in Centrifuge Bowls

Mechanical stress on the bowl can be calculated from the bowl rotational speed and diameter using Equation 14-4.

$$\sigma = k\, n^2\, D_b^2 \qquad (14\text{-}4)$$

Increasing either of these design parameters increases the stress on the bowl; and the greater the stress on the bowl, the greater the likelihood of mechanical failure. Equation 14-3 indicates that the centrifugal field produced, F_c, is proportional to the product of the bowl diameter and the square of the rate of rotation. As a consequence of the relationships shown in Equations 14-3 and 14-4, doubling the bowl speed and halving the bowl diameter would not effect the mechanical stress on the bowl but would double the applied centrifugal field. Therefore, in order to achieve the desired F_c at the lowest stress, centrifuges are designed to use the smallest practical bowl diameter operating at high speed.

Number of Centrifuges

In a full-scale utility FGD system, the byproduct solids production rate is higher than the capacity of individual centrifuges commercially available for this service. Therefore, multiple centrifuges are run in parallel to process the slurry. Also, when batch machines are used, the use of multiple centrifuges allows for the dewatering process to appear almost continuous. It is standard practice to allow for equipment redundancy by installing spare machines. One spare machine will usually be installed on each generating unit. If a secondary dewatering system will serve more than one generating unit, the spare centrifuge may serve either unit.

Solid-bowl decanters used in FGD byproduct dewatering service have a typical maximum capacity of 11 to 13.6 tonnes/h (12 to 15 tons/h). The capacity of vertical-basket centrifuges used in this service is about 0.9 tonne (1 ton) per batch, while hourly capacity depends on the byproduct characteristics. Obviously, 90% solids can be reached in less time than 95% solids. Cake washing also extends the batch cycle time. Typical cycle times are five to six batches per hour with cake washing and a commercial-quality gypsum product, or up to ten batches per hour for a throwaway product (3). As an example of the number of centrifuges that may be required at a large FGD installation, one station in the United Kingdom has 42 centrifuges to dewater the gypsum produced by six 660-MWe units. This station uses hydrocyclones for primary dewatering and produces gypsum at the rate of about 90 tonnes/h (82 tons/h) average or 600 tonnes/h (545 ton/h) maximum.

14.3 Material Selection

The wetted parts of solid-bowl decanter centrifuges are typically fabricated of stainless steels or other alloys for two reasons: to resist the corrosive effects of the slurry and to withstand the high stresses involved in rotating at such high speeds. Materials used in the fabrication of the bowl and scroll of decanter centrifuges include Type 317LMN stainless steel and 254 SMO (a 6-Mo superaustenitic stainless steel). Since vertical-basket centrifuges operate at much slower speeds, the basket and housing can be rubber-lined, with Type 317L stainless steel or nickel-based alloys used for fittings. The filter medium in the basket is typically Type 316 stainless steel with 40- to 55-μm openings. This screen is a "wear" item that is replaced every three to four months.

Abrasion resistance is another major concern in centrifuge design because of the high speeds and abrasive solids. Abrasion is a particular problem on the scroll conveyor tips in solid-bowl decanters. This area is typically fitted with removable tiles, which can be made of tungsten carbide or other materials. Tests have shown that sintered tungsten carbide outperforms materials such as nickel alloys, Stellite™, and aluminum oxide ceramics (4).

14.4 Recommendations

- Selection of the appropriate type of centrifuge depends on the FGD process and the byproduct disposition. The solid-bowl decanter centrifuge is best suited for the small solids produced by lime-based or inhibited-oxidation, limestone-based FGD processes. The vertical-basket centrifuge is better for the forced-oxidation, limestone-based process--with either washed or unwashed cake.

- Centrifuges should be considered as an alternative to vacuum filters when cake dryness is a primary concern, since the centrifuge product is typically 5 to 10% drier.

14.5 References

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15.0 CONTINUOUS EMISSION MONITORING (CEM) SYSTEMS

The environmental laws of the United States, as well as those of numerous other countries, require continuous monitoring of emissions from power plants stacks. The systems used to perform this continuous monitoring are called continuous emission monitoring (CEM) systems. This section discusses CEM systems for coal-fired power plants with FGD systems.

A CEM system consists of the following components:

- Gas-analyzer interfaces (i.e., sampling probes);
- Analyzers for the targeted pollutants;
- Gas flow meters;
- Opacity meters; and
- A data acquisition and handling system (DAHS) to manage the instrumentation and capture the data in a standardized format conforming to regulatory requirements.

In the United States, the minimal analytical suite for an existing coal-fired power plant with FGD consists of SO_2, oxides of nitrogen (NO_x), carbon dioxide (CO_2), opacity, and gas flow rate. Both existing and new plants must monitor the stack gas for ammonia if it is being injected into the furnace to reduce NO_x emissions. Other countries or regulatory jurisdictions (e.g., air quality management districts) may impose other or additional requirements. Commercial instrumentation exists to monitor at least the following additional parameters: oxygen (O_2), carbon monoxide (CO), hydrocarbons, hydrogen chloride (HCl), total mercury, and elemental mercury (1-5).

Even in the absence of regulatory requirements, the utility may elect to expand the analytical suite for its own benefit to enhance boiler operation (for example, by monitoring O_2 to optimize combustion efficiency). As discussed in Part I, Section 4.10--

Process Control and Instrumentation, the data from the CEM system are also used by several FGD process control systems. Thus, CEM systems perform three equally important functions:

- They provide the emissions information required by environmental regulations;
- They provide plant management with critical information which can be used to control boiler operation; and
- They provide information needed by the FGD process control systems.

This section addresses some general considerations of the selection of CEM systems.*

15.1 Types Available

As discussed above, a CEM system consists of a series of analyzers and meters interfaced with a DAHS. Each of the analyzers or meters are either *extractive* or *in situ*, depending on where the sample is analyzed with respect to the flue gas. Any particular CEM system may have a combination of extractive and in situ analyzers and meters.

The major categories of analyzers and meters are the following:

- Gas analyzers to measure specific gaseous pollutants;
- Gas flow meters; and
- Opacity meters.

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* CEM technology is rapidly developing at this time, and it is likely that some of the information contained in this section may be superseded by future developments of CEM technology.

15.1.1 Extractive Gas Analytical Systems

Extractive gas analysis systems remove a representative sample of gas from the stack or duct via a probe, condition that gas stream in some way, and supply the conditioned stream to one or more laboratory-grade analytical instruments for analysis. Three types of extractive analytical systems are available:

- Wet-extractive systems;
- Dry-extractive systems; and
- Dilution-extractive systems.

Figure 15-1 provides a schematic comparison of these three types of systems.

Wet-Extractive Gas Analytical Systems

Wet-extractive analytical systems use specialized gas analyzers [modified to operate at flue gas temperatures of 180 to 250°C (360 to 480°F)] to measure pollutant concentration in a sample of flue gas from which all particulate matter has been removed. Gas is drawn from the stack through a probe, and particulates are filtered out at that point. The composition of the gas is not otherwise altered. The moist, dust-free gas is transported in heat-traced lines from the probe to a remotely located environmental enclosure (typically a trailer or similar shelter). The heated lines must be maintained between 180° and 250°C (360° and 480°F) to prevent condensation of sulfuric, sulfurous, hydrochloric, nitric and possibly other acids which would invalidate the analytical results as well as cause severe corrosion of the sample lines. The entire gas path through the analytical train must also be maintained at the elevated temperatures, preventing condensation of acid and moisture and allowing analysis of the total sample.

Wet-extractive CEM systems determine the concentration of constituents such as HCl and ammonia, which cannot be determined by dry-extractive CEM systems (see

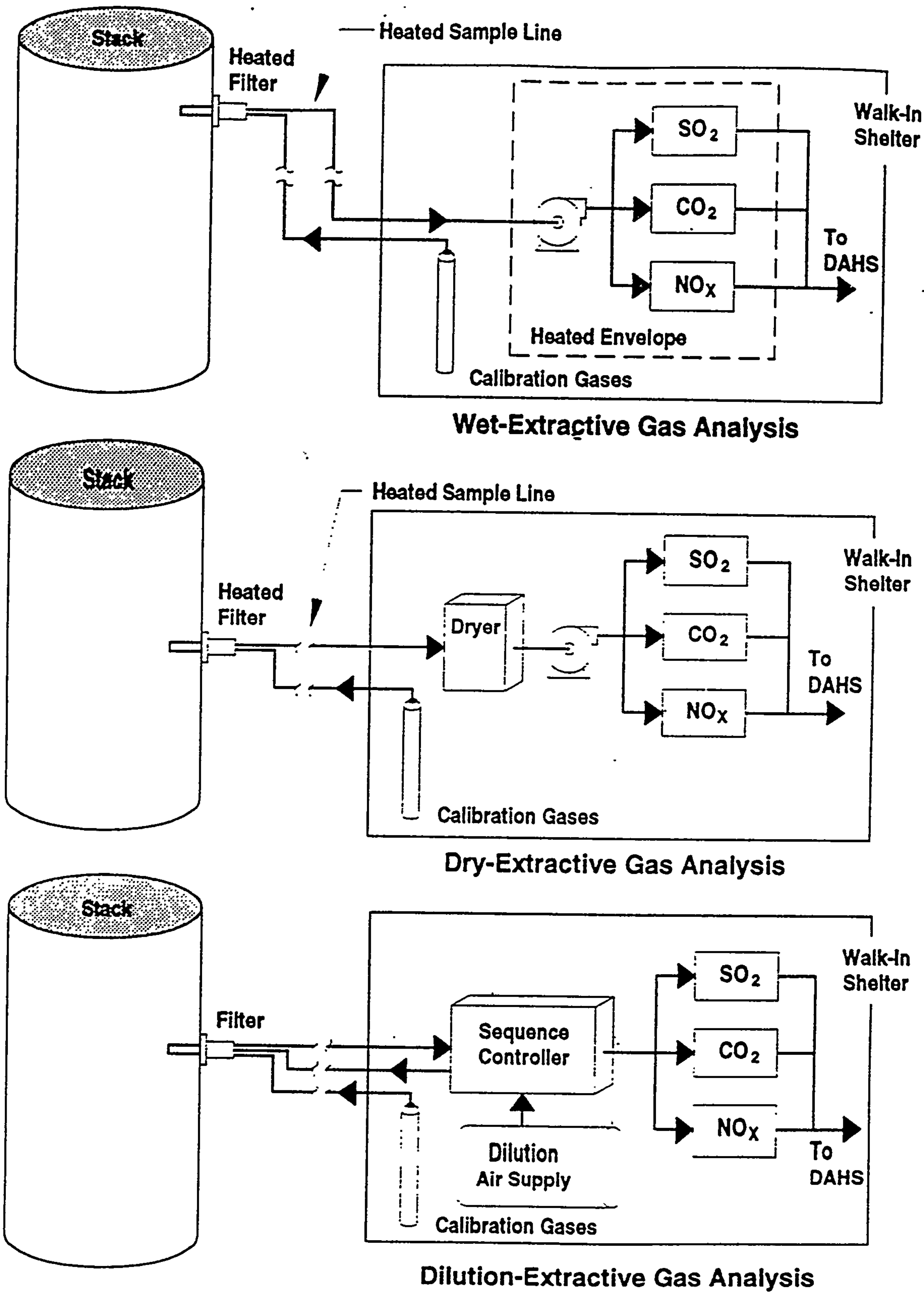

Figure 15-1. Schematic Diagrams of the Three Basic Types of Extractive Gas Analysis Systems

below). Because the gas stream is not altered prior to analysis, these systems have the potential to be among the most accurate measurement techniques available.

At this time, wet-extractive systems are offered by a limited number of vendors and are significantly more expensive than dry-extractive CEM systems. However, in some circumstances, the advantages of wet-extractive CEM may outweigh these disadvantages. As an example, a wet-extractive system may be justified if the utility must measure ammonia emissions downstream of a selective catalytic reduction (SCR) system installed for nitrogen oxides control.

Dry-Extractive Gas Analytical Systems

Dry-extractive analytical systems use conventional gas analyzers to measure pollutant concentrations in a sample of flue gas from which all particulate matter and water vapor have been removed. Gas is drawn from the stack through a probe, and particulates are filtered out at that point. The moist, dust-free gas is transported in heat-traced lines from the probe to a gas dryer module in which the moisture is removed by a combination of refrigeration, condensation, and passage through water-excluding membranes or molecular sieve beds. This drying step also removes other highly polar gaseous constituents such as ammonia and HCl. The gas train downstream of the dryer module need not be heat-traced since drying eliminates the potential for acid condensation. In particular, drying the gas stream means that the gas path through the analytical instruments need not be heated. Proper sample extraction and conditioning is critical, because it minimizes corrosion and maintenance requirements and increases the accuracy of the dry-extractive analysis.

Conversion of the analyzer volumetric concentrations to mass concentrations in the flue gas requires a correction for the moisture removed from the gas during conditioning. This moisture must be measured, or an estimate made, adding complexity to the system and potentially lowering the reliability and accuracy of the dry-extractive analysis.

Dilution-Extractive Gas Analytical Systems

Dilution-extractive analytical systems use dilution to avoid condensation within the extracted gas stream without the need to heat-trace the entire analytical train. As with the preceding methods, the flue gas is extracted from the stack through a probe and filtered at the sample point to remove particulates. The gas sample is then diluted with clean dry air* at the probe, eliminating the need for moisture removal and heat-tracing downstream of the probe. Precise dilution is achieved by using critical orifices (sonic orifices) to control both the flue gas and dilution air flow rates.

Pollutant concentrations are measured by analyzers designed to accurately measure ambient pollution levels below 1 part per billion** (ppb). Dilution ratios of 12:1 to more than 700:1 are used to match the flue gas concentration to the analytical ranges of the analyzers (2).

Dilution may occur in situ (inside the stack liner) either at the probe tip before filtering, or just after the glass wool or sintered metal particulate filter. Such in situ probes must be removed periodically from the gas stream for maintenance. Alternatively, the gas can be filtered and diluted ex situ just outside the stack in an ex situ probe assembly, using a high-velocity cyclonic particulate separator. With an ex situ probe, dilution occurs just downstream of the particle separator. Although extractive dilution increases complexity, both because the flow rates of the two gas streams must be precisely controlled and because exacting purity certification of the dilution air is mandatory, ex situ dilution-extractive systems constituted the majority of chemical CEM systems procured for FGD continuous emission monitoring as of 1993 (2).

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* The dilution air is dehydrated to a dew point below -40°C (-40°F) and scrubbed of all traces of sulfur dioxide, carbon monoxide, carbon dioxide, oxides of nitrogen, moisture, and other analyte gasses. The dilution of the flue gas with this air stream greatly reduces the dew point of the combined stream.

** Billion equals 10^9 in the U.S. custom and corresponds to the British milliard.

Analytical Instruments

Regardless of the extractive technology used, the analytical instruments fall into two categories:

- Single constituent analyzers; and
- Multi-constituent analyzers.

Single constituent analyzers are off-the-shelf ambient air analyzers, or modifications of such instrumentation, and rely on relative absorption of selected frequencies of infrared or ultraviolet radiation, chemiluminescence, or flame ionization, depending upon the species of concern. CEM systems using single-constituent analyzers have a series of analyzers in a train to produce data required for each species of concern. Most current utility extractive CEM systems have used this approach (2,6).

Recent developments in Fourier transform infrared (FTIR) spectroscopy have led to the production of multi-constituent analyzers, in which the analysis of all analytical targets is simultaneous within the same instrument. These systems have the added advantage that analyte target selection is under software control, and the analytical suite can be readily altered in response to foreseeable future changes in the CEM monitoring requirements (3,6).

Using either approach, the instruments are calibrated daily using calibration gases of precisely known compositions.

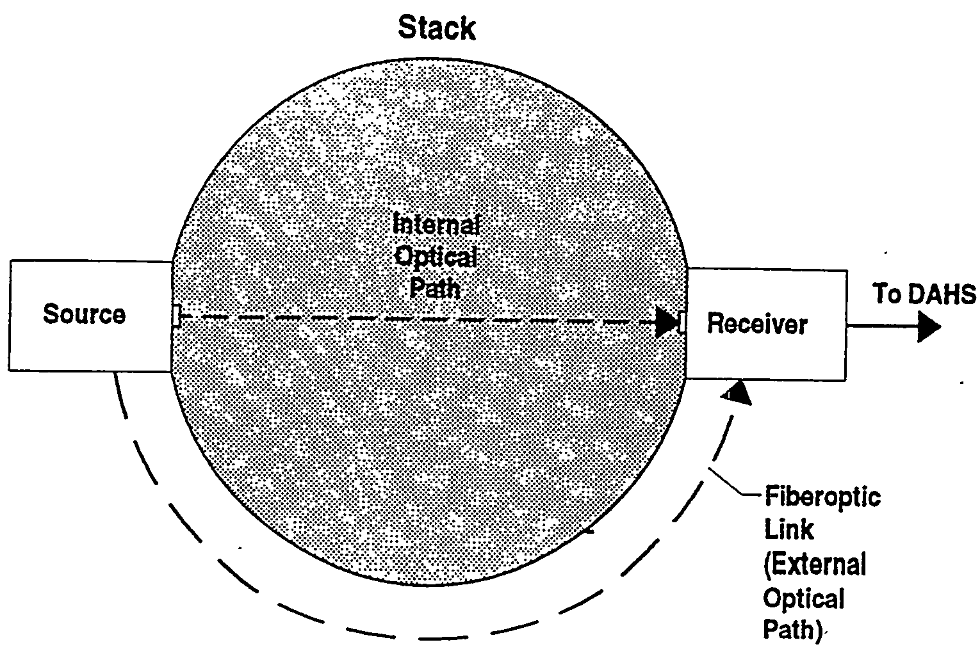
15.1.2 In Situ Gas Analytical Systems

In situ analytical systems analyze the flue gas directly within the stack at whatever conditions exist in the gas stream. No conditioning of the gas sample is required, and, unlike extractive systems, all of the sampling and analytical equipment is in one central location. Early in situ probes measured the concentrations of single pollutants at the probe tip, using either solid-state electrolyte technology or absorption spectrography. Absorption spectrography typically uses dual-wavelength ratioing methods in either the ultraviolet or infrared portions of the electromagnetic spectrum in an optical chamber at the probe tip (6). The practicality of these single-point, single analyte sensors has decreased greatly as the number of analytes of concern has increased.

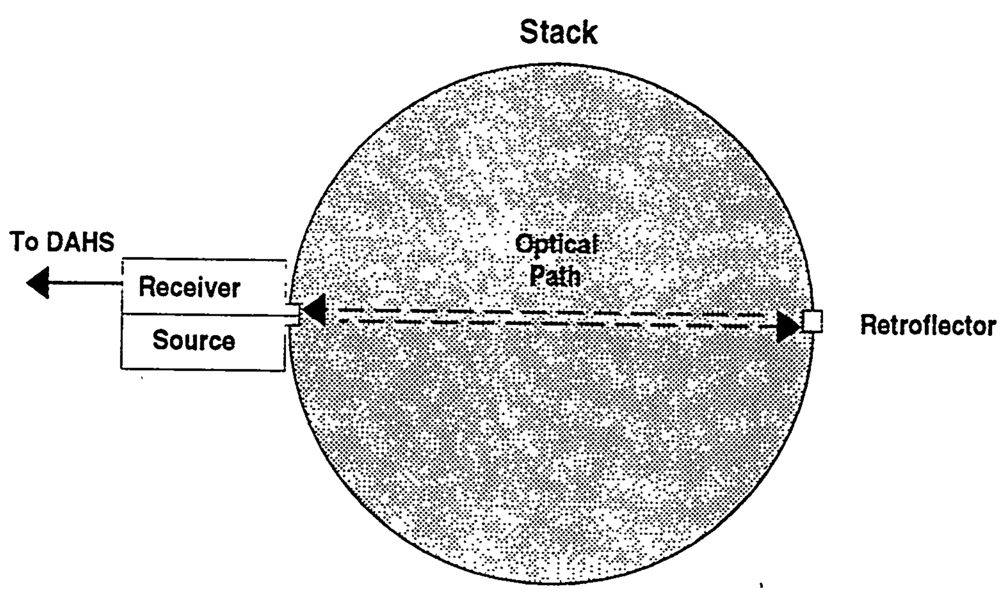
However, absorptive spectroscopy methods have been adapted to create in situ, across-the-stack analyzers, which produce an average analysis along a line traversing the stack. Across-the-stack analyzers can be single or dual pass systems, compared schematically in Figure 15-2. In single-pass systems, Figure 15-2a, the analytical beam enters the stack through an optical window and traverses the gas stream to a detector on the opposite stack wall. A fiber optic cable provides a second optical path from source to detector external to the stack, and pollutant concentration is proportional to absorption of the selected radiation wavelength. The use of the external fiber optic light path means that the instrument does not have to be pre-calibrated for path length across the stack.

In dual-pass configurations, Figure 15-2b, the analytical beam enters the stack through an optical window, strikes a retroflector on the opposite wall, and is reflected back through the same optical window. The instrumentation compares the brightness of the source and return beams, and computes the pollutant concentration from the absorbance. Dual-pass analyzers must be pre-calibrated for the path length across the stack.

The potential accuracy of across-the-stack gas analyzers is significantly compromised by problems with drift, limited span distance, and optical fouling. Drift problems result when the zero value and upscale span value change significantly from calibration to calibration. This problem can occur when the ambient conditions are not properly accounted for, and often happens when the zero point is extrapolated from upscale measurements. Span distance problems occur when the instrument is unable to transmit sufficient energy over the entire measurement distance.



a) Single Pass in Situ Analyzer



b) Dual Pass in Situ Analizer

Figure 15-2. Schematic Comparison of Single-Pass and Dual-Pass In Situ Analyzers

In situ systems eliminate the complexity of the extractive sample lines and need for a trailer-sized instrumentation shelter. However, in situ systems place the complex electronic hardware directly on the stack, a potentially hot and corrosive environment that is a difficult operating environment for delicate electronics. In addition, the equipment may be difficult to access for maintenance. For these reasons, in situ gas analyzers are generally expected by several authors to remain a relatively minor player as more operators install CEM systems for environmental regulatory compliance (2,3,6).

15.1.3 Flow Rate Monitors

Gas analyzers provide results on a per-volume basis, while U.S environmental regulations require reporting on a mass per unit time or per unit heat input (J or million Btu) basis. In order to perform the necessary calculations, the gas flow rate must be accurately determined while the gas composition is being analyzed. Three types of in situ flow meters are used:

- Differential temperature meters;
- Differential pressure meters; and
- Doppler monitors.

Differential Temperature Flow (DTF) Meters

Differential temperature flow (DTF) meters rely on a hot-wire anemometer that determines flow rate from the amount of heat dissipated to the flue gas. Each monitoring point consists of a thermowell containing a pair of resistance-temperature detectors (RTDs) and a low power heater which preferentially heats one of the RTDs. The temperature difference between the two RTDs is greatest when the gas flow rate is zero, and decreases with increasing flow rate. Ideally, a third, reference RTD is placed in a separate, co-located thermowell to measure the gas temperature, and improve accuracy by allowing a correction for fluctuating flue gas temperature. Typically, three or four monitoring points are used.

While DTF meters are simple and expose no delicate components to the flue gas, they are susceptible to vibration failure, fouling by particulate deposition, and cannot be used if significant quantities of water droplets are present in the gas stream since these droplets strongly affect heat dissipation from the sensor (and would be interpreted as increased velocity). In addition, DTF meters make point measurements in the gas flow and can give misleading results if the gas flow is highly stratified and the sensors are not correctly placed.

Differential Pressure Flow (DPF) Meters

Differential pressure flow (DPF) meters place an annubar or pitot tube into the flue gas stream and measure the pressure differential between upstream and downstream flow. This pressure differential is proportional to gas velocity.

Annubar probes, Figure 15-3a, span the stack diameter and contain a number of holes spaced along the length of the probe. The differential pressure across the annubar is proportional to the average gas velocity through the stack.

The pitot tube, Figure 15-3b, on the other hand, has a single pair of openings, one facing upstream and the other facing downstream. By definition, the pitot tube makes point measurements. The potential effects of stratification can be overcome by either inserting a number of pitot tubes, or by having a single tube automatically traverse the stack (1,2).

The differential pressure flow method is the U. S. Environmental Protection Agency (EPA) reference method for flow rate measurement, and can be used in both wet and dry stacks. However, the probes are susceptible to vibration damage and plugging by particulates (2,6). The potential for plugging problems is greater in wet stacks.

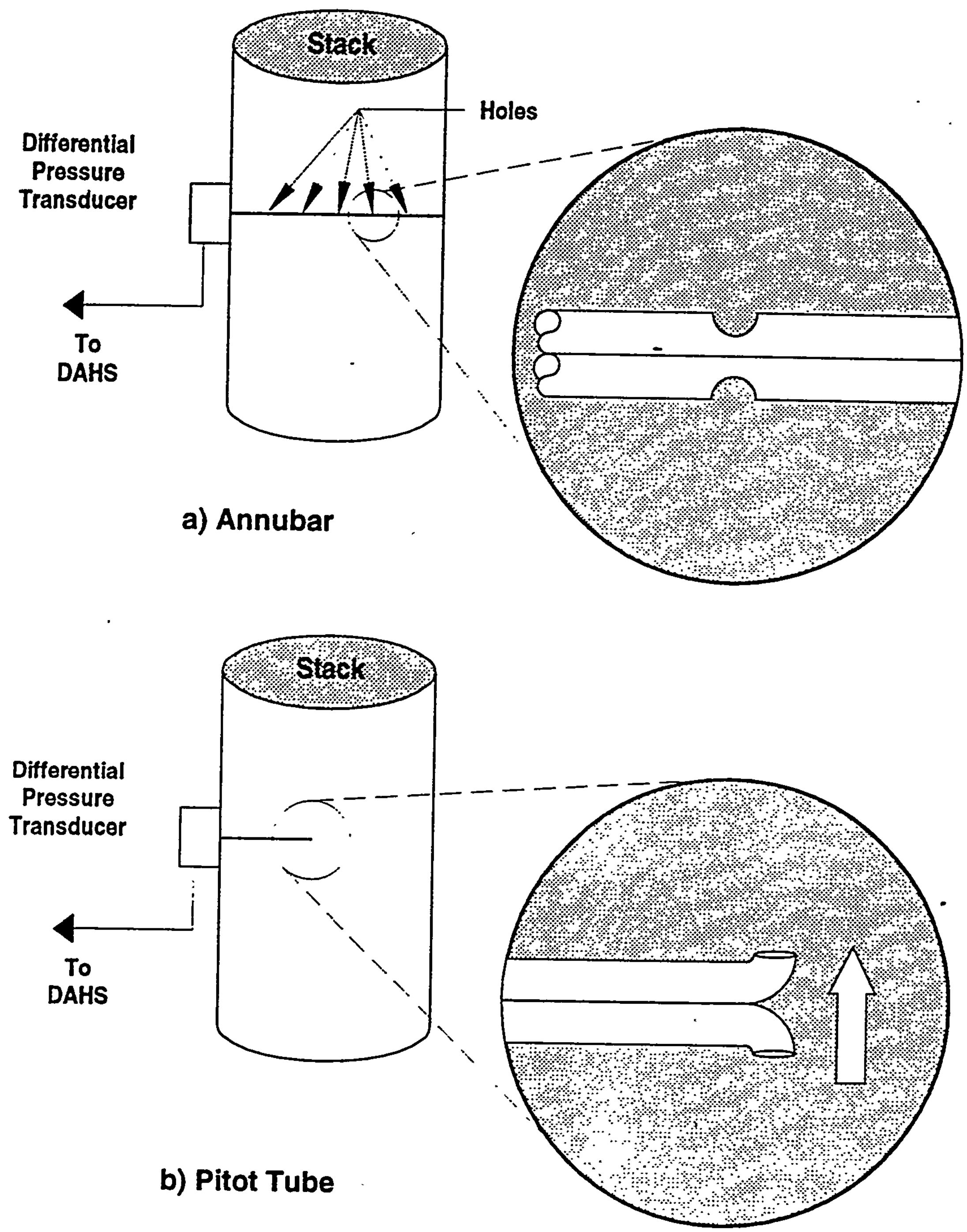


Figure 15-3. Annubar and Pitot-Tube Differential Pressure Flow Meters

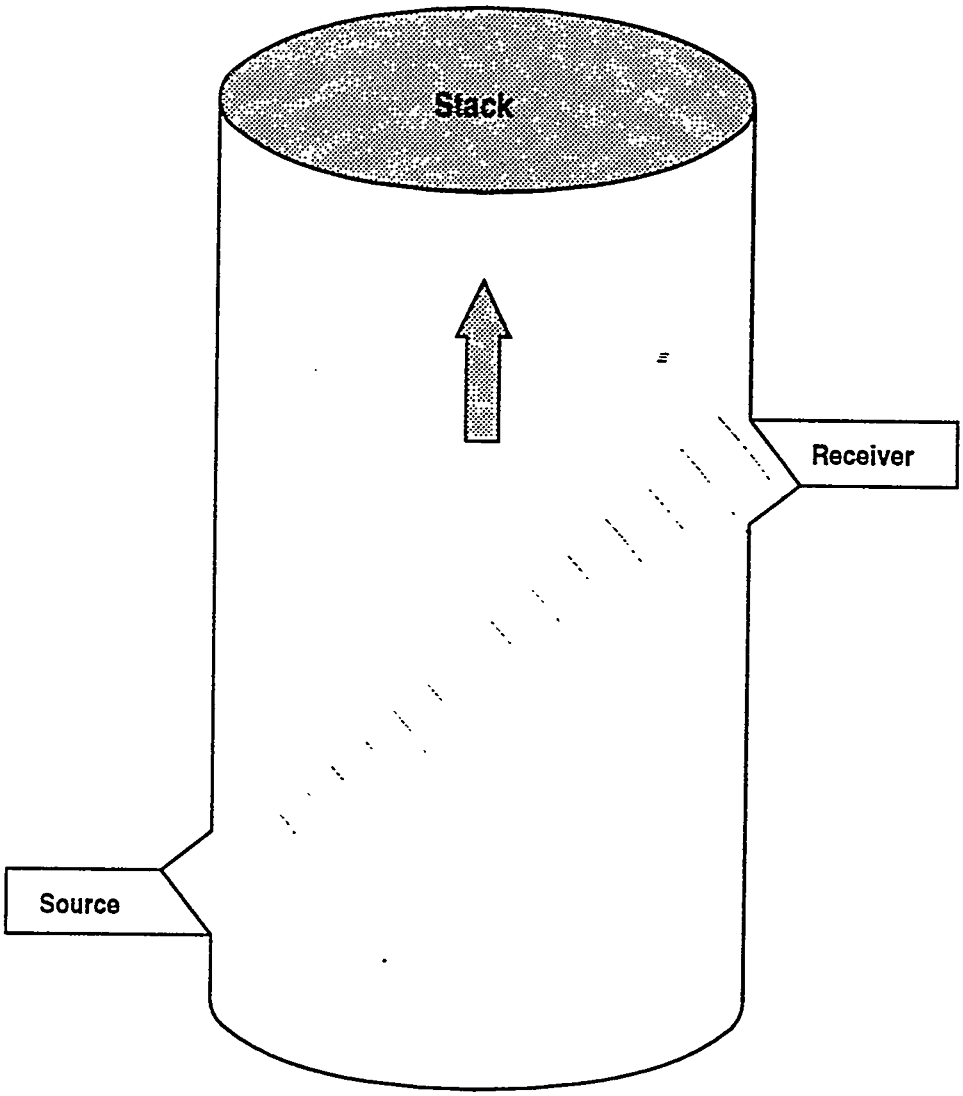
Doppler Flow Meters

Doppler flow meters, also called differential frequency or transit time flow meters, are a recent development, used primarily in power plant applications. An ultrasonic transducer is placed in the stack such that the ultrasonic beam is projected upward at a 45° angle to a matching receiver placed on the opposite wall of the stack, Figure 15-4. Gas velocity is determined by the doppler shift in the ultrasonic frequency between the transmitter and receiver.

While doppler meters are relatively new, they have been demonstrated to meet EPA relative error and accuracy requirements, are not subject to fouling by fly ash, are not adversely affected by vibration, can be used in both wet and dry gas streams, and measure the average gas velocity across the stack (2,6).

15.1.4 Opacity Meters

Opacity meters determine the visual opacity of the flue gas stream by measuring the attenuation of a beam of light transiting the stack. Opacity monitors may be either single- or dual-pass designs. In the single-pass design, light from a helium-neon laser (543 nm) transits the stack from an optical source window to a detector on the opposite side. The source and detector are externally linked by a fiber optic reference path around the stack, similar to the single-pass across-the-stack gas analyzers shown in Figure 15-2. In dual-pass systems, a beam of light (575 nm) from a light-emitting diode (LED) source is transmitted across the stack to a retroflector which reflects the beam back to the optical window, also as shown in Figure 15-2. Calibration of either system is achieved by the use of a rotating calibration disk inserted between the source and the optical window. This rotating window has calibration segments of known light absorptive power. The calibration procedure generates a "dirty window" correction for the gradual fouling of the optical surfaces. This automatic calibration occurs about once per second for many systems. Dual-pass systems must be pre-calibrated for the beam length (stack width), but pre-calibration is not necessary



Doppler Velicometer

Figure 15-4. Doppler Flow Meter

for the single-pass system. All optical surfaces of the single-pass system are checked during calibration, but the retroflector of the dual-pass system cannot be checked during calibration. Opacity is directly proportional to attenuation with either design.

15.2 Design Considerations

15.2.1 Process Considerations

The primary process consideration that affects CEM selection is whether the gas stream to be monitored contains, or may contain, moisture droplets. The presence or absence of moisture droplets affects method selection for gas flow rate determinations and the suitability of across-the-stack analytical instrumentation.

15.2.2 Mechanical Considerations

As mentioned previously, CEM probes can be subjected to intense vibrational loading, and vibration (fatigue) failure requires consideration. Wet- and dry-extractive system sample lines should have a continuous downward slope between the stack and the analyzer shelter to avoid pooling of condensation.

15.2.3 Other Considerations

If the CEM system is to function efficiently and contribute to the improved operation of the plant and FGD system, some fundamental guidelines should be considered during the CEM selection process (5).

- The system should be engineered for the specific application;
- The sampling system design should take into account site- and application-specific conditions, the reliability of the components, and the durability of construction materials;

- The accuracy and reliability of the analytical instruments must be considered;

- The hardware and software capabilities of the DAHS must be consistent with the plant's operating and regulatory requirements;

- The system must have sufficient redundancy that the utility does not suffer unacceptable regulatory penalties due to "lost data"; and

- The CEM and DAHS should be evaluated for ease of use, service, and vendor support.

In addition, the design and procurement of the CEM should consider the following:

- Selection of the basic procurement strategy;
- Definition of the analytical suite;
- Selection of probe location points;
- Instrument selection;
- DAHS selection;
- Maintainability;
- System checkouts; and
- Certification and overall schedule.

Basic Procurement Strategies

The first decision that the utility must make concerns the basis procurement strategy. There are four basic procurement strategies for CEM systems (6).

- The plant may rely on an *analyzer supplier* who provides pre-packaged CEM systems featuring its own equipment. Typically several pre-engineered packages are offered from which to choose. Although this approach can cost less, system certification and interfacing with the governing regulatory agencies are left to the plant. Another key disadvantage is the inability to intermix brands of analyzers and customize the design.

- The plant may rely on a *systems integrator* who provides flexibility in design while giving the plant the security of guaranteed performance and certification. An integrator may mix brands of analyzers and select from assembly-line or custom sampling systems. The increased cost of using a systems integrator is frequently offset by the enhanced CEM design and guaranteed performance and certification.

- The plant may rely on a *CEM specialist*, whose only business is emissions monitoring. Such companies specialize in large, multi-CEM installations complete with shelters and data acquisition and handling systems. Their CEM systems are generally designed around one or two brands of analyzers and feature proprietary software for reporting. They offer guaranteed performance, annual software upgrade contracts, and quarterly on-site certification assistance. While this option is the highest priced of the four options presented, it offers the highest level of security with minimum plant personnel involvement.

- If the plant has specialized analyzer shops, or ready access to them, the work can be done in-house. Typically, control-system engineers design and install the CEM, while environmental engineers are responsible for system qualification tests performed for EPA inspectors. If many CEM systems are to be deployed, it may pay the utility to develop these areas of expertise in-house.

While in-house design and deployment can potentially reduce cost if the utility has the corporate resources, it will rapidly become the most expensive alternative if the utility does not. The utility should consider very carefully its ability to design and install a CEM system, and the expertise of its plant chemistry and instrumentation personnel before deciding on its basic procurement strategy.

Definition of the Analytical Suite

The current CEM analytical suite for FGD systems of new and existing coal-fired plants was discussed above. However, the utility should be aware that the monitoring requirements are evolving rapidly at this time (mid-1995), and the utility should conduct a detailed review of the most recently promulgated and currently proposed regulations to assure that the CEM system is designed in conformance with the most current regulations.

Monitoring Point Location

CEM regulations require monitoring of the gas in the stack and may require monitoring at other points as well. In addition, the utility may elect to monitor for some of the CEM constituents at additional points to improve process control. For example, when multiple absorber modules discharge to a common stack liner, the utility may elect to monitor the individual module outlet ducts in addition to monitoring the stack. This allows the utility to better determine the origin and cause of an excursion in the stack emission rates.

The precise location of the probes within the stack or ductwork is absolutely critical to the overall success of the CEM program. The probes must be placed to obtain representative samples of the flue gas. Prior to retrofitting CEM systems to existing FGD processes, thorough flow tests should be conducted to accurately define the velocity profile within the duct or stack. Particular attention should be paid to cyclonic flow conditions, unusual velocity profiles, and changes in profile as a function of varying unit load. In the case of new coal-fired plants, an initial modeling of gas flow within the duct or stack replaces the flow test. The initial results may reveal the need for more elaborate modeling, the possible use of flow straighteners, and the development of correction factors to calibrate the monitors for accurate data reduction and reporting. Even with this initial effort, operating experience may show that it is necessary to reposition one or more of the probes (4).

Instrument Selection

The designer must next decide whether to use in situ or extractive gas analyzers, and if extractive systems are selected, whether the extraction will be wet, dry, or diluted. The merits and drawbacks of the various options were summarized earlier in this section. If extractive technologies are used, then the locations of the instrument shelter(s) and the runs of the sampling lines must be decided upon. If extractive designs are selected, the designer must also decide whether to use a train of single constituent analyzers or to select a multi-constituent analyzer. The gas flow monitor and opacity monitor are by definition in situ devices.

Data Acquisition and Handling System (DAHS) Selection

The intensive and elaborate data acquisition, manipulation, and reporting requirements of the CEM regulations can be met in one of three ways:

- Use of a CEM system vendor's dedicated DAHS. Once all of the components are interconnected, this alternative requires only modifying the basic or standard reporting formats to the specific plant requirements and learning how to operate the software.
- Use of a stand-alone, PC-based DAHS system. However, this option can require the design of a custom interface to the CEM system instrumentation, as well as development of software to complete the environmental reports. Neither of these activities is trivial.
- Use of the generating plant's central computer. If the CEM system is retrofit to an existing plant, the utility may elect to modify the existing plant computer system, adding appropriate inputs and outputs, altering the system database, defining report contents and formats, and implementing software changes.

The best approach for a specific DAHS depends upon the utility's applicable CEM system experience, the organization's in-house computer programming capability, the degree of system expertise, and the utility's preference for uniformity and standardization among plants (4).

For the greatest operating flexibility and maximum return on the CEM system investment, the DAHS should allow simultaneous user access to current information from several work stations, such as the analyzer building, the plant control room, the plant engineer's office, and the corporate compliance engineer's office. The data reliability requirements of the CEM regulations make redundant data residence highly desirable, and serial configuration so that data can be restored to either upstream or downstream components is very strongly recommended (7).

Telecommunications from a central location offers CEM system operators several advantages. Reporting CEM data to a central location can minimize plant personnel workload by streamlining the preparation and submittal of the EPA reports. While continuous, real-time monitoring of emissions from every stack in the utility system at the central office is not necessary for regulatory compliance, it may be beneficial in assuring compliance because of the central responsibility for early detection and reporting of non-compliance situations. Also, centrally stored CEM data can be easily restored to the plant system if the need should arise, and thus can add a measure of security to the system.

Batch reporting of CEM data to a central location can be accomplished by modem, but continuous real-time monitoring at a central location requires a dedicated carrier medium. Both types of telecommunications system must be designed for high reliability.

When multiple generating units are located at the same site, each will have its own CEM system, but the option exists to manage all data processing through a single DAHS. The apparent savings from using a single, expanded DAHS can be offset by several factors. For example, the capacity of the computer hardware has to be tailored to the number of units at each site. The engineering effort to specify the hardware and to select and customize the software increases significantly. Using an individual DAHS for each unit allows the selection of identical modular hardware and software throughout the system, simplifying procurement, software development, and maintenance personnel training. An individual DAHS for each unit requires a large number of identical devices; however, this rarely results in reduced unit prices from suppliers. This configuration also increases the number of interfaces with the utility's telecommunications system (7).

Regardless of the DAHS used, thorough documentation of all software modifications is absolutely essential to long-term operability.

Maintainability

A maintainable system uses a design based on highly reliable components and adequate redundancy to prevent long periods of missing data. A maintainable system employs special buildings to house analyzers and computers and provide weather protection for stack-mounted equipment. It has easily accessible and maintainable instruments on the stacks which are frequently housed in enclosures that are appropriately heated or air-conditioned to meet instrument temperature requirements and provide adequate and safe working conditions. Maintainability requires the installation of appropriate lifts, support rails, and electrical outlets on the stack. A maintainable system requires adequate uninterruptible power supplies to critical components to prevent lost or corrupted data.

Maintainability also means committing sizable resources to instrument calibration and high maintenance standards because even short periods of instrument downtime can result in costly regulatory penalties. It can mean installing a redundant instrument train. Finally, it means buying from a well-established vendor that is likely to remain in business so that a long-term source of technical support and parts is available.

System Checkout

The various system subassemblies should be shop-tested to the maximum extent possible with wiring interfaces coupled whenever possible to minimize field connection errors which can be difficult to diagnose and correct.

It is prudent to conduct extensive debugging tests prior to the test witnessed by the governing regulatory agency or authority. This will resolve any operating problems or anomalies that might lead to costly retesting. This system testing should include the full range of normal and anomalous operating conditions, such as power interruptions, loss of instrument air, or sample conditioning problems (7).

Certification and Overall Schedule

In the United States, certification of the CEM requires a 6-month window in the project schedule. The EPA must be notified 30 days prior to the actual certification testing date. One month should be allotted to conduct the test and prepare the required reports and applications to the EPA, who then requires 120 days to act upon the application. Utilities operating under other or additional environmental authorities may encounter different regulation-driven certification schedules.

Experience has shown that realistic lead times for CEM equipment are seven to eight months. If a reasonable time frame is allowed for initial CEM development, overall system procurement, installation design, and construction work, it can easily take 18 months to attain a certified CEM installation.

15.3 Material Selection

The flue gas environment being monitored by CEM systems is potentially extremely corrosive because of the presence of acid gases, chlorides, and particulates. Probes and components within the stack or duct, such as gas sample probes, annubars, and pitot tubes, are typically constructed of Alloy C-276 (2). Other C-Class alloys (including Alloys C-22™, 59™, 622™, and 686™) can generally be interchanged with Alloy C-276. Titanium might also be used. Tantalum can provide extreme corrosion resistance for small critical parts exposed to the environment. Fused quartz, borosilicate glass, the fluoropolymers shown in Table 15-1, and similar materials may have roles in the construction of specific in situ devices.

Table 15-1

Fluoropolymers used in CEM Systems

Generic Name	Chemical Name	CAS Registry No.	Common Trade Names	Common Use Form(s)	Continuous Temperature Limit
PTFE	poly(tetrafluoroethylene)	9002-84-0	Teflon TFE	Semi-rigid tubing and gaskets	260°C 500°F
FEP	poly(tetrafluoroethylene-*co*-hexafluoropropylene)	25067-	Teflon FEP	Semi-rigid tubing and gaskets	205°C 400°F
Fluoroelastomers	Poly(vinylidene fluoride-*co*-hexafluoropropylene)	9011-17-0	Fluorel Viton A Tecnoflon Dai-El	O-ring seals	315°C 600°F
	poly(vinylidene fluoride-*co*-hexafluoropropene-*co*-tetra-fluoroethylene)	25190-89-1	Viton B Viton G Dai-El G-501		
	poly(vinylidene fluoride-*co*-tetrafluoroethylene-*co*-per-fluoromethyl vinyl ethyl)	56357-87-0	Viton GLT		
	poly(vinylidene fluoride-*co*-1-hydropentafluoropropylene)	32522-63-9	Tecnoflon SL		
	poly(vinylidene fluoride-*co*-1-hydropentafluoropropylene-*co*-tetrafluoroethylene)	29830-35-1	Tecnoflon T		

The gas path of wet-extractive analyzers should probably be made of C-Class alloys despite the use of heat-tracing designed to prevent acid condensation. This precaution is justified since a loss of heat-tracing on tubing made of less corrosion-resistant material could result in serious corrosion, and more importantly, contamination of the tubing that would be difficult to correct. C-class alloys should be used upstream of the drying modules of dry-extractive analyzers, and upstream of the dilution point of dilution-extractive systems. PTFE tubing (see Table 15-1) can be used in place of C-class alloys at temperatures up to 260°C (500°F) in applications where mechanical stiffness is not required. PTFE is effectively inert to the FGD environment, even if acid condensates form. A wide variety of PTFE fittings and valves are also available from several commercial sources.

Once the gas has been cooled and dried or diluted, the gas path can be made of Type 304L or 316L stainless steel, PTFE, or FEP tubing (see Table 15-1). A variety of fluoroelastomers can be used for O-ring seals, as shown in Table 15-1. The actual gas path is frequently a combination of these materials.

As discussed previously, gas sampling probes, pitot tubes, annubars, and doppler velicometers are typically equipped with moderate-pressure, instrument-air purges to clear accumulated particulate matter. The optical surfaces of opacity and in situ analytical devices can also be equipped with purge air to reduce fouling of critical surfaces.

15.4 Recommendations

- Individuals responsible for design or specification of the CEM systems must stay abreast of the changing regulatory requirements for such systems.
- Successful implementation of a CEM system requires a large initial and ongoing commitment of resources on the part of the utility.
- Unless the utility has extremely sophisticated in-house capability, the most satisfactory results will probably be obtained by subcontracting the design and implementation of the CEM either to a CEM specialist or to a systems integrator.

- Currently, dilution-extractive gas analysis (with either single- or multi-constituent analyzers) appears to be the monitoring method of choice, but in situ, across-the-stack technology is developing rapidly. Designers should review the current status of the competing technologies.

- If extractive gas analysis is used, the designer should carefully consider use of multi-component FTIR analysis because of the increased analytical flexibility and facility with which the analytical suite can be changed.

- Doppler velocimetry (ultrasonic or transit-time flow metering) is preferred to measure the gas velocity through the stack, particularly in units with a wet stack.

- Across-the-stack instruments with single-pass optics appear to offer distinct maintainability advantages over dual-pass systems.

- Monitoring data should be maintained in redundant files to minimize the potential for data loss. The DAHS should be able to transfer data files between users.

15.5 References

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16.0 PROCESS SUMPS AND TANKS

This section contains information related to process and washdown sumps and those process tanks that are not described in other sections of the manual. These process tanks include the following:

- Thickener/hydrocyclone underflow and overflow tanks;
- Vacuum filter/centrifuge process water tanks;
- Makeup water/mist eliminator wash water tank; and
- Reaction tank emergency dump tank.

Absorber module reaction tanks are described in Part I, Section 4.3--Reaction Tanks; thickener tanks are described in Part II, Section 11.0--Thickeners; and reagent and chemical additive storage tanks are described in Part I, Section 4.7--Reagent/Additive Preparation Equipment. In general, the information provided in this section is also applicable to these other tanks.

16.1 Types Available

A variety of FGD process sumps and tanks are used to collect and store FGD system process fluids. These vessels can be categorized by their location and by the type of process fluid they contain.

Vessels can be categorized as being either above or below ground level. Generally, below-grade vessels are called "sumps" and above-grade vessels are called "tanks"; however, exceptions are possible. In most FGD systems, below-grade sumps are installed to facilitate drainage from other vessels that are located at or near ground level. As an example, a below-grade sump is located near the absorber module reaction tanks to collect drainage from these tanks, slurry piping flush and drain water, and miscellaneous process leaks. If the secondary dewatering system's vacuum filters are located at ground level, then the vessels used to collect filtrate and the vacuum pump seal water would both be below-grade sumps; if the vacuum filters are located on an elevated floor, then above-grade tanks could be used. Obviously, building and area washdown sumps must be located below grade.

Vessels also can be categorized as containing either a slurry or clear liquor. The major design difference between slurry and clear liquor vessels is that vessels containing a slurry require agitation and may need an abrasion-resistant lining. In practice, a vessel may contain a clear liquor most of the time, but periodically receive a slurry. In this case, the vessel must be designed on the basis of the slurry characteristics.

16.2 Design Considerations

The design of FGD sumps and tanks generally follows standard mechanical and civil engineering guidelines. However, a few specific design considerations are discussed below.

16.2.1 Process Considerations

The major process considerations controlling the design of process sumps and tanks are the following:

- The vessel's required capacity;
- The need for a tank roof; and
- The use of a reaction tank emergency dump tank.

Vessel Storage Capacity

Sump and tank volumes are usually defined in terms of residence time at a defined unit throughput (e.g., 12 hours' storage at the design flow rate), based on the usable volume of the vessel. The vessel's usable volume is defined as the volume between the vessel's minimum low liquid level and the normal high liquid level and is less than its total calculated volume.

The minimum low level is frequently determined by the liquid level needed to prevent cavitation of the pumps connected to the vessel. Pump cavitation is the flashing of liquid water into vapor because of very low liquid pressure on the suction side of the pump [inadequate net positive suction head (NPSH)], and the subsequent collapsing of the vapor bubbles in the higher pressure portion of the pump. Cavitation causes pump vibration and can damage the pump linings, bearings, and other components. The required NPSH varies with pump design and capacity, but typically sufficient NPSH at the pump impeller is provided by a slurry depth of 0.6 to 1 m (2 to 3 ft) above the top of the pump suction line of a horizontal pump.

If the vessel uses an agitator, the minimum liquid level also may be established by the minimum submergence of the agitator impeller. Agitator impellers must be submerged in the process fluid to develop good mixing patterns and to prevent mechanical damage to the agitator because of an under-loaded or unevenly loaded impeller. The minimum level for slurry agitation depends on the type and arrangement of the agitator(s) and the design of the vessel. Impeller submergence in the range of 0.6 to 2 m (2 to 6 ft) is typical, but may be even greater in a large diameter tank.

The normal high level on a below-grade sump is typically at or below the sump's lowest liquid entry point. In an above-grade tank, the maximum level is below the elevation of the tank's overflow pipe.

The required usable volume depends on the design and operation of the equipment the vessel serves. As an example, a thickener underflow tank may have a usable capacity of 8 to 24 hours (or more), depending on FGD process and operating factors such as the SO_2 removal rate and the utility's desire to limit the secondary dewatering equipment's hours of operation (e.g., one shift per day, seven days per week).

Open- or Closed-Top Design

Both sumps and tanks can be constructed with or without a water-tight roof. Many FGD process tanks are of the open-top design. In many cases, however, the top of the tank may be covered with bar grating to provide a safe working surface for agitator maintenance and to prevent debris from entering the tank. Tanks located inside of buildings are usually covered to control indoor humidity. Floor sumps are often provided with a solid or bar grate cover, both for safety and to prevent debris from entering the sump. Where bar-grate tops are used, the grating is designed to be easily removed to facilitate maintenance and cleaning.

Reaction Tank Emergency Dump Tank

When an absorber module's reaction tank is drained for maintenance or repair, the slurry (containing unreacted reagent and byproduct solids) can be saved and reused if an emergency dump tank is available. As the reaction tank is drained, the slurry is pumped to the emergency dump tank. When the reaction tank is returned to service, the tank is refilled with slurry from the emergency dump tank. This reduces the time required to return to process chemical equilibrium, reduces reagent consumption, and minimizes liquid surges in the FGD process. Many recent FGD systems have installed emergency dump tanks capable of holding the contents of one reaction tank. Reaction tanks are typically the largest tanks in an FGD system, with typical total volumes of 1900 m^3 (500,000 gal) or more. The emergency dump tank should be near the absorber area to minimize the length of piping runs and pump capacity.

16.2.2 Mechanical Considerations

Mechanical considerations applicable to FGD system process sumps and tanks include the following:

- Provisions for solids suspension;
- Provisions for solids separation; and
- Level control.

Solids Suspension

All sumps and tanks that may receive a slurry must have a method of maintaining slurry solids in suspension to allow the pumps to remove a homogenous slurry mixture and to prevent the vessel from filling with settled solids. Top-entry agitators are typically used on all slurry sumps and tanks, other than the reaction tanks (see Section 6.0--Tank Agitators). For most efficient mixing, the best design has the ratio of liquid depth to tank diameter equal to 1:1.2 (1). Baffles should be installed as described in Part II, Section 6.2.2.

A suitable support for the top-entry agitators must be provided. This usually involves support steel beams spanning the vessel. For aboveground tanks, the support must extend to grade at both ends of the span. Agitator support by the tank wall is possible only on relatively small steel tanks or tanks fabricated of concrete. The agitator support steel must be stiff enough to resist movement caused by the dynamic forces acting on the impeller.

Instead of (or in addition to) agitators, washdown sumps sometimes use other methods of mixing, such as air or water sparging and vertical pump-mounted agitators. Figure 16-1 shows how water nozzles can be installed near the suction of a vertical pump to mix settled solids. The water agitation may be used for a short period just prior to starting the sump pump, or for as long as the pump runs, if the solids tend to settle quickly. The

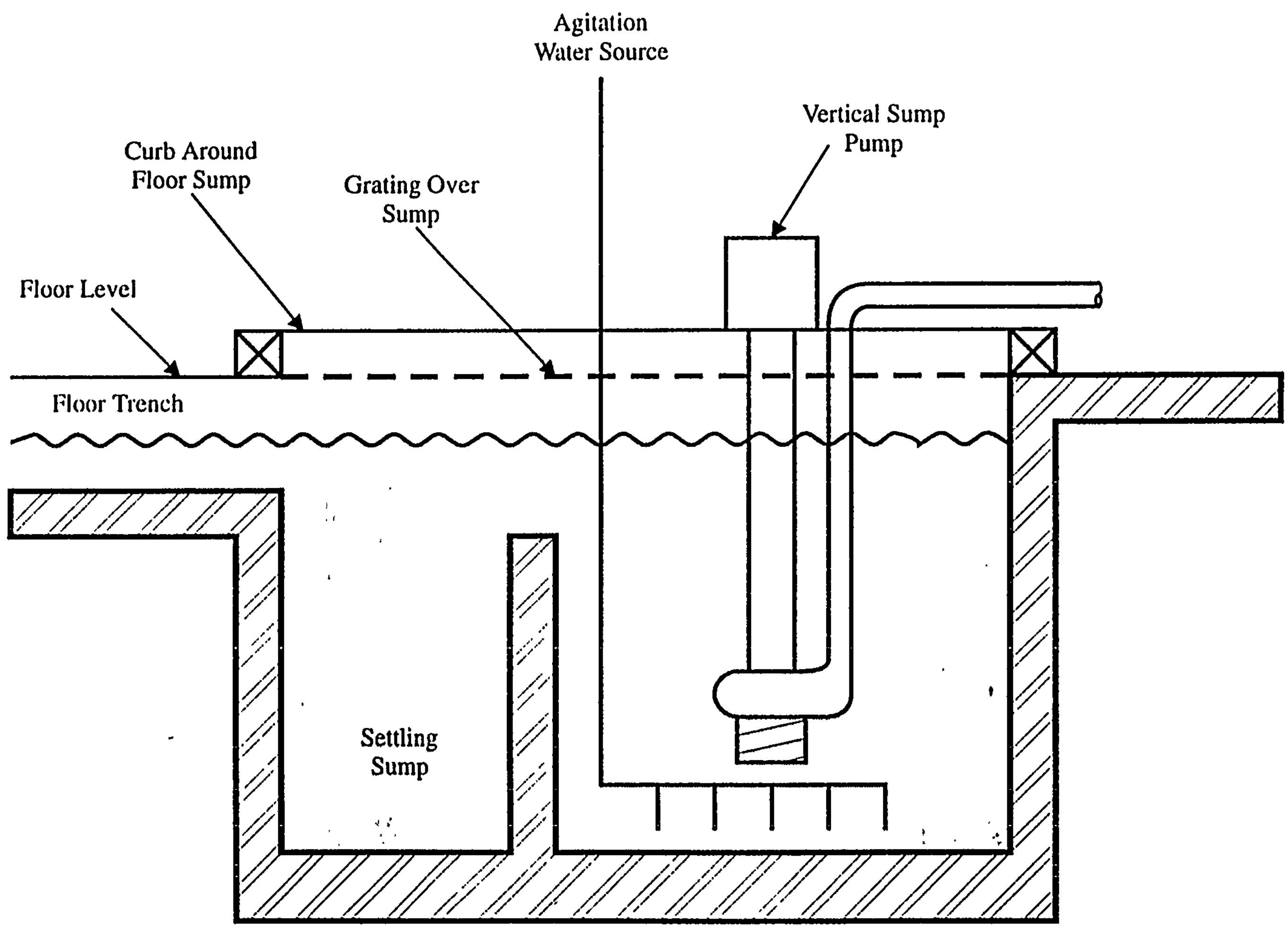

Figure 16-1. Washdown Sump with Solids Separation Basin

pump-mounted agitator has an agitator impeller mounted below the pump suction and mounted on the same drive shaft as the vertical pump. This impeller prevents clogging of the pump suction but does not provide complete mixing in the sump.

Solids Separation

Sumps collecting area washdown water and floor drainage can receive coarse solids and debris that can clog the sump pump. Therefore, it is important to collect these solids and prevent them from reaching the pump. This can be accomplished by placing grating or screens in the sump or trenches and by using a sump design with a separate settling chamber, as shown in Figure 16-1. The sump in the figure has two separate basins; the solids settling chamber overflows to the pump basin. Periodically, this settling chamber must be manually cleaned using shovels or a vacuum truck. This design has proved especially useful in the limestone reagent preparation area. If washed into the washdown sumps, coarse, unground limestone that spills from the conveyors and feeders in this area would damage the sump pump impellers and downstream piping.

Level Control

Some sumps and tanks are maintained at a relatively constant level, while others have a fluctuating level. In both instances, some type of liquid level monitoring instrumentation is required. Level control instrumentation is discussed in detail in Part I, Section 4.10.2--Tank Level.

Table 16-1 shows the types of level control used on various FGD tanks. In the sumps and tanks with "constant" level control, the level control equipment maintains the liquid level within a relatively narrow range by controlling the position of a makeup water valve. Sumps and tanks with "variable" level control are allowed to operate within a much wider range before action is taken. For instance, a high-level signal from a floor sump level sensor causes the sump pump to start and run until a low level in the sump is reached. In

Table 16-1

FGD Tank Level Control

Tank Name	Level Control
Reagent slurry storage tank	Alarm
Ball mill sump	Constant
Chemical additive storage tank	Alarm
Thickener/hydrocyclone overflow tank	Constant
Thickener/hydrocyclone underflow tank	Variable
Reaction tank emergency dump tank	Variable
Makeup water/mist eliminator wash tank	Constant
Floor and washdown sumps	Variable

some variable level tanks, such as the thickener underflow storage tanks, reaching a specific low level in the tank may not automatically initiate any process. Instead, the level sensor triggers an alarm to alert the operator to initiate an action, such as stopping the secondary dewatering equipment. Even in tanks with "alarm" level control, however, the level sensor will initiate a shutdown of the pumps if the liquid level falls below the level needed to prevent pump cavitation.

16.2.3 Other Considerations

Maintenance of sumps and tanks during outages should be considered during the initial design and arrangement of the FGD system. Tank drain valves should be located at as low an elevation as possible to facilitate draining of the tanks. Slurry tanks should have access hatches located in the walls near the bottom of the tanks. During an outage, maintenance personnel will enter the tanks for routine inspections and to perform maintenance on linings and agitators. Locating the tank drain lines or access doors flush with the tank bottoms can greatly facilitate cleaning the tanks. Solids that have accumulated in the tank can be quickly washed out the doors and into a nearby sump. Some utilities have installed large doors [2 m by 3 m (6 ft by 9 ft)] flush with the bottom of slurry tanks. This allows a small front loader to drive into the tank to remove settled solids. Although most prevalent with reaction tanks, the use of such doors is also useful with other large slurry tanks such as the reaction tank emergency dump tank.

Roof panels or grating should be easily removable to facilitate lowering scaffolding and materials into the tank during maintenance of the tank linings and agitators.

16.3 Material Selection

Part I, Section 5.0--Materials-of-Construction Options, is a thorough discussion of materials of construction and contains information specific to sumps and tanks. The reader is referred to that section for detailed information that may not be provided below.

Below-grade sumps are typically constructed of concrete. Although area washdown sumps may not need to be lined, sumps that receive process tank drains should be lined to protect the concrete from sulfate attack and protect the reinforcing steel from the corrosive effects of the slurry. The most common lining materials for below-grade sumps are reinforced resin coatings and ceramic tile over a urethane mastic membrane. When reinforced resin coatings are used, they are frequently formulated with abrasion-resistant fillers such as alumina or silicon carbide flour, and even alumina spheres. Reinforcement can be either flakeglass filler or fiberglass cloth, with cloth being the more durable. Reinforced resin linings and ceramic tile are frequently used in combination, with ceramic tile on the floor and a short distance up the walls, and reinforced resin over the remaining wall surface.

Most aboveground tanks are constructed of carbon steel attached to a concrete ring foundation. The tank floor may be concrete or steel. All steel tanks should be lined to protect against corrosion, erosion, or both. Corrosion of bare carbon steel reagent tanks can be expected to be increasingly severe with increasing chloride content in the limestone slurry makeup water. The most common lining materials are reinforced resin linings and ceramic tile over a urethane membrane. As with concrete tanks, these two materials are frequently used in combination, with ceramic tile on the floors and lower walls, and reinforced organic resin on the upper walls.

16.4 Recommendations

- Sumps and tanks should be designed for solids separation and/or solids suspension. A vessel that accumulates solids will cause maintenance problems.

- Sumps and tanks should be designed to facilitate maintenance through the use of large access doors, clean-out ports, and removable roof panels.

- The materials of construction should be selected on the basis of the potential erosive and corrosive conditions. Although other process tanks are in a less severe environment than the reaction tanks, erosion and corrosion can still be major problems.

16.5 References

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PART III
FGD SYSTEM PROPOSAL EVALUATIONS

1.0 INTRODUCTION

Part III of this manual provides an overview of the recommended procedures for evaluating proposals received from FGD system vendors.

1.1 Objectives

The objectives of Part III are the following:

- To provide recommended procedures for evaluating the technical aspects of proposals; and
- To provide recommended procedures for determining the total costs of proposals considering both initial capital costs and annual operating and maintenance costs.

1.2 Organization and Content

As illustrated in Figure 1-1, Part III is divided into three major topics: a brief introduction, technical evaluations, and economic evaluations.

Section 2.0 presents a discussion of the steps that should be followed in conducting a technical evaluation of alternative FGD proposals. This evaluation focuses on confirmation that the proposed FGD system will reliably achieve the required SO_2 removal efficiency and that the technical details of the specification have been met. The technical evaluation also quantifies the effects of the proposals on other systems at the generating plant.

Section 3.0 presents a discussion of a method to compare the proposals on a common economic basis, with three recommended procedures:

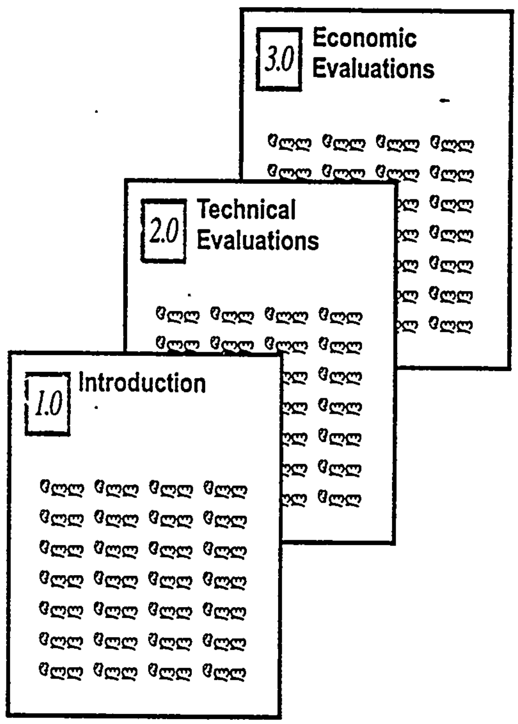


Figure 1-1. Part III Organization

- Determining the total initial capital cost of each proposal;
- Projecting the annual operating and maintenance costs over the economic evaluation period; and
- Combining the initial capital and annual costs to compare the total cost of each proposal on a levelized basis.

2.0 TECHNICAL EVALUATIONS

The first step in a technical evaluation is the comparison of the FGD system proposals received from the vendors. This comparison considers the following aspects of the vendors' proposals:

- Does the proposal contain the specified performance guarantees?
- Does the proposal contain the specified equipment and material warranties?
- Does the proposed equipment meet the specified technical requirements?
- Does the proposed system cover the specified scope of supply?
- Are proposed exceptions to the equipment technical requirements and scope of supply acceptable?
- Is the proposed FGD system arrangement acceptable in terms of the plant area used and effects on other plant equipment and systems?
- Does the proposed FGD system arrangement allow for sufficient accessibility to efficiently maintain and operate the equipment?
- Is the proposed control and instrumentation equipment sufficient to achieve stable operation of the FGD process?
- Can the proposed design reasonably be expected to achieve the required performance guarantees?

As these technical questions are answered, the proposal evaluators form opinions on the overall technical quality of the alternative proposals. Section 2.10--Overall Weighting of Technical Evaluation Criteria discusses a method of quantifying these opinions into a set of comparable values.

2.1 Attainment of Performance Guarantees

An FGD specification contains many performance guarantees, which can be divided into two general classes: 1) those that deal with emissions or environmental factors and 2) those that deal with economic factors.

Emission and environmental factor guarantees cover the compliance of the FGD system with applicable environmental regulations and may include the following:

- SO_2 removal efficiency (outlet SO_2 emission rate);
- Outlet particulate emission rate;
- Mist eliminator performance (water droplet emission rate);
- Byproduct solids composition and moisture content; and
- Wastewater composition and volume.

Vendors seldom take explicit exception to emissions and environmental guarantees such as the SO_2 removal efficiency guarantee because the utility usually has no latitude to grant a waiver to the required values. In some cases, however, the vendor may apply explicit or implicit conditions that may make attaining or verifying the guarantee very difficult. For example, the SO_2 removal efficiency guarantee could be conditioned on the use of very high reagent reactivity, long removal efficiency averaging times, or the use of chemical additives under some operating conditions. Where such conditions are considered by the utility to be unacceptable, the vendors should be directed to revise their proposals and identify any resulting proposal design or cost changes.

Economic guarantees may have environmental consequences, but are primarily concerned with the operating cost of the FGD system and are used in the economic evaluation of the proposals. These guarantees may include the following:

- Electrical power consumption;
- Flue gas pressure drop (overall and across specific components);
- Reagent utilization (reagent consumption);
- Water consumption for each source of makeup water; and
- Overall FGD system reliability and availability.

These economic guarantees may be expressed in other ways or may even be redundant. For example, a guarantee on maximum reagent consumption (e.g., kg limestone per hour) is not needed if the vendor has guaranteed the reagent utilization used to achieve the specified SO_2 efficiency. This is because the quantity of reagent used is a function of the amount of SO_2 removed, the reagent utilization, and the reagent composition.

A well-written specification will include a detailed test program for verifying that the system has achieved the specified performance guarantees. If, for example, the specification requires an electric power consumption guarantee, the specification will identify where and how the power consumption of the system will be measured and under what FGD system operating conditions. The proposal evaluation should confirm that the vendor has not taken any unacceptable exceptions to this test program. The vendor should be notified to correct such exceptions and to identify any resulting proposal design or cost changes.

2.2 Attainment of Equipment and Material Warranties

Equipment and material warranties are similar to economic performance guarantees in that they affect the operating cost and reliability of the FGD system. Examples of required equipment and material warranties contained in the specification include the following:

- The materials of construction will be suitable for the corrosive and erosive conditions experienced in the FGD system;

- The FGD system design will be suitable for load-following of the steam generator; and
- Equipment components will attain specific performance requirements (e.g., maximum noise level, design codes and standards, and component life).

In order to be enforceable, the specification must contain detailed language on how the achievement of the equipment and material warranties is to be measured. The utility proposal evaluators must carefully review each proposal to identify any exceptions or limitations to the warranty or testing that the vendor may have included. These exceptions and limitations may be the source of technical cost adjustments or differential support equipment adjustments (see Part III, Section 3.1--Determination of Total Initial Capital Cost).

2.3 Attainment of Technical Requirements

A typical FGD specification contains thousands of technical requirements covering every aspect of the FGD system design. These requirements cover the chemical, mechanical, electrical, and structural design of the FGD system. Parts I and II of this manual provide a discussion of the many technical considerations involved in FGD system design and specification. Within the limited time available for evaluating FGD proposals from several vendors, it is not possible to verify that each proposal meets every requirement. Therefore, the evaluation must rely on verification of technical requirements that are critical to the successful operation of the system.

While the proposals must conform to all of the technical requirements contained in the specification, there is a limited set of requirements that are critical to the efficient and reliable operation of the FGD system. A list of typical critical technical requirements is presented in Table 2-1. Each utility may construct this set of critical requirements differently, reflecting their previous experience with FGD systems or system components. The list may be expanded or reduced to meet specific concerns and the time available for the proposal evaluation.

Table 2-1

Typical Critical Technical Requirements

Chemical Requirements	
• Design flue gas conditions	• SO_2 removal efficiency
• Liquid-to-gas ratio	• Solids/liquid mass balance
• Byproduct composition	• Solids retention time
• Reagent utilization	• Wastewater composition and volume
Mechanical Requirements	
• Flue gas distribution and velocities	• Specified equipment types and vendors
• Absorber spray distribution	• ME wash spray distribution
• Materials of construction	• Equipment capacities and sparing
• Design codes	• Slurry piping velocities
• Sound pressure levels	• Design margins
Electrical Requirements	
• Design codes	• Equipment types and vendors
• Power consumption	• Design margins
• Materials of construction	• Enclosure types
Structural Requirements	
• Design codes	• Maximum deflections
• Design loads	• Supports
• Arrangements	• Floor trenches and sumps

Another objective of technical requirement evaluation is to detect areas where the vendors may have misread or misinterpreted the specification. By conducting this evaluation at an early stage in the procurement process, problem areas can be corrected at least cost to the utility and the vendors. It is also extremely important to identify technical exceptions that have been incorporated into the FGD system design, but not stated in the vendor's list of exceptions. These so-called "silent exceptions" are often difficult to discover unless the reviewer is very familiar with the specification and conducts a thorough technical review.

2.3.1 Verification of Critical Chemical Requirements

Because an FGD system is basically a chemical process, the chemical requirements are often the first set of requirements examined during the proposal evaluation effort. The utility proposal evaluator may wish to begin by reviewing the process chemistry discussion presented in Part I, Section 3--Lime- and Limestone-Based FGD Process Chemistry.

The evaluation should start with verification that the specified set of design conditions has been used. Especially important is adherence to the specified flue gas flow volume, SO_2 content, particulate loading, temperature, and pressure. Special care should be taken to ensure that the system design inlet flue gas conditions encompass all specified operating conditions, including prolonged operation at the maximum flue gas flow rate and SO_2 generation rate. The evaluation should also verify that the vendor has accepted the specified qualities of the reagent (lime or limestone) and makeup water sources. Vendors occasionally qualify their performance guarantees on the basis of the use of a reagent with a specific reactivity. This may impose limitations on the acceptable sources of reagent and is, therefore, generally unacceptable. Vendors should provide designs capable of handling any of the specified design conditions, including reagent quality. Similarly, a proposal may require a quality or quantity of makeup water that is unavailable.

If the specification includes requirements on L/G, reagent utilization, solids retention times, byproduct composition, and wastewater blowdown composition, these requirements should be verified by examination of the proposal data sheets and solids/liquids mass balances. Each specification should be carefully reviewed to identify any explicit or implicit assumptions the vendors may have included that may limit the operation of the FGD system or impose differential support equipment costs. For example, a proposal might include an assumption that blowdown entering the wastewater treatment system has a consistent composition or is at a constant flow rate. This could require the installation of a surge tank that must be furnished by the vendor or included as a differential support equipment cost adjustment.

The utility proposal evaluators may also verify the overall FGD system performance of the vendors' proposals using a chemical process simulation computer program such as FGDPRISM.™ The use of FGDPRISM in verifying the performance of proposed FGD systems is discussed in more detail in Part III, Section 2.11--Verification of Proposal Values Using FGDPRISM and in Part IV--Use of FGDPRISM in System Design and Proposal Evaluation.

2.3.2 Verification of Critical Mechanical Requirements

Table 2-1 lists several critical mechanical requirements that should be verified by examining the proposal technical data sheets and drawings. An area of detailed review during the proposal evaluation is the vendors' adherence to the specified equipment types and manufacturers. The proposal evaluators should review the proposals to determine that the proposed equipment types and manufacturers either meet the specification provisions or have been identified in the vendors' list of exceptions.

The utility proposal evaluators may be tempted to assume that review of the mechanical design of the proposal is not required because the specification requires the vendors to state any exceptions that have been taken with the technical requirements.

Experience has shown, however, that verification of critical mechanical requirements will often identify intentional or unintentional deviations that are not reported as exceptions. The preparation of an FGD system proposal requires the combined efforts of many individuals and is subject to a strict timetable. For these and other reasons, the vendor's list of exceptions may not contain every technical exception taken. Although the utility can argue that the provisions of the conformed specification supersede any such exceptions, it is far better to identify and discuss these areas during the proposal evaluation process to avoid problems later. The evaluation of alternative equipment is discussed in more detail in Section 2.4.

2.3.3 Verification of Critical Electrical Requirements

Of the electrical requirements listed in Table 2-1, the verification of power consumption may be the most important. The specification usually requires the submission of a motor list with the proposal. The utility proposal evaluators should verify that all major motors are included in the vendors' lists and that the lists are consistent with the vendors' electric power consumption guarantees. A knowledgeable electrical engineer should review each vendor's electrical design for adherence to the provisions of the specification and applicable codes and standards.

2.3.4 Verification of Critical Structural Requirements

Extensive structural data for the proposals are not typically available during the technical evaluation process. Verification of adherence to the specified structural requirements may be limited to review of the proposal to identify any technical exceptions not listed in the proposal. Special attention should be given to incorporation of any special structural requirements that are unique to the site. These special requirements could include those involving seismic design or unusual soil/foundation conditions.

2.4 Evaluation of Technical Exceptions and Options

As discussed previously in Section 2.3, the utility proposal evaluators may identify proposal provisions that do not meet the technical requirements of the specification. These may be in the form of either stated or unstated exceptions, and may be judged by the evaluators to be either acceptable or unacceptable.

There are several reasons that an FGD vendor may include technical exceptions in response to even the clearest, most carefully crafted specification. Often a vendor will propose a technically acceptable, lower-cost approach to achieving the specifications' goals that is not covered by the specifications' technical requirements. Also, every FGD vendor's design contains technical aspects that are unique to that vendor, some of which may be in conflict with provisions of the specification. In addition, the vendors are constantly revising and improving their designs to take advantage of the latest information from research and existing operating facilities. This information may not have been available for use in the preparation of the specification. These alternative approaches, unique design aspects, and new designs are strongly promoted by the vendors in their proposals in order to differentiate themselves from their competition and minimize their evaluated cost. The technical evaluation provides a method to consider such factors and to determine the most technically advantageous design from among the competing processes.

As stated previously, the vendor's technical exceptions may be judged by the proposal evaluators as either acceptable or unacceptable. Frequently, a detailed discussion with the vendor is required to reach a conclusion on an exception's acceptability. Where the exception is judged by the proposal evaluators to be unacceptable, the vendor should be notified to amend its proposal to meet the specification requirements, and to submit any resulting cost adjustments.

Often, options to the base FGD system covered by the specification are considered during the proposal evaluation process. These options may be either solicited by the specification or may be submitted unsolicited by one or more of the vendors. Solicited options may cover areas where the utility would like proposal cost data before making a final decision. These areas may include the following:

- A process option such as production of commercial-quality gypsum;
- A performance option such as achievement of a higher SO_2 removal efficiency through use of a performance-enhancing chemical additive;
- A design option such as the use of fewer, higher-capacity absorbers or pumps;
- A materials-of-construction option such as alloy versus lined carbon steel construction of the absorber;
- An equipment option such as the use of horizontal belt vacuum filters rather than rotary drum filters; and
- A scope-of-supply option such as including wastewater treatment equipment in the FGD system vendor's scope.

FGD system vendors frequently offer several options to their base proposal. These options may result from the vendors' attempts to make their proposal more technically attractive to the utility or more economically competitive. The following are examples of typical unsolicited vendor options:

- A vendor-specific or unique process option not covered by the specification;
- Alternative equipment types, materials of construction, or suppliers not allowed by the specification; and
- An increased (or, less frequently, reduced) scope of supply or services.

Utilities have established various ways of considering solicited and unsolicited options. Major considerations in this decision are the limited amount of time available for proposal evaluation and the desire to evaluate all vendors on a common technical basis. If an option may be seriously considered as a substitute for the base proposal, the technical review of the option should be as thorough as the review of the base proposal. Otherwise, it may be possible to limit the technical review of options to those submitted by the vendor(s) with the most advantageous base proposal. Further discussion of the evaluation of options is provided in Part III, Section 3.4--Solicited and Unsolicited Options.

2.5 Confirmation of the Specified Scope of Supply

Even though the specification may be very clear regarding the required scope of supply, vendors may submit a proposal that has either a larger or smaller scope. This may be due to vendor design preferences, the details of their specific design, a misinterpretation of the specification, or other factors. Therefore, each proposal must be reviewed to compare the specified and proposed scopes of supply, and any deviations from the specifications must be identified. All interfaces between utility-furnished and vendor-furnished equipment and services should be carefully examined to identify such scope-of-supply problems.

A frequent source of scope-of-supply deviations is an unclear or misinterpreted interface point between the utility-furnished and vendor-furnished equipment. For example, the specification may state that makeup water for the reagent preparation equipment will be furnished by the owner at a connection in the reagent preparation area. One vendor may assume that the branch isolation valve in this line is a utility-furnished item; another may assume it to be vendor-furnished and include it in the proposal's scope.

Another source of scope-of-supply changes results from a vendor's reluctance to supply equipment outside its area of expertise. For example, an FGD supplier might take exception to furnishing a wastewater treatment system if it has had no previous experience in wastewater treatment. Conversely, a vendor may propose to increase its scope of supply to take advantage of its expertise in areas such as foundations or bulk material handling.

It is important for all the proposals to be evaluated using the same scope of supply. Any deviations from the specified scope of supply should be discussed with the vendor and corrected prior to economic evaluation of the proposal to ensure that all proposals are evaluated on a common basis. The scope-of-supply adjustment cost will be used to adjust the vendors' initial proposal costs, as discussed in Part III, Section 3.1.2.

2.6 Determination of Differential Support Equipment Requirements

Another major reason for conducting the technical evaluation is to identify differential support equipment requirements. Each FGD vendor's proposal contains technical aspects that will impose requirements on generating plant equipment and systems outside the vendor's scope of supply. These imposed requirements can have significant differential cost impacts on the utility's total cost to install the FGD system.

Differential support equipment requirements, also called differential balance of plant (BOP) requirements, may affect the following utility-furnished equipment and services:

- Pumps and piping systems;
- Service water and cooling water supplies;
- Service and instrument air supplies;
- Fans, ductwork, and chimney;
- Electrical switchgear and equipment;
- Yard piping;
- Foundations and supports;
- Buildings and enclosures;
- Demolition or relocation of existing equipment and structures;
- Earthwork, roads, and site drainage; and

- Pond and landfill sites.

For example, the proposed flue gas pressure drop across the FGD system affects the sizing and cost of the ID fans, their motors, and their electrical supply equipment. At an existing site, the proposed pressure drop could determine whether the existing fans have sufficient capacity or booster fans are required. A more complex differential support equipment adjustment cost occurs when the specification provides for the vendor to erect the FGD system on foundations furnished under another contract. During the technical evaluation period, an estimate of the foundation requirements for each proposal would be required.

Fortunately, in conducting a comparison of alternatives, only the differential support equipment requirements must be determined. For example, if all the proposals require relocating an existing road, only differential relocation requirements (if any) between the proposals must be considered. If approximately the same road location would be used for all proposals, there would be no differential requirement. The use of differential requirements in the proposal evaluation reduces the amount of effort the utility's proposal evaluators must expend without affecting the evaluation's final conclusions. It must be noted, however, that if a total installed cost of the FGD system must be determined, the use of differential support equipment requirements would not be appropriate. In that case, all support equipment requirements for each proposal must be quantified. The effect of differential support equipment requirements on the economic evaluation process is discussed in Part III, Section 3.1.3.

2.7 Evaluation of Equipment Arrangement

The general arrangement of an FGD system can affect the ability of the utility generating station personnel to maintain and operate the system efficiently. The arrangement also has a major effect on the cost of support equipment such as foundations and enclosures. Generally the specification will include some boundaries within which the FGD absorbers and support systems must be installed. In reviewing the vendors' proposed FGD system arrangements, the utility proposal evaluators should consider how well the vendors have balanced the following factors:

- Integration with interfacing and existing equipment;
- Limitations on future construction activities;
- Maintenance access to the equipment; and
- Operation and supervision of the processes.

A detailed discussion of FGD system arrangement is presented in Part I, Section 4.11--Equipment Arrangement Considerations.

If significant changes in the arrangement of the equipment are needed, the vendors should be notified to amend their proposals to correct the identified problems and to submit any resulting cost adjustment. The overall rating of the proposed equipment arrangements can be quantitatively assessed, as discussed in Part III, Section 2.10.

2.7.1 Integration with Interfacing and Existing Equipment

The locations of interfacing and existing equipment have a major effect on the layout of the FGD system. The arrangement of the absorbers, for example, should minimize ductwork lengths between the ID fans and the absorber inlets and between the absorber outlets and the chimney to minimize future ductwork maintenance and flue gas pressure drop. The reagent preparation equipment and byproduct dewatering equipment should be located where the handling and temporary storage of large volumes of materials can be accommodated without disrupting coal and ash handling activities. The FGD system arrangement should minimize restrictions on maintenance access to other plant components located at the rear of the steam generator, such as the air heaters, particulate control device (ESP or fabric filter), ID fans, and chimney.

The evaluators should also consider how efficiently the vendor has used the available land and how the arrangement will affect the proposals' differential support equipment requirements. Inefficient use of the available space may restrict future, unforeseen construction and may result in higher costs for furnishing electric power, makeup water, and compressed air to the absorber and support systems. If the FGD system will be enclosed in a building, then the efficient layout of the system is important in minimizing the cost of the building and incidentals such as lighting, heating, and ventilation equipment.

2.7.2 Limitations on Future Construction Activities

If the utility contemplates expanding the generating station at a future date, the utility proposal evaluators should review the proposed FGD system arrangements to identify any limitations imposed on the arrangement of the future equipment. These limitations could also include effects on constructability of future units at the site by restricting the delivery or erection of major equipment components.

2.7.3 Maintenance Access to the FGD Equipment

Good physical access to all of the FGD system components is vital to the reliable operation of the system. Access is especially important around the major mechanical components such as ball mills, lime slakers, slurry pumps, and dewatering equipment. Sufficient work areas should be provided for in-place repair of such equipment. These work areas should include space for the erection of temporary hoists and for equipment removal access lanes when removal for replacement or shop repair is required. The absorber slurry recycle pumps used in FGD systems have grown to a size such that a dedicated, overhead trolley crane can usually be justified to facilitate their maintenance and removal. Where equipment such as mist eliminators is located above grade, hoists and drop areas should be provided to lower the equipment to grade for repair or replacement.

The proposal evaluators should also review the locations and elevations of access platforms, stairs, ladders, and elevator landings to assess the accessibility of all maintenance locations in the system. Locations of special concern include isolation dampers, ductwork, absorber spray levels, mist eliminators, and damper drives. Stairs are preferred over ladders.

2.7.4 Operation and Supervision of the FGD Process

The evaluators should review the location and arrangement of the local control room(s) for the FGD process, the reagent preparation equipment, and byproduct dewatering equipment to ensure that the operators have good physical access to the equipment. In the cases of additive preparation and byproduct dewatering, visual access to the system from local control rooms may be advantageous in supervising their operation. If control rooms are included in the vendor's scope of supply, the layout of the control rooms and panels should be included in this review.

If significant changes in the arrangement of the system are needed to improve the operation of the FGD system, the vendor should be directed to amend its proposal to correct the identified problem and to submit any resulting cost adjustment. The overall rating of the operation and supervision of the FGD system can be assessed, as discussed in Section 2.10.

2.8 Evaluation of Reliability/Maintainability

The utility proposal evaluators should attempt to assess the comparative reliability and maintainability of the proposals received. Reliability is a measure of how long the proposed equipment will operate between failures, often expressed as mean-time-to-failure (MTTF). Maintainability is a measure of how difficult it will be to repair a component assuming sufficient maintenance access has been provided, often expressed as mean-time-to-repair (MTTR). Within the limits of the specification, the vendors have considerable latitude to propose a wide variety of approaches to the design of an FGD system. In a effort to minimize initial capital cost, the vendors may be tempted to sacrifice some reliability and maintainability. A detailed discussion of factors affecting the reliability of FGD systems is presented in Part I, Section 6--System Reliability.

Some types of equipment are either inherently easier or more difficult to maintain and operate than others. For example, a bank of hydrocyclones is easier to maintain and operate than a thickener performing the same primary dewatering function. Similarly, some proposals may provide higher redundancy or more reliable equipment than others. Qualitative judgments on the MTTF and MTTR of critical FGD system components may be made on the basis of experience with similar equipment. If the utility has not operated similar equipment before, conversations with other utilities, equipment suppliers, and qualified consultants is highly recommended.

While it is usually not feasible to conduct a detailed reliability/maintainability analysis of all proposals within the time constraints of the evaluation, the utility proposal evaluators can review the proposal to identify strengths and problem areas. The overall rating of the reliability and maintainability of the FGD system can be assessed as discussed in Part III, Section 2.10.

2.9 Evaluation of Controls and Instrumentation

The control of an FGD system depends on both feedforward and feedback control of a number of components and subsystems. A discussion of the advantages and limitations of the various control approaches is presented in Part I, Section 4.10--Process Controls and Instrumentation. The utility proposal evaluation team should include a knowledgeable control engineer who can review the following:

- Stability of the overall process control scheme;
- Control logic diagrams for individual control loops; and

- Proposed instrumentation types and compatibility with interfacing systems.

If significant changes in the control logic of the system or individual instruments are needed to improve the operation of the FGD system, the vendor should be directed to amend its proposal to correct the identified problem and to submit any resulting cost adjustment. The overall rating of the controls and instrumentation can be assessed as discussed in Section 2.10.

2.10 Overall Weighting of Technical Evaluation Criteria

Several of the technical evaluation criteria discussed previously provide qualitative rather than quantitative results. In assessing the overall quality of alternatives, it is difficult to compare such qualitative results from different aspects of the proposed designs. For example, one proposal may provide very good maintenance access to the equipment, but impose difficult limitations on the construction of any future facilities at the station. The importance of each of the evaluation criteria discussed will also vary from site to site. In the example cited, limitations on future construction may not be a serious problem at the site under consideration.

A technical evaluation scoring system such as the one presented in Table 2-2 provides a methodology for comparing the relative technical strengths of alternatives even if precise quantitative data are not available. The procedure generates an overall rating score for each proposal considering a number of independent evaluation criteria. This procedure is well adapted to calculations using electronic spreadsheet techniques that allow rapid computations and consideration of alternatives.

The first step in creating a technical evaluation scoring system is to select the technical criteria on which the evaluation will be based. In the case of Table 2-2, the evaluation criteria discussed in the preceding sections of Part III were used, with the exceptions of attainment of the performance guarantees and of the equipment and material

Table 2-2

Example of Overall Technical Evaluation Scoring Table

Evaluation Criteria	Weighting Factor	Proposal A		Proposal B		Proposal C	
		Score (1 - 10)	Weighted Score*	Score (1 - 10)	Weighted Score	Score (1 - 10)	Weighted Score
Attainment of Technical Requirements							
Chemical	5	5	2.5	7	3.5	4	2.0
Mechanical	2	5	1.0	6	1.2	4	0.8
Electrical	1	5	0.5	4	0.4	5	0.5
Structural	2	5	1.0	7	1.4	7	1.4
Subtotal	10		5.0		6.5		4.7
Attainment of Scope of Supply	10	5	5.0	7	7.0	4	4.0
Differential Support Equipment Requirements	10	5	5.0	7	7.0	4	4.0
Equipment Arrangement							
Integration with other equipment	20	5	10.0	8	16.0	2	4.0
Limitations of future construction	5	5	2.5	7	3.5	8	4.0
Maintenance access	15	5	7.5	6	9.0	4	6.0
Operation and supervision	10	5	5.0	5	5.0	4	4.0
Subtotal	50		25.0		33.5		18.0
Maintainability/Reliability	10	5	5.0	6	6.0	4	4.0
Controls and Instrumentation	10	5	5.0	4	4.0	5	5.0
Total (out of 100 possible)	100		50.0		64.0		39.7

* Weighted Score = Weighting Factor x Score ÷ 10

warranties. Vendors should be directed to modify their proposed systems such that any exceptions to the performance guarantees can be removed from their proposals. No proposal should be evaluated in detail if it is unable to achieve these critical requirements. The vendors should either revise their proposals to eliminate exceptions to the equipment and material warranties or a technical cost assessment should be added to their proposal price to compensate for such deficiencies.

Attainment of technical requirements and scope of supply were added to the table even though the vendors would be asked to modify their proposals to meet the requirements of the specification during the proposal evaluation process. During the relatively short period of time available for the technical evaluation, it is unlikely that all technical exceptions to the proposal will be identified. Including these criteria in the evaluation weighting table allows the evaluator to downgrade those proposals with extensive technical adjustments as an allowance for undetected exceptions and deficiencies.

As shown in the table, a general evaluation criterion such as attainment of technical requirements can be broken down into subcategories or, as in the case of attainment of scope of supply, used as a single criterion without affecting the procedure. The table should contain as many (or as few) evaluation criteria as the utility proposal evaluators wish to consider.

The next step is to assign weighting factors to each evaluation criterion. For convenience, the total of all evaluation criteria may be set at a simple number such as 100. The weighting factor for each evaluation criterion is assigned on the basis of the relative weight that this criterion will be given in the evaluation. In the example table, the integration of the FGD system with other equipment (under the Equipment and Arrangement category) is given a rating of 20. The total of all equipment arrangement criteria is 50. This means that 50% of a proposal's total technical evaluation score will be on the basis of the equipment arrangement criteria. Likewise, the table shows that each of the other five evaluation criteria contribute 10% of the weighted score.

The specific weighing factors used in Table 2-2 are for purposes of illustration only. Setting evaluation criteria weighting factors is highly subjective and will vary for every utility and project. The weighting factor given to "maintenance access" in the example table indicates that this criterion is three times as critical to the technical evaluation as "limitations on future construction" at this specific application. Under a different set of circumstances, the relative weights given to these criteria might be reversed.

Next, each proposal is scored on each of the criteria. For simplicity, the score is based on a scale from 1 to 10, with 10 being the highest score. The scoring system used is based on utility preference, and many other scoring systems would be equally valid. Like the assignment of weighting factors, the scoring is not a precise activity. Often a score of 5 will be given to a proposal that meets, but does not exceed, a criterion. Other proposals are scored above or below that value based on their merits relative to that baseline proposal. Where more than one utility proposal evaluator is involved in the technical review of the proposals, it may be advantageous to have each evaluator conduct the scoring independently and discuss the reasons for significant variations.

The weighted score is the weighting factor multiplied by the criterion score. In the example, the product of these two numbers is divided by 10 to produce a maximum total score of 100. The total weighted score is the sum of the individual weighted score for each criterion. Comparing the total weighted score provides an indication of the comparative overall technical strength of each proposal. The relative strengths and weaknesses of each proposal are indicated by the relative score on each criterion. The magnitude of a proposal's total weighted score is not as important as its score relative to the other proposals. If the above scoring suggestion was followed, a proposal that just met or was average on every criterion would have a total score of 50.

Because of the subjective nature of assigning values to the weighting factors and scores, the utility proposal evaluators may wish to perform one or more sensitivity analyses by varying the factors and examining the resulting weighted scores. Typically, a superior proposal will score well over a wide range of weighting factors.

2.11 Verification of Proposal Values Using FGDPRISM

Part IV, Section 3--Proposal Evaluations, gives a detailed discussion of the recommended procedures for using the FGDPRISM program to verify the design values submitted by the FGD system vendor. The FGDPRISM program was developed by the Electric Power Research Institute for FGD system process simulation. Using the proposal values for L/G, reagent utilization, and physical design, the program can be used to verify the guaranteed SO_2 removal efficiency. The program can also estimate the makeup water requirements and the composition and quantity of FGD system byproduct and untreated wastewater blowdown. The program is also frequently used to evaluate absorber scaling potential by predicting relative saturation levels of calcium sulfate and calcium sulfite in the scrubbing slurry.

As noted in Part IV, the results predicted by FGDPRISM should be considered to be an indication of the expected range of values rather than an absolute confirmation of the process design. If the utility has previously performed an FGDPRISM calibration study using the same fuel, reagent, and FGD process configuration (or has access to such data), the degree of confidence in the results predicted by the program is higher. However, this is unlikely to be the case for every vendor's proposal. The greater the disparity between the existing data base and the proposed design, the less confidence should be placed in the program's results.

Perhaps the best use of FGDPRISM during proposal evaluation is to provide a comparison of FGD system design margins. In this role, the program may identify which vendor's proposed system can be expected to most reliably achieve the specified SO_2 removal efficiency and have the most flexibility in responding to process variations. Where the program identifies significant differences between the predicted and proposed process values, the vendor should be notified and asked to comment on their design and possible areas of process improvement. This inquiry should result in process changes or clarification of the vendor's proposal.

As an example, assume that three proposals have been received for a limestone-based FGD system and that all of them use the same reagent utilization and guarantee the same SO_2 removal efficiency. The principal differences between the proposals are the proposed L/G values, numbers of spray levels, and slurry chloride levels, as shown in Table 2-3.

Using information on the chemical composition of the fuel, limestone reagent, makeup water source(s) and each proposal's physical and chemical data, FGDPRISM can be used to predict the system's SO_2 removal efficiency. Based on the example data in Table 2-3, Proposal A would be expected to meet the guaranteed efficiency. Proposal B would be considered to be the most conservative design and the most likely to maintain the specified removal efficiency on a long-term basis or during upset conditions such as load swings. The performance of Proposal C would be marginal and the utility may want to discuss the system's design with the vendor before committing to such a system even if the overall evaluated cost of the proposal is lower than the other alternatives.

It should be emphasized that the most important result presented in Table 2-3 is the relative SO_2 removal efficiencies of the alternatives, not the actual predicted efficiencies. FGDPRISM would not be recommended as a design value verification tool until the program has been calibrated on a very similar set of design and operating conditions.

Table 2-3

Example of FGDPRISM Results

Design Value	**Proposal A**	**Proposal B**	**Proposal C**
L/G, liter/Nm^{3*}	12.75	15.5	11.4
Reagent utilization, lb-mol Ca/lb-mol SO_2 removed	1.10	1.10	1.10
Slurry chloride level, mg/L Cl^-	30,000	30,000	25,000
Number of Spray Levels	4	5	4
SO_2 removal efficiency, %			
Guaranteed	90	90	90
Predicted by FGDPRISM	91	95	88.0

* 1 liter/Nm^3 = 7.46 gal/1000 actual cubic feet times the pressure and temperature corrections from "normal" to "actual" flue gas conditions. "Normal" conditions are 1 atmosphere and 298 K.

3.0 ECONOMIC EVALUATIONS

The objective of an economic evaluation is to identify the proposal with the lowest total cost considering both the initial capital cost and the annual costs for operation and maintenance. This simply stated objective can be a difficult and time-consuming process because it assumes that all of the capital costs and annual costs can be identified and quantified. In actual practice, identification and quantification of all of the costs resulting from installation of an FGD system can be a very difficult task within the time constraints of the proposal evaluation process. However, without an evaluation of the total cost of the proposals, the true lowest cost proposal cannot be determined. Awarding a contract on the basis of capital cost alone is not prudent. A thorough analysis as discussed below may lead to a significant reordering of the vendors' proposals.

The first step in the economic evaluation is to identify the capital and annual costs of each proposal. After these costs are quantified, economic evaluation methods are applied to compare the total cost of owning and operating the FGD system alternatives.

A number of terms are used in this section that may not be familiar to readers who are not regularly involved in economic evaluations. These terms are printed in **boldface type** on their first use and defined in Section 3.5--Glossary of Terms.

For a more thorough discussion of engineering economic analysis, the reader is encouraged to refer to one of the many textbooks prepared on this subject (1-4). In addition, most electric utilities have established their own economic evaluation procedures using company-specific criteria.

3.1 <u>Determination of Total Initial Capital Cost</u>

It is vital to the economic evaluation process for the initial capital costs of all the alternatives to be evaluated on a common technical basis. The base proposal cost is provided by the vendor with his proposal. In order to accurately compare the **total initial capital costs** of several proposals, the following additional cost items must be quantified and added to the base proposal cost:

- Technical adjustment costs;
- Scope-of-supply adjustment costs;
- Differential support equipment adjustment costs; and
- Economic adjustment costs.

3.1.1 Technical Adjustment Costs

Technical adjustment costs are the costs associated with bringing a vendor's proposal up to the technical requirements of the specification. As discussed in Part III, Section 2--Technical Evaluations, one or more of the vendors may not initially offer a system that meets all of the specified technical requirements. When a vendor is requested to modify its proposal to meet the specification requirements, it is also requested to identify any resulting changes to its proposal price. For example, a vendor may increase its proposal price to supply pumps from the specified pump manufacturer rather than the one initially proposed. Alternatively, for competitive reasons, the vendor may choose not to change the proposal price in response to requested changes.

In the evaluation of a complex system such as an FGD system, it is not unusual to see technical adjustment costs applied in many areas. Even if the vendors have generally been responsive to the specification requirements, the total technical adjustment cost can amount to 2 to 5% of the original proposal price. Where a vendor has taken a substantial number of unacceptable exceptions to the specification's requirements, the technical adjustments may exceed 10% of the proposal price.

In cases where it is not possible for the vendor to respond in a timely manner, it may be necessary for the utility's proposal evaluators to estimate various technical adjustment costs on the basis of experience or contact with other equipment suppliers. However, these estimates should be checked against the quotations by the FGD system vendor before a final decision is made.

3.1.2 Scope-of-Supply Adjustment Costs

Scope-of-supply adjustment costs are the costs associated with bringing all of the vendors' proposals up to the specified scope of supply, as discussed in Section 2.5. If a vendor enlarges the proposed scope of supply to include additional equipment, a cost credit can be deducted from the proposal price. If time allows, the scope-of-supply adjustment cost should be obtained from the vendor. However, as with technical adjustments, the utility's proposal evaluators may need to estimate these cost adjustments because of evaluation time constraints.

3.1.3 Differential Support Equipment Adjustment Costs

As discussed in Section 2.6, each proposal imposes unique requirements on generating plant equipment and systems outside of the vendor's scope of supply. A list of typical utility-furnished equipment and services is presented in Section 2.6. As discussed in that section, the proposal evaluation is usually based on differential adjustment costs rather than absolute costs. This greatly simplifies the evaluation by permitting costs that are common to all proposals to be eliminated from consideration.

Unlike the previous adjustments to the initial proposal cost, the differential support equipment costs are estimated by the utility proposal evaluators rather than by each vendor. Also, these costs tend to be approximations rather than the result of detailed engineering. This lack of precision provides another reason for relying on differential rather than absolute cost adjustments.

3.1.4 Economic Adjustment Costs

The preceding three cost adjustments bring the initial capital costs of the alternative proposals to the same technical basis as of the date of the proposal. The economic adjustment costs cover expenditures incurred from the date of contract award to the commercial operation of the FGD system. These economic adjustment costs include **escalation** and **allowance for funds used during construction.**

Escalation

Historically, the costs for materials, equipment, and labor have risen over time. This increase in prices is termed "escalation" and is usually expressed as an annual percentage. Most large, multi-year construction projects, such as installation of an FGD system, allow the contractor to recover the additional costs resulting from cost escalation during engineering, fabrication, and erection. The escalation rate may be tied to a general escalation rate such as the **Producer Price Index** or to one or more of several commodity price indices published by government agencies. The cost escalation indices and calculation procedures are contained in the purchase specification or the vendor's proposal. It is common for vendors to propose that a portion of their price is firm (not escalated) and that different escalation indices be used for the labor and materials portions of their bids. A detailed discussion of escalation indices and calculation procedures is beyond the scope of this manual.

For the economic evaluation of FGD proposals, the utility proposal evaluators can calculate the escalation cost adjustment either by using projected cash flows provided by the vendors, or by making simplifying assumptions. A common simplifying assumption is to calculate a single escalation factor to be used for all vendors based on a typical cash flow. This single escalation factor would be applied to the total initial capital cost.

Allowance for Funds Used During Construction

The interest on money paid to the vendor prior to commercial operation of the FGD system is termed "allowance for funds used during construction" (AFDC or AFUDC). AFDC is calculated from the date of the payment to the date of commercial operation. As with escalation, the AFDC can either be calculated on the basis of each vendor's projected cash flow, or an assumed cash flow can be used for all vendors. If a single cash flow is used, the AFDC can be determined as a single factor applied to the total initial capital cost.

The interest rate used to calculate AFDC will be unique to each electric utility and the current economic conditions.

3.2 Determination of Annual Operating and Maintenance Costs

Annual operating and maintenance costs encompass the recurring costs associated with operation of an FGD system and include the following:

- Electric power;
- Reagent and additives;
- Byproduct disposal;
- Makeup water;
- Wastewater treatment;
- Operating labor; and
- Maintenance materials and labor.

These recurring costs should be projected for every year of plant operation or for every year of the capital recovery period where shorter evaluation periods are used. Basic to this effort is the preparation of a unit load model projecting annual fuel consumption, estimation of any future fuel quality changes, and selection of **commodity price indices**. The price indices are used to project the future unit costs for each year of the evaluation period. As in the case of determining the capital cost of FGD system support equipment (Section 3.1.3), operating cost calculations can be simplified by considering only differential annual costs between alternatives.

3.2.1 Electric Power Costs

The equipment data sheets of a well-constructed specification will ask the vendors to provide information on the power requirements of all major components. From this information, the utility's proposal evaluators can develop electric motor lists and estimate the total electric power consumption of the FGD system as a function of unit load and fuel quality. This is done by determining which components would be in service under each set of unit operating conditions and for how many hours per day. This information can be included in the proposal data required from the vendors for the equipment within their scope of supply; however, equipment outside of the vendors' scope of supply must be considered in developing the total electric power requirements. Depending on the specification's scope of supply, this additional equipment could include ID fans, reagent handling conveyors, instrument air compressors, and water supply pumps.

Some components require special consideration to determine what fraction of their total power consumption is attributable to operation of the FGD system. For example, the pressure drop across the FGD system is only a part of the total demand on the ID fans and varies with unit load (flue gas volume). Only the ID fan power consumption attributable to the FGD system's requirements should be used in the economic evaluation.

These power requirements are converted into annual costs using the utility's unit load model, fuel quality assumptions, and auxiliary power cost [cost per kilowatt-hour (kWh)] projections. The result is an estimate of the electrical power cost for each year of the evaluation period.

3.2.2 Reagent, Additive, and Other Chemical Costs

The consumption of lime or limestone reagent and any chemical additives used is primarily a function of the amount of SO_2 removed from the flue gas. The annual consumption of reagent and additives can, therefore, be calculated on the basis of the unit load model, fuel quality, SO_2 removal efficiency, and vendor-furnished reagent and additive consumption data (e.g., reagent stoichiometry). These annual consumption values are converted into annual costs by multiplying them by the projected actual reagent and additive unit costs (cost per kg) each year of the evaluation period.

Chemicals used for wastewater treatment or other purposes in the FGD system can be handled in the same manner as reagent except that their annual consumptions rates may be dependent on a different set of operating factors. The calculation of annual chemical costs for each year of the evaluation period is still required.

The cost of reagent, additives, and chemicals is one of the areas where the use of differential costs can be especially helpful in reducing the economic evaluation effort. For example, if all of the vendors guaranteed the same reagent stoichiometry and SO_2 removal efficiency, then there would be no differential reagent costs between alternatives.

3.2.3 Byproduct Disposal Costs

The byproduct produced by the FGD system may be either a solid waste requiring disposal in a landfill or a commercial product that will be sold for off-site use. In both cases, the annual quantity of byproduct material should be calculated for every year of the evaluation period. The annual quantity of byproduct is a function of the amount of SO_2 removed, the reagent stoichiometry, reagent quality, and FGD system operating parameters such as degree of sulfite oxidation and moisture content. If the byproduct is to be stabilized (mixed with fly ash) or fixated (mixed with fly ash and lime) prior to disposal, the quantities of fly ash and lime used must also be considered.

If the system produces a solid waste, then the annual quantities of byproduct are multiplied by the projected disposal unit cost (cost per kg). The unit cost must include transportation to the landfill and landfill operation. For the purposes of proposal evaluations, landfill operation costs often include an allowance for installation of any required linings and leachate collection/treatment systems. These costs can also be considered as differential support equipment costs.

If the system produces a commercial product, then the annual quantities of byproduct are multiplied by the projected unit revenue (revenue per kg), and the annual revenue is treated in the evaluation as a negative cost. The evaluation should use the net unit revenue of byproduct sales in this calculation. The net unit revenue would subtract any costs to the utility in supporting the sales. These supporting costs could include costs for the following:

- Byproduct marketing;
- Special handling or storage requirements;
- Disposal of byproduct that does not meet the user specification; and
- Installation of any wastewater treatment equipment.

As a result of these supporting costs and a low selling price, the net revenue for production of a commercial-quality byproduct may be zero or even a net cost to the utility. Even with these limitations, production of commercial-quality gypsum can reduce total byproduct disposal costs.

In many cases, byproduct disposal costs can be eliminated from the economic evaluation process. There is usually a large degree of uncertainty regarding the unit cost of byproduct disposal (the unit revenue of commercial sales) and a relatively minor difference between the quantities and qualities of byproduct generated by the alternative proposals. This results in a small differential cost between alternatives and a high degree of possible variation. Therefore, neglecting this byproduct disposal from evaluation of annual costs may be justified if the method of ultimate disposal is the same for all vendors.

Byproduct disposal costs can be very critical, however, where there are substantial differences in byproduct quality between alternatives. If, for example, one vendor's proposed system is capable of producing a commercial-quality gypsum and identifies a local market for this material, that proposal could receive a differential credit for byproduct sales. Even when only a portion of the total byproduct can be sold or the net unit revenue is negligible, the elimination of that portion of the byproduct disposal cost can have significant cost savings over the proposal evaluation period.

3.2.4 Makeup Water Costs

Initially, evaluation of makeup water costs appears to be similar to evaluation of reagent costs in that similar process alternatives should require approximately the same quantity of makeup water to replace the water lost in cooling the flue gas and in the byproduct solids. The proposals may vary significantly, however, in their requirements on the quality of the makeup water needed for various uses in the system. Proposals that are able to use a greater proportion of their total makeup water from plant wastewater sources may have a significant cost advantage over proposals that require higher quality water from plant makeup or service water systems. Conversely, proposals that use plant wastewater as a makeup water source may have higher wastewater discharge requirements in order to control the slurry chloride level (see the following section).

Considering these factors, the determination of makeup water costs can generally be limited to differential use of service water. The annual consumption of service water is calculated in much the same manner as electric power, that is, by tabulating the components that use service water (pump seals, lime slakers, ME washing, byproduct washing spray, etc.) and their annual hours of operation based on unit load model and fuel quality. The total annual quantities are converted to annual costs by multiplying each year's service water consumption by the unit cost of service water (cost per liter).

When differential use of service water between alternatives is small, the annual cost of makeup water can be neglected in the evaluation.

3.2.5 Wastewater Treatment Costs

Annual costs associated with the treatment of the FGD system chloride purge wastewater stream can be handled in several different ways, depending on the differential quantity and quality of wastewater generated, local environmental regulations, and specified FGD system scope of supply.

In addition to the quantity of wastewater generated, the chemical quality of the wastewater produced may differ with respect to levels of total suspended solids (TSS), total dissolved solids (TDS), and organics that produce a chemical/biochemical oxygen demand (COD/BOD). If the differences in wastewater quantity and quality between alternative proposals are small, the differential cost of wastewater treatment would also be small and can be neglected in the evaluation. In some cases, the FGD systems may not produce a wastewater discharge that requires treatment.

A discussion of FGD system blowdown treatment is presented in Part I, Section 4.9--Chloride Purge Wastewater Treatment. As discussed in that section, the degree of wastewater treatment necessary prior to discharge will depend on the chemical quality of the wastewater stream, the size and character of potential receiving streams, and the local environmental regulations. In some cases, the discharge of even treated wastewater may be prohibited because of water quality considerations. All of these factors affect the unit cost (cost per liter) of treating the chloride purge stream.

If the chloride purge wastewater treatment system is included in the FGD vendor's scope of supply, the differential wastewater treatment cost will be composed of energy, chemicals, maintenance, and labor costs. In this case, these costs could be considered in the annual cost categories and there would be no separate wastewater treatment cost.

If the chloride purge wastewater treatment system is not included in the FGD vendor's scope of supply, the proposal evaluation could be performed by either of two methods. In the first method, the proposal evaluators must estimate the cost of installing and operating the treatment system. The capital cost is handled as a differential support equipment cost (see Sections 2.6 and 3.1.3), and the differential annual operating costs are handled as discussed above. This method is the more accurate of the two alternatives, but also is the more time-consuming. The second method uses an estimated unit treatment cost for each stage of treatment (such as suspended solids removal, metals precipitation, pH adjustment, etc.). The unit costs include both capital and operating costs in a single value. The estimate is based on typical costs for the types of treatment operations required. This method is much quicker than the first method, but also less accurate.

3.2.6 Operating Labor Costs

An FGD system requires a significant operating labor force since the system must be manned 24 hours per day, 7 days per week. In some cases, support systems such as the reagent preparation system and the byproduct dewatering system are designed to operate only one shift per day, 5 to 7 days per week. While the proposal evaluation can estimate the annual payroll costs of operating labor, frequently there is little difference between the labor requirements of alternative proposals, and operating labor can be neglected in the evaluation.

3.2.7 Maintenance Materials and Labor

Unlike operating labor, there may be significant differences between alternative proposals in the amounts of maintenance materials and labor required. These differences arise from differences in design approaches, equipment suppliers, and materials of construction. Therefore, a significant effort must be made during the proposal economic evaluation to identify and quantify differential annual maintenance costs.

In many cases, it is easier for the utility proposal evaluators to identify differences between design approaches than it is to quantify a resulting differential annual cost. For example, the specification may permit the use of either rotary drum or horizontal-belt type vacuum filters for secondary dewatering of the byproduct solids. While there are differences in the filter cloth replacement frequency and cost between these two alternatives, the differences in annual cost may be difficult to quantify because of a lack of maintenance data. Determining maintenance cost differences between alternative suppliers of the same component may be even more difficult. For these reasons, many proposal evaluations concentrate on the more easily quantified maintenance cost differences that arise from alternative materials of construction.

As discussed in Part I, Section 5--Materials-of-Construction Options, there are a wide variety of material options for construction of the FGD system components, including alloys, lined carbon steel, and fiber-reinforced plastic (FRP). In a specific application, these materials have different service lives and maintenance requirements that can affect the annual maintenance cost.

As an example, consider two proposals that have taken different approaches to the selection of materials of construction of the absorber in a system with a high level of chlorides in the scrubbing slurry. Vendor A has proposed carbon steel clad with a highly corrosion-resistant nickel alloy. Vendor B has proposed a polyester lining over carbon steel plate. As discussed in Part I, Section 5, the alloy-clad steel construction should last the lifetime of the FGD system and require only periodic inspection and minor repair of the alloy welds. In contrast, a fraction of the polyester-lined absorber surface will require repair every year, and complete replacement will be required two or more times during the life of the system. In order for the two proposals to be evaluated on an equal basis, the costs of these future maintenance activities must be estimated for every year of the evaluation period.

Obviously, materials-of-construction differences (where permitted by the specification) could occur in many other areas, including the ductwork, mist eliminator, recirculation tanks, slurry pump impellers, and slurry piping. Where possible within the time limitations of the proposal evaluation, the differential annual maintenance costs should be estimated for all of these areas of the FGD system. The data used to make these differential cost estimates are often difficult to obtain. Typical sources are the utility's maintenance records for similar equipment (when available), contacts with other utilities with experience using this equipment, equipment vendor estimates, and any proposal materials' warranties.

3.3 Economic Evaluation of Total Costs

There are several classical methods of conducting an economic evaluation of alternatives: the **capitalized cost method**, the **annualized cost method**, the **total present value method**, and the **capital recovery period method**. Each of these methods is valid and will result in the same overall ranking; however, each has its inherent strengths and weaknesses. The choice among them is based on utility management preferences and standard economic evaluation procedures. This manual will use the capital recovery method because it is frequently used by electric utilities to justify capital expenditures and it provides a good comparison of the relative effects of capital and annual costs on the evaluation.

In conducting an economic evaluation by the capital recovery basis, the evaluator determines the **total initial capital cost** and calculates the cumulative **present value** of the **fixed charges** on this amount over the total operating life of the system. The evaluator then projects the annual operating and maintenance costs for each year of operation. For each year, the cumulative total present value is then calculated using the following formula:

$$\Sigma_x \text{ PV of Total Cost} = \Sigma_L \text{ PV of Fixed Charges} + \Sigma_x \text{ PV of Annual Costs} \qquad (3\text{-}1)$$

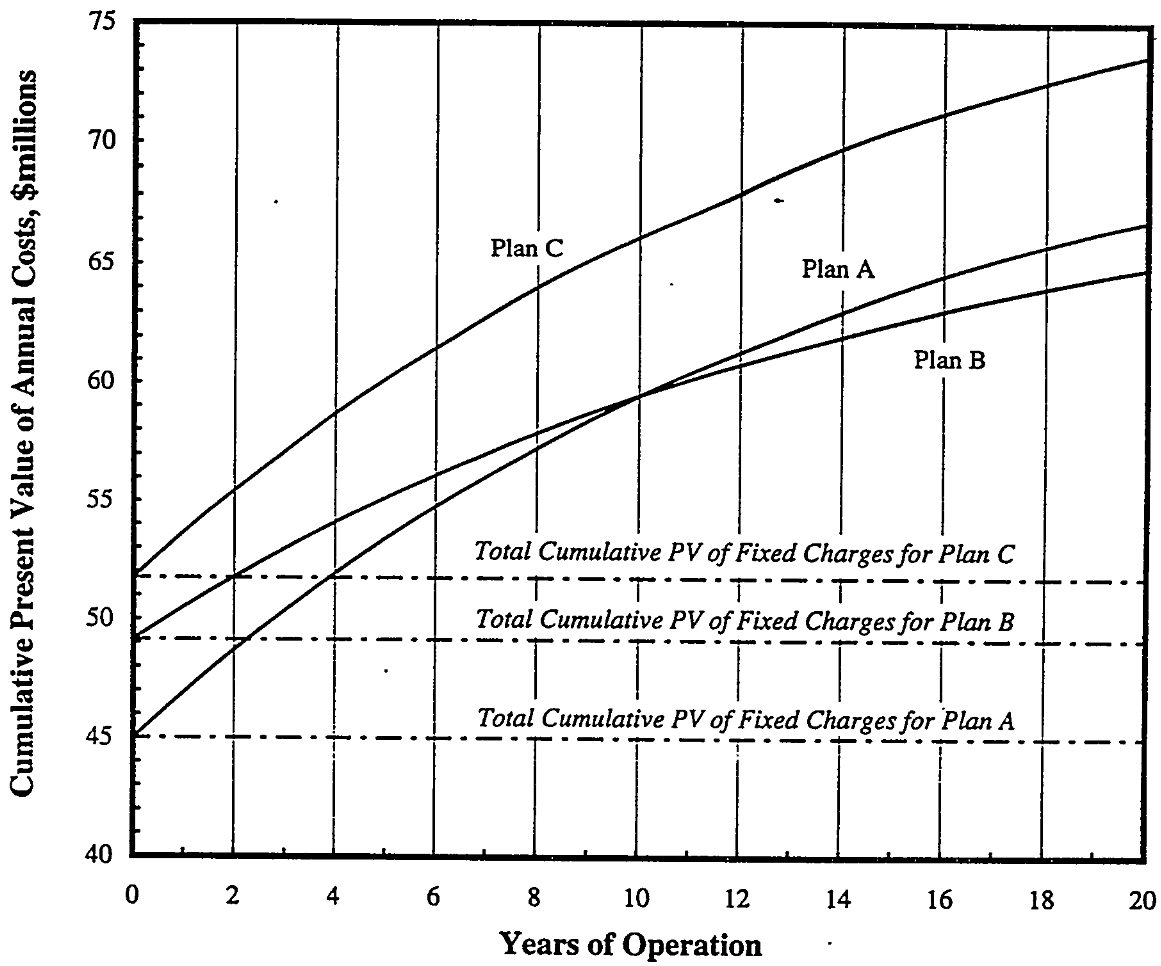
where: Σ_x PV = Cumulative present value from commercial operation through year "x"; and
Σ_L PV = Cumulative present value for life of system.

The results are usually presented graphically, as shown in Figure 3-1. In this example, Plan A has the lowest initial capital cost but the greatest annual cost. Plan A has the lowest cumulative total present value until the tenth year, after which Plan B has the lowest total present value. Plan B remains the lowest cost alternative for the remainder of the evaluation period. Plan B is said to have a **capital recovery period** of 10 years.

Electric utilities often evaluate capital investments in terms of capital recovery periods. The savings in annual costs must "recover" the differential capital expense between alternatives within a fixed number of years. In the above example, Plan A would be selected if the utility's capital recovery period was less than 10 years; Plan B would be selected if the recovery period were over 10 years. At 10 years, the two plans have equal cost.

As shown in Figure 3-1, some alternatives may not have a capital recovery period. Plan C has the highest initial capital cost and comparatively high annual costs. The cumulative present value of the total cost for Plan C is never lower than either Plan A or Plan B. In the example, Plans A and C have approximately the same annual costs, as shown by their parallel cumulative present value curves. Where plans have little or no differential annual costs, the economic comparison of alternatives can be made on the basis of total initial capital cost by itself.

Part V of this manual presents a case study example of the economic evaluation of a typical FGD system proposal using the capital recovery procedure.



In this example, Plan B has capital recover period of 10 years with respect to Plan A.

Figure 3-1. Capital Recovery Method of Economic Evaluations

3.4 Solicited and Unsolicited Options

As discussed in Section 2.4, the proposal evaluation process must often consider solicited and unsolicited options to the base FGD system covered by the specification. The procedure for evaluating such options is usually established by the utility prior to receiving the proposals. Major considerations in this decision are the limited amount of time available for proposal evaluation and the desire to evaluate all vendors on a common technical basis.

One common method is to determine which vendor has the lowest evaluated cost based on meeting the requirements of the base specification. The evaluation of solicited and unsolicited options is then limited to this vendor only. This method has the advantage of evaluating all proposals on a common technical basis and of limiting the initial proposal evaluation effort. If necessary, the evaluation of options could be delayed and conducted in more detail. It has the disadvantage of not considering whether the optional proposal(s) offered by another vendor would have been more advantageous.

If the utility has solicited options that could have major technical or economic effects on the proposals received, consideration of these options is usually included in the initial proposal evaluation effort. Examples of such options are the production of commercial-grade gypsum, the use of fewer, larger-capacity absorbers, and the use of alternative materials of construction. This approach increases the proposal evaluation effort and duration but will identify advantageous alternatives to the base system submitted by other vendors.

The most difficult proposals to evaluate within the time and budget constraints are those containing unsolicited vendor options. If the option covers a vendor-specific or unique process, it may be possible to substitute the optional proposal for the vendor's base proposal in the evaluation. If alternative equipment types, materials of construction, or suppliers are permissible for one vendor, it may be useful to request technical adjustment costs for similar options from the other vendors. This lengthens the duration of the evaluation process, however, and has the potential to compromise proprietary proposal information. Consideration of optional scopes of supply is almost always discussed only with the vendor with the lowest evaluated cost based on the specified scope.

3.5 Glossary of Terms

A glossary of economic terms used in this section of the manual is provided in the following paragraphs.

Allowance for Funds Used During Construction. Allowance for funds used during construction (AFDC or AFUDC) covers the cost of money paid to vendors prior to the commercial operation of the FGD system. For example, payment for engineering may be made four years before commercial operation of the system. Also, periodic progress payments based on the percentage of the project completion are also customary. AFDC is calculated base on the following equation.

$$AFDC = Cost_x \cdot [(1+i)^{\Delta t} - 1] \qquad (3\text{-}2)$$

where:
- $AFDC$ = Allowance for funds used during construction, \$;
- $Cost_x$ = Cost in year "x", \$;
- i = Interest rate, decimal; and
- Δt = Interval between payment and commercial operation, years.

Where several payments are made over the course of the construction project, the total AFDC is the sum of the AFDC for the individual payments. This calculation can be simplified (with a loss of accuracy) by assuming that all payments are made at a single time such as the midpoint of the construction effort.

Annualized Cost Method. The annualized cost method of economic evaluations compares the total levelized annual cost of alternatives. The total **levelized**

annual cost is the sum of the levelized **fixed charges** and the levelized annual operating costs. The proposal with the lowest total levelized annual cost is the most advantageous.

Capital Recovery Period Method. The capital recovery period method of economic evaluations is a method of comparing the total costs of one system with a comparatively lower initial capital cost and higher annual operating cost to an alternative system with comparatively higher initial capital cost and lower annual operating cost. First, for each alternative, the total present value of the annual fixed charges on the total initial capital cost of each alternative is calculated. Then for each year, the cumulative present values of the alternatives' annual operating costs through that year are calculated. The total cumulative annual cost for each year is the total present worth of the fixed charges plus the cumulative present value of the annual operating cost through that year (see Part III, Section 3, Equation 3-1). Two alternatives have equivalent costs in the year when their total cumulative annual costs are equal. That year is the capital recovery period (or payback period on the differential capital investment). Electric utilities often have standard capital recovery periods for justification of capital projects.

Capitalized Cost Method. The capitalized cost method of economic evaluation is the inverse of the annualized cost method. In this method, the annual operating costs are converted into an equivalent capital expenditure that can be added to the total initial capital cost. The first step in this method is to convert the actual non-uniform series of annual costs into a levelized annual cost. This levelized value is converted to an equivalent capital investment by dividing by the levelized fixed charge rate and added to the total initial capital cost. The proposal with the lowest total capitalized cost is the most advantageous alternative.

Commodity Price Indices. Commodity price indices are published by the U.S. government for a wide variety of construction commodities such as structural steel and nickel alloy plate. These indices are published periodically throughout the year and measure the relative changes in the cost of these commodities at the wholesale level.

Escalation. The price of most goods and services has historically risen over time. In order to determine the cost for purchases in the future, the current costs must be escalated to the year of purchase. The escalated cost at a future date is calculated by the following equation:

$$Cost_x = Cost_0 \cdot (1+e)^{\Delta t} \tag{3-3}$$

where:
$Cost_x$ = Cost in year "x," $;
$Cost_0$ = Cost in the base year, $;
e = Escalation rate, decimal; and
Δt = Interval between base year and year "x," years.

Fixed Charges. Fixed charges are annual costs of ownership of a capital asset that are independent of the extent to which the asset is used. The annual fixed charge rate (FCR) is expressed as a percentage of the initial capital cost. The calculation of the FCR varies from utility to utility, but usually consists of the following components:

- Return on investment;
- Asset life;
- Depreciation;
- Taxes; and
- Insurance.

The FCR is usually expressed as a levelized value, which results in a uniform series of annual fixed charges over the life of the equipment.

Levelized Annual Cost. Levelizing annual costs is a technique for converting a series of non-uniform annual payments (or revenues) in to an equivalent series of uniform payments. The two series are equivalent if they have the same total present value. The levelized annual cost is calculated by the following procedure.

- Calculate the present value of each payment in the non-uniform series;
- Sum the present values of the series to obtain a total present value;
- Sum the PVFs for every year of the series regardless of whether a payment was made in that year; and
- Divide the total present value by the sum of the PVFs to obtain a levelized annual cost.

The reciprocal of the sum of the PVFs is termed the uniform series present value factor (USPVF) and can be used to convert any present value cost into an equivalent levelized series of annual payments.

Present Value. Present value (PV) is a method of expressing the current value of a future (or past) expenditure. The value of the future expenditure is discounted using the following equation:

$$PV = \frac{FV}{(1+i)^t} \tag{3-4}$$

where:
PV = Present value (value of payment at present time), \$;
FV = Future value (value at the actual time of payment), \$;
i = Interest rate, decimal; and
t = Time interval between present and future purchase date, years (note: for future expenditures, "t" is positive; for past expenditures "t" is negative).

The term $1/(1+i)^t$ is called the present value factor (PVF) and is an important component of a number of the economic evaluation terms.

Producer Price Index. This index is one of several U.S. government price indices that measure the cost of goods in the economy. The producer price index is published periodically throughout the year and measures the relative price changes in the cost of good sold at the wholesale level.

Total Initial Capital Cost. The total initial capital cost includes the following components:

- Vendor proposal cost;
- Technical adjustment costs;
- Scope-of-supply adjustment costs;
- Differential support adjustment costs; and
- Economic adjustment costs (PV of escalation and AFDC at the date of commercial operation).

3.6 References

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PART IV
USE OF FGDPRISM™ IN FGD SYSTEM OPTIMIZATION, PROPOSAL EVALUATION, AND DESIGN

1.0 INTRODUCTION

The Flue Gas Desulfurization PRocess Integration and Simulation Model (FGDPRISM™) is a process simulation program tailored to wet limestone-based and magnesium-enhanced lime-based FGD systems. FGDPRISM development was funded by the Electric Power Research Institute (EPRI). The model is available for use by EPRI members and can be licensed by other parties (such as universities, vendors, and consultants) outside of EPRI. Non-EPRI member utilities can access the model only through licensed third parties such as consultants or A/E firms and must pay a royalty fee for each use. The model can be run on a personal computer (PC), but because of its complicated calculations, requires a high-end PC such as a 486DX- or pentium-based machine. Further information on the model requirements and licensing arrangements can be obtained directly from EPRI.*

The FGDPRISM model is based primarily on fundamental engineering principles. The model predicts the chemical and physical phenomena that occur in FGD systems, including vapor-liquid mass transfer (SO_2 absorption and CO_2 desorption/absorption) and solid-liquid mass transfer (precipitation and dissolution). Unlike models that are best-fit regressions of operating data, the fundamental basis of FGDPRISM enables predictions of scrubber performance over a wide range of system configurations and operating conditions. Models which are based solely on fitting operating data generally are not very accurate when extrapolating beyond the limits of the data used to develop the model.

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1.1 Objectives

The primary objective of Part IV of this manual is to provide the utility engineer who has a special interest in the capabilities of FGDPRISM with more detailed discussions of its uses, requirements, and limitations. The information provided should assist the engineer in determining whether FGDPRISM will be a useful tool on a specific FGD project.

1.2 Organization and Content

As shown in Figure 1-1, Part IV is organized into three key areas. Each of these areas represents an application of FGDPRISM in the SO_2 scrubbing industry:

- Optimization of existing FGD system operations;
- Evaluation of vendor proposals for new FGD systems; and
- Bid specification preparation/process design.

Section 2.0 covers the first of these areas, which represents the majority of applications and the original intent for the model during its development. This use of the model is the most straightforward and is usually based on calibration of the model to the actual FGD system under study. Section 3.0 describes ways in which the model has been used by utilities and consultants to evaluate vendor proposals for new FGD systems. This application requires a more thorough understanding of the model capabilities and limitations because actual full-scale system performance data are not available for the specific design being evaluated. Section 4.0 discusses the third area where FGDPRISM has been applied, in the preparation of bid specifications by utilities and their consultants, and in the design of new FGD systems by process vendors. This area of application requires the most complete understanding of and experience with the model.

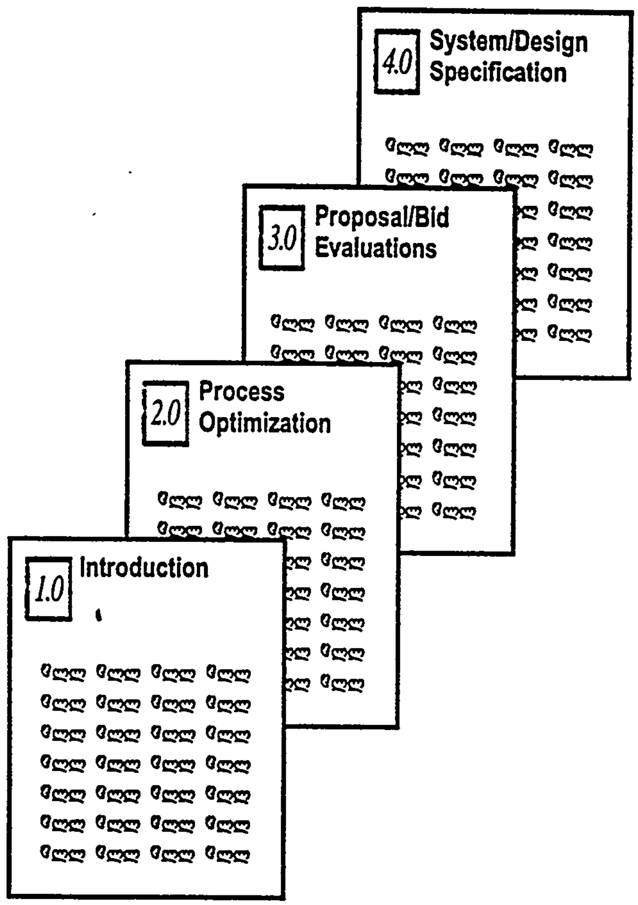

Figure 1-1. Part IV Organization

2.0 PROCESS OPTIMIZATION

FGDPRISM can be used to evaluate proposed chemical and/or mechanical modifications to an existing system. These modifications might be upgrades to improve performance or different modes of operation to achieve the same performance at lower cost. For example, one possible application would be to use the model to evaluate and optimize trade-offs between limestone utilization and the number of absorber modules and/or absorber spray pumps in service as a function of coal sulfur content and unit load. For these types of applications, the model must first be calibrated to determine the fundamental mass transfer coefficients that govern performance of the particular FGD system under study. Once the model is calibrated, predictions for alternate operating conditions can be made. The following sections will briefly discuss the calibration procedure and then present examples of potential uses of the calibrated model for optimizing plant operations.

2.1 FGDPRISM Model Calibration

Certain aspects of scrubber performance are site-specific and not easily predicted from fundamental principles. Where possible, these aspects are addressed by calibrating FGDPRISM using actual data for a minimum number of operating scenarios. The calibration is performed primarily to account for each application's unique absorber arrangement and type of limestone. Once calibrated, the model can then be used to extrapolate to conditions where operating data are not available (e.g., after chemical or mechanical modifications). In this way, an optimum set of operating setpoints can be determined prior to implementation of a proposed system change (such as different coal sulfur, increasing removal, etc.), and different options can be compared on a consistent basis.

FGDPRISM requires a significant amount of detail about the FGD system to predict system performance. Most of this information is related to the mechanical configuration and chemistry of the system, and includes items such as tank volumes, scrubber dimensions, header and nozzle positions, gas flows, liquid flows, and chemistries. A list of input requirements is provided in Table 2-1.

There are two major steps in calibrating FGDPRISM for a specific FGD system. The first is to use the observed material balance characteristics of the system to extract information that is difficult to measure directly. The second is to determine the FGDPRISM parameters that allow the model to simulate the vapor-liquid and solid-liquid mass transfer characteristics of the system.

When performing an overall material balance, the FGD system feed and product streams are examined without considering the internal details of the absorber. For instance, an overall system material balance simulation performed using FGDPRISM would be done with a user-specified value for SO_2 removal in place of the detailed mass transfer calculations that predict absorber performance. The user specifies the inputs to the system and the model calculates the outputs (i.e., byproduct solids, wastewater blowdown, and outlet flue gas).

The material balance option of the model can be used to extract information that cannot be easily measured. For example, physically measuring the hydrochloric acid (HCl) concentration in the flue gas is difficult. However, this information can be easily determined using material balances around the entire FGD system. Since all chloride absorbed from the gas must leave the system in either a liquid blowdown stream or with the liquor associated with the byproduct solids, the amount absorbed can be estimated by measuring the levels in the liquid blowdown (if any) and the byproduct solids. Similarly, the amount of magnesium that dissolves from the limestone can be estimated from an overall material balance. The overall system material balances not only allow estimation of missing data, but also help the user understand how the process is operated.

To calibrate FGDPRISM for the site-specific mass transfer characteristics of an absorber, performance data at a minimum of three system chemistries are required:

Table 2-1

FGDPRISM Input Requirements

Parameter	Data Requirements	Optional Data
Generating unit	Flue gas temperature Flue gas pressure Flue gas dust content	
	Combustion Parameters: Coal composition, Turbine output, Unit heat rate, Ambient air temperature, Ambient air humidity, Flue gas O_2 content *OR* Inlet Gas Parameters: Gas composition, Gas flow rate	
Makeup water	First Makeup Water Stream Composition pH Temperature	Second Makeup Water Stream Composition pH Temperature Flow rate
Reagent	Composition Particle size distribution *OR* Mesh sizes	
Additive	Additive type Solution concentration Additive concentration Additive composition	

Table 2-1

(Continued)

Parameter	Data Requirements	Optional Data
System Generating unit	SO_2 removal (initial guess) Oxidation Vapor pressure of CO_2 above scrubber liquor Reagent ratio (1/utilization) Scrubber feed flow rate Waste solids content Recycle slurry solids content	Gas bypass Blowdown flow Dust removal HCl removal HF removal Filter cake wash ratio
Scrubber	Scrubber dimensions Header flow percentages Header spacing Gas and liquid film thicknesses (Mass transfer coefficients)	<u>Packing</u> Packing height Specific surface area <u>Tray</u> Configuration (hole layout, hole size, and pressure drop) *OR* Mass transfer area
Nozzles	Droplet diameter (sauter mean) Nozzle pressure drop Nozzle coefficient Nozzle cone angle Number of nozzles Nozzle positions	
Reaction tank	Volume	
Equilibrium	<u>Rate Equation Parameters for Limestone Dissolution</u> Reaction rate constant *OR* Dissolution rate constant Surface area factor	<u>Precipitation Rate Constants:</u> Gypsum Solid solution

1) A high-removal case, where the SO_2 removal is limited only by the mass transfer to the slurry droplets (gas-film resistance), such as occurs with the use of high concentrations of dibasic acid (DBA) or formate chemical additives;

2) A low-removal case, where the SO_2 removal is limited to some extent by a lack of alkalinity (liquid-film) resistance (i.e., low pH operation); and

3) One case between the two extremes noted above.

Figure 2-1 illustrates the data points required to calibrate FGDPRISM. For this example, the model calibration will be based on three data points at pH 5.2 (shown as open symbols). SO_2 removal varies from approximately 82% to 98% over the range of DBA concentrations from 600 ppm to 5400 ppm. These data points show an initial sharp increase in SO_2 removal from the low-removal case at 600 ppm DBA to the midpoint with 1500 ppm DBA. From the midpoint to the high-removal case, additional DBA has less of an effect on performance, indicating that the system is approaching gas-film limited conditions. Additional data for pHs of 4.6, 5.6 and 5.75 (shown as solid symbols in Figure 2-1) are available to verify the calibration parameters.

A test plan to gather the necessary data should include not only the three calibration points, but also some additional operating conditions to verify the model's predictive capabilities after calibration. Additional operating scenarios typically include the use of different numbers of absorber spray headers in service, intermediate pH values, lower chemical additive concentrations, and different flue gas velocities. In most cases, the test program can be completed in less than one week.

Normally, the testing is performed on a single absorber module, with gas sampling performed at the module inlet and outlet so that the individual module performance can be measured. Liquid and solid samples of the recirculating slurry are taken and analyzed for major species (Ca^{++}, Mg^{++}, Na^{+}, Cl^{-}, $CO_3^{=}$, $SO_3^{=}$, and $SO_4^{=}$) at each condition where SO_2

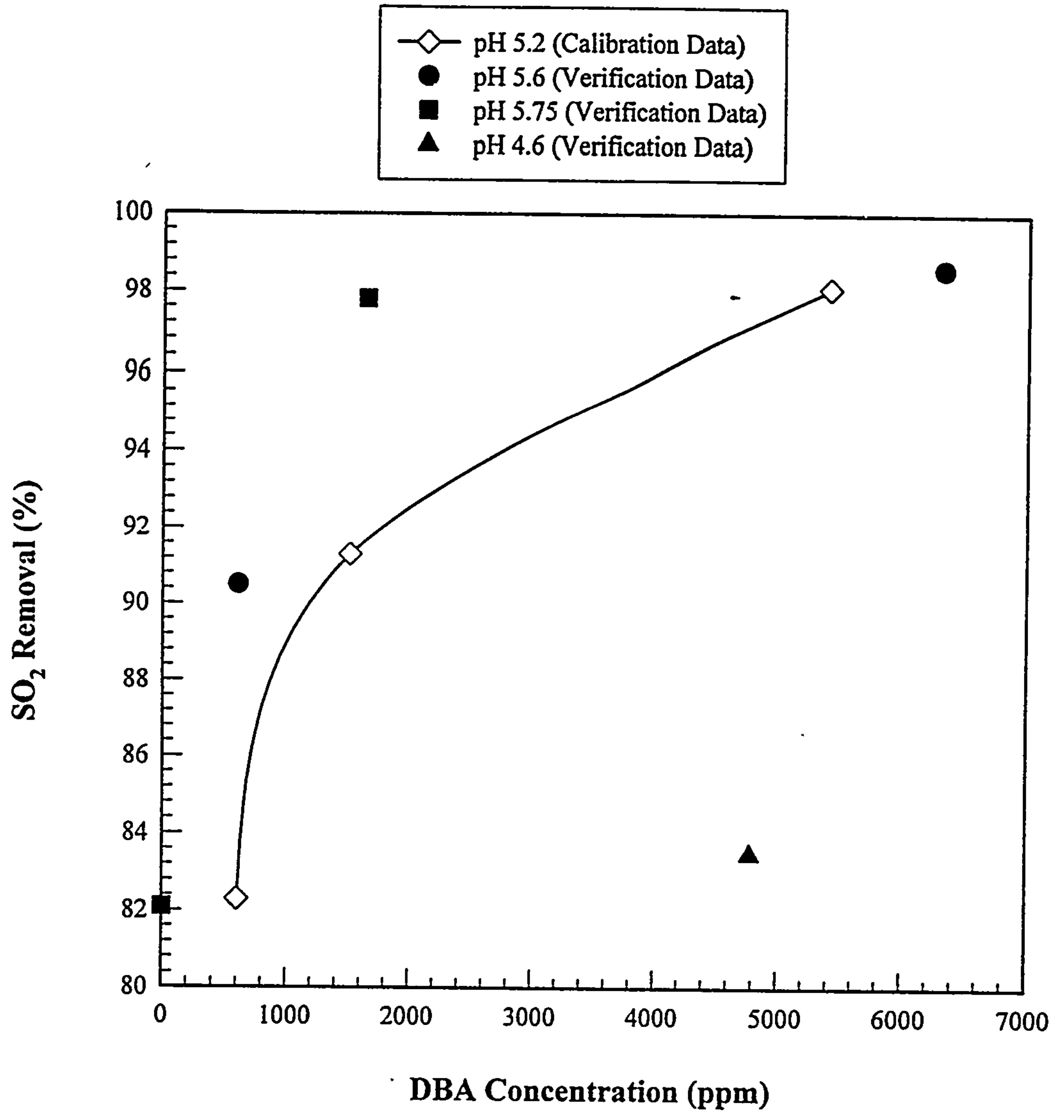

Figure 2-1. Example FGDPRISM Calibration Data Points

removal is measured to provide the necessary data for calibration. Additional samples may be required, depending on the system arrangement. For example, if hydrocyclones are installed, the byproduct solids may have a different solid-phase composition than the circulating slurry. In that case, samples of the byproduct solids should be taken as well as samples of the circulating slurry. With this methodology, two to four tests can be conducted each day, for a total of 8 to 12 tests during one week (allowing 1 to 2 days for equipment setup and takedown)

Recent applications of FGDPRISM have indicated that different film coefficients may need to be used to accurately predict system operation at significantly different gas velocities (e.g., 3.5 m/s vs. 4.5 m/s), especially for spray towers. Figure 2-2 illustrates FGDPRISM calibration results using the same film coefficients for all cases. The model's predictions show a steep decrease in SO_2 removal (increase in the outlet SO_2 concentration) as gas velocity increases. However, actual results (depicted by open symbols) show a much less significant change in removal than predicted (depicted by solid symbols). Changing the film coefficients as a function of gas velocity significantly improves the model's predictions as compared to actual results, as shown in Figure 2-3. This is thought to be due to increased holdup of the slurry droplets at higher gas velocities, enhancement of the mass transfer coefficients resulting from higher relative velocities between the slurry droplets and the gas, and/or better gas-liquid distribution. As indicated by the previous example, if model predictions are to be made at different loads, or with different numbers of modules in service, then data should be taken so that any effect on calibration parameters can be evaluated.

FGDPRISM has been calibrated for a wide variety of FGD systems. Some of the configurations successfully simulated by the model include the following:

- Open spray towers;
- Spray towers with trays or packing;
- Dual-loop systems;

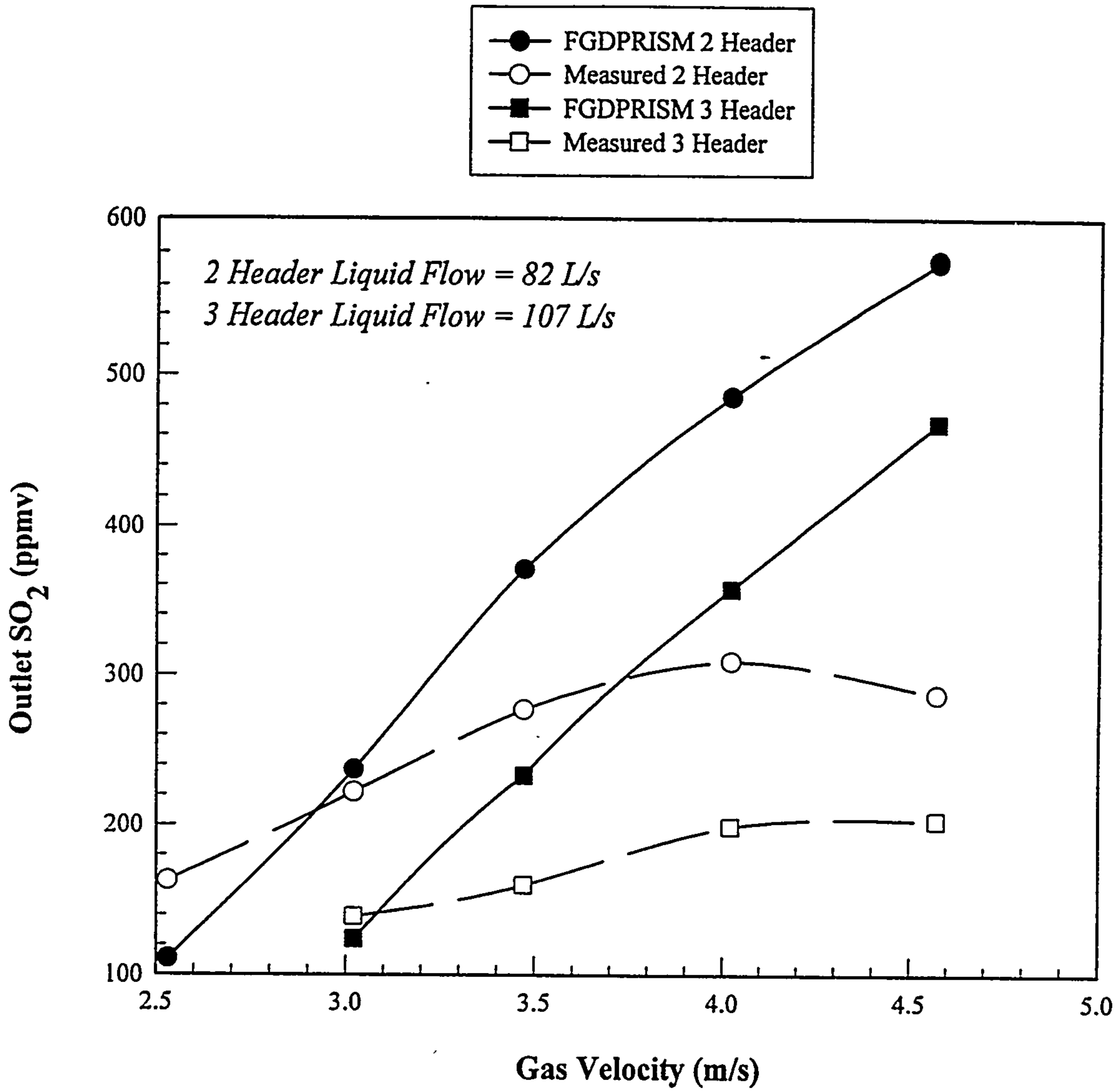

Figure 2-2. Example FGDPRISM Calibration Results without Film Adjustments

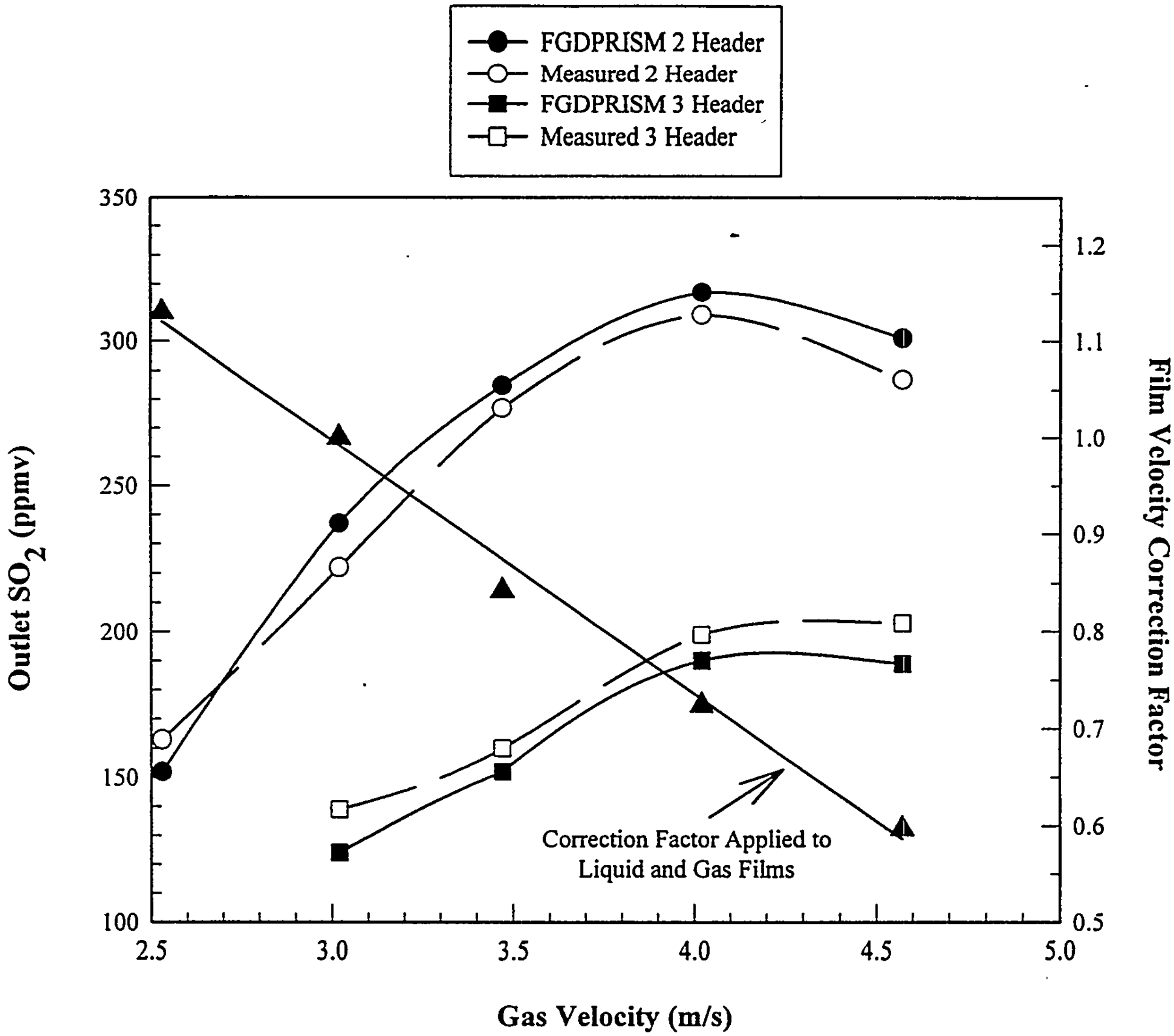

Figure 2-3. Example FGDPRISM Calibration Results with Film Adjustments

- Cocurrent towers with packing;
- Horizontal cross-flow scrubbers; and
- Venturi absorbers.

In most cases, one of the system configurations provided with the model can be used, but in certain instances (e.g., the horizontal cross-flow absorber), special configurations can be assembled. This is possible because of the modular construction of the model. If a specific situation does not seem to fit one of the configurations supplied, then an EPRI representative should be contacted to determine if development of a special configuration is warranted.

2.2 Using FGDPRISM to Optimize Existing Plant Operations

Once the model is calibrated and can accurately predict the performance of a specific FGD system, it can be used to examine different operating scenarios and/or provide input to an economic analysis to determine the least-cost operating conditions for the calibrated system. For example, the model can be used to evaluate alternative operating modes for improving SO_2 removal, increasing reagent utilization, minimizing the potential for scale, or contributing to an overall plant systems integration project. Several examples of applications are presented in this section.

Many FGD system owners and operators are interested in evaluating ways of increasing the SO_2 removal efficiency achieved by an existing FGD process. There are many ways this can be accomplished. However, not all methods are equally effective for all FGD systems. The effectiveness of a given method depends on the current condition and performance of the system. For example, some systems may already be gas-film limited (large excess of alkalinity in the scrubbing slurry); therefore, adding alkalinity-enhancing chemical additives such as DBA will not be very effective. Alternatively, systems that are not gas-film limited may benefit greatly from the addition of a very small quantity of a chemical additive.

Some options that FGDPRISM can be used to investigate are the following:

- Change in liquid-to-gas (L/G) ratio;
- Comparison of different chemical additives;
- Change in limestone grind fineness;
- Change in limestone type (available $MgCO_3$, overall reactivity, etc.);
- Operation at different limestone utilization levels (pH's);
- Change in system water balance;
- Increase/decrease in packing height (for a packed tower);
- Use of a different packing type (more/less open area);
- Installation of a tray; and
- Combinations of the above options.

A brief description of how FGDPRISM can be used to evaluate each of these options is presented below.

2.2.1 L/G Ratio

While the use of chemical additives such as DBA or sodium formate can improve SO_2 removal, their use also allows manipulation of another variable which can be used to minimize operating costs--the L/G ratio. When an additive is used, it may be more cost-effective to operate fewer absorber spray headers/pumps, depending on the cost of electricity to run the pump and the manpower and materials to maintain it versus the cost of the chemical additive. FGDPRISM can be used for this evaluation, eliminating the need to operate the actual FGD system under every potential scenario to gather operating data.

Figure 2-4 illustrates the results of FGDPRISM simulations that were used to investigate the trade-offs between SO_2 removal [plotted as number of transfer units (NTUs), $\ln(SO_{2in}/SO_{2out})$] and chemical additive concentration for three absorber spray pump arrangements (three, four, and five pumps in service). It should be noted that these results are

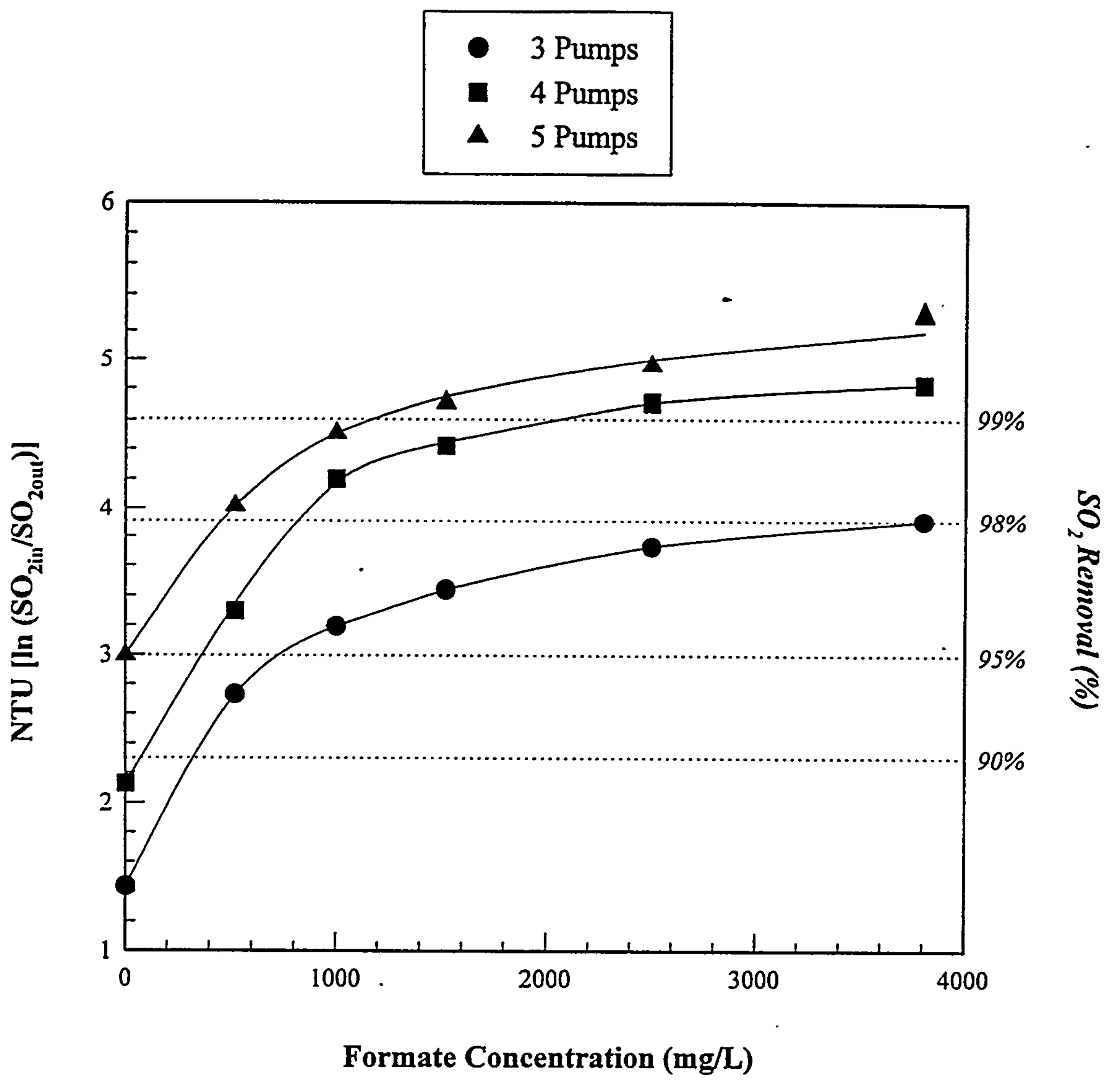

Figure 2-4. Formate Concentration

not universal. They will differ for each particular FGD system, depending on the mechanical design and the chemistry of the particular system (makeup water composition, limestone composition, amount of HCl in the flue gas, amount of SO_2 in the flue gas, etc.). The system represented in Figure 2-4 normally operates without chemical additives, and achieves approximately 90% SO_2 removal (NTU = 2.2) with four pumps in service [L/G = 13.5 L/Nm^3 (93 gal/1000 ft^3)].

If the goal is to achieve 99% removal (NTU = 4.6), then FGDPRISM predicts that the concentration of formic acid required in the circulating slurry is about 2500 ppm with four pumps operating, as shown in Figure 2-4. The modeling results also show that if one pump is turned off (three pumps operating), then the goal of 99% cannot be achieved, regardless of the formic acid concentration. If five pumps are operated, the 99% removal goal is predicted to be achievable using about 1500 ppm formic acid. All of the curves in Figure 2-4 show a tendency to approach the gas-film limit as more formic acid is added. As the gas-film limit is approached, increasing the level of formic acid becomes less effective because the resistance to SO_2 absorption is essentially due to gas-film resistance. Only increasing the interfacial surface area (by increasing L/G) or decreasing the gas-film thickness (by increasing gas velocity) is effective at this point.

If the goal is only 95% removal (NTU = 2.9), then the FGDPRISM predictions show that there are at least three ways it can be met. An additional absorber spray pump can be operated (five pumps) without the addition of formic acid. Alternatively, operating with a formic acid concentration of about 250 ppm at the current L/G of 13.5 L/Nm^3 is predicted to give 95% SO_2 removal, as is operation at a formic acid concentration of about 750 ppm at a reduced L/G of 10.3 L/Nm^3 (which corresponds to operating with three pumps). The best mode of operation cannot be determined from the predictions shown in Figure 2-4 alone. Determining which case is the lowest-cost alternative depends on the costs to operate and maintain three to five slurry pumps versus the cost of formic acid.

Figure 2-4 shows only formic acid concentration. The actual chemical additive consumption rate is the critical value for an economic analysis. FGDPRISM estimates the additive consumption on the basis of the desired concentration and the predicted loss rates of the additive, through mechanisms such as degradation, coprecipitation, vaporization, and losses with liquids that leave the process. The model should be used first to construct curves like those in Figure 2-4. Then, when intermediate points of interest have been identified, additional FGDPRISM simulations can be performed to determine chemical additive consumption rates at those specific conditions.

Another situation in which changes in L/G might be of interest is the one in which the gas flow rate through the absorber changes. Gas flow rate is affected by changes in the unit load, the amount of gas bypassed, or the number of towers in service. Increasing the gas flow rate through a tower, by decreasing the bypass or reducing the number of towers in service, will result in better gas distribution in the absorber but will decrease the L/G ratio. Decreasing the bypass will decrease the scrubber SO_2 removal efficiency, but increase the system SO_2 removal (since a larger fraction of the total gas stream is scrubbed). Further increases in system SO_2 removal can then be achieved through system modifications such as operating at higher pH, operating with more absorber spray pumps, the addition of chemical additives, etc. FGDPRISM can be used to optimize operating conditions resulting from closed or reduced bypass or even treating additional flue gas from another unit.

2.2.2 Chemical Additives

With FGDPRISM, one has the ability to model FGD system performance when using adipic acid, DBA, formic acid, and sodium formate as SO_2 removal enhancement additives. The removal performance of these chemical additives is generally similar, with adipic acid and DBA having a slight performance advantage because they buffer at a higher pH. However, the consumption rates for these additives are quite different and depend on site-specific parameters such as liquor composition (especially calcium and chloride concentrations), oxidation mode (natural, inhibited, or forced oxidation), liquor temperature, and other factors. There is not always a clear choice between chemical additive types from a performance standpoint, but in some cases one additive can be significantly less expensive to use than another. This kind of analysis can be used to choose the most economical additive for achieving a desired SO_2 removal. Additional information on chemical additives is presented in Part I, Section 9.0--Chemical Additive Considerations.

2.2.3 Limestone Grind

As discussed in Part I, Section 8.4.1--Effect of Limestone Particle Size on FGD System Performance, one relatively easy modification that can be made at some FGD systems is to produce a finer limestone grind. FGDPRISM accounts for the limestone grind fineness in computing the limestone dissolution rate in the reaction tank and absorber. The limestone feed grind can be entered into the model in one of two ways. A complete particle size distribution of the feed limestone is the preferred method. However, if such data are not available, an estimate of the limestone particle size distribution can be made by the model if the user enters two mesh sizes and the fraction passing through each. A finer grind can reduce the amount of limestone required (higher reagent utilization) to maintain a specified pH and SO_2 removal. A finer grind can also increase SO_2 removal efficiency for operation at the same reagent utilization as a coarser grind. Finally, operation with a finer grind may also be a viable approach for reducing the amount of excess limestone present in the byproduct gypsum solids. The level of $CaCO_3$ present in byproduct solids is important if the byproduct is to be sold as commercial-quality gypsum.

2.2.4 Limestone Type

Limestone composition and reactivity can also be important factors in the optimization of an FGD system. FGDPRISM uses a semi-empirical rate expression for predicting limestone dissolution in the reaction tank and absorber. The rate of dissolution is dependent on the particle size distribution, as discussed above, but is also dependent on the reactivity, which may differ among limestones. The reactivity can be measured using a laboratory procedure or it can be determined by calibrating the model to actual operating data (pH as a function of limestone utilization).

While limestone reactivity can be important, another significant factor is the level of soluble magnesium carbonate ($MgCO_3$) in the limestone. This can be more important in some systems than others, depending on the process chemistry. It is most important in systems with low chlorides and inhibited oxidation, since these systems rely heavily on liquid-phase alkalinity to achieve SO_2 removal. More soluble $MgCO_3$ fractions in the limestone result in higher liquid-phase Mg^{++} and $SO_3^{=}$ concentrations, which tend to increase SO_2 removal. Additional discussions of the role of magnesium in FGD system process chemistry are presented in Part I, Sections 3.4.1--Magnesium and 8.2.1--Limestone Composition.

The FGDPRISM model requires that the user specify the total and soluble fractions of $MgCO_3$ in the limestone. The model will then calculate the resulting liquid-phase composition and the impact on SO_2 removal. Thus, the model could be used to help in evaluating the use of different limestones, provided that each limestone is accurately characterized with respect to reactivity and soluble $MgCO_3$ content.

2.2.5 Reagent Utilization

FGD systems have some flexibility in their operation with respect to the pH value at which they normally run. This can be recommended by the vendor or can be determined by the utility during normal operation. Operating at higher pH requires the addition of more limestone and results in higher SO_2 removal. An upper limit on operating pH is set by both technical and economic factors. As slurry pH increases, reagent utilization decreases, which results in more excess limestone in the circulating slurry. To prevent the formation of solid deposits (scale) in the mist eliminators, a minimum value of about 85% utilization is recommended. As a general rule of thumb, FGD systems should not be operated at reagent utilization values below that level. A detailed discussion of FGD system process chemistry is presented in Part I, Section 3.0--Lime- and Limestone-Based Wet Scrubbing Process Chemistry.

While SO_2 removal can be increased by operating at higher pH, other methods, such as a combination of higher pH with other operating modifications, may result in lower costs. The FGDPRISM model can be used to evaluate these trade-offs, since it can predict the effect of limestone utilization on pH and SO_2 removal. One example would be to use the model to examine the trade-offs of running fewer absorber spray pumps, but with a higher slurry pH (lower reagent utilization) compared to running more pumps at a lower pH (higher reagent utilization). The model can be used to predict the pH and limestone utilization required for each pump configuration to achieve the desired level of SO_2 removal. Then the economic trade-offs of limestone utilization, grinding, etc. can be compared to operating and maintenance costs for the pump. This type of evaluation is very similar to the one described previously which examined chemical additive use.

2.2.6 FGD System Water Balance

Changes made to overall plant operations (for example, a change in the source of makeup water used in the FGD system) can often affect the FGD system. Often a cascaded plant water balance is implemented to minimize both fresh water use and wastewater discharges at the station. This may involve the reuse of wastewater from one plant subsystem as makeup water to another. A common example would be the use of cooling tower blowdown as makeup water for the FGD system. Since makeup water quality can have significant impacts on the FGD system operation, this should be thoroughly studied prior to implementation. Additional information on the FGD system water balance is contained in Part I, Section 3.5--Lime- and Limestone-Based FGD Process Material Balance.

The FGDPRISM model is well suited for this type of investigation. The model calculates the system chemistry from material and energy balances and uses fundamental engineering principles to determine the effect of liquor composition on SO_2 mass transfer.

The model, however, does not predict the impact on sulfite oxidation and solids dewatering properties. A change in these properties could result if the new makeup water contained compounds such as scale or corrosion inhibitors, which are normally used in cooling water systems.

2.2.7 Scaling Potential

An application of FGDPRISM similar to examining changes in the system water balance is to evaluate the potential for scale formation. Changes in the composition of mist eliminator wash water can lead to the formation of scale deposits, which can have a detrimental effect on mist eliminator performance. Although FGDPRISM does not simulate mist eliminator performance, the model will predict the relative saturation of solid species in process streams. These results indicate if conditions for scale formation are favorable. This capability of FGDPRISM can be used to examine the effect of water sources or combinations of water streams on mist eliminator performance.

Scale can also form on other internal scrubber surfaces, such as trays and packing. The labor and maintenance associated with removing scale can be significant. Factors that contribute to scale formation include low reagent utilization, reduced slurry flow rates or increased gas flow rates (changes in L/G), changes in the system water balance, the degree of sulfite oxidation, and other chemistry effects. Although FGDPRISM cannot predict oxidation, the model can be used to evaluate changes in the gypsum relative saturation resulting from changes in operating conditions. For example, FGDPRISM results can be used to examine the gypsum relative saturation of the scrubber liquor above and below a tray or packing for various unit loads.

2.2.8 Internal Packing

The role of internal packing in SO_2 removal efficiency of an absorber module is discussed in Part I, Section 4.2.1--Absorber Design Alternatives. One option for increasing

SO_2 removal in an FGD system that utilizes packing is to increase the amount of packing. Alternatively, other plants have considered removing some or all packing from the FGD system because of plugging or access problems. The impact that these changes will have on system performance can be predicted by FGDPRISM, once the model is calibrated for the specific installation. Another option that a utility might want to consider is changing the type of packing. This has been done at some facilities that experienced scaling problems when using a packing with a high specific surface area (m^2 surface area per m^3 packing). The packing was replaced with a more open type, thus alleviating scale formation. However, this will decrease the total surface area available for mass transfer, so compensating changes must be made to maintain the same SO_2 removal. This could involve increasing pH (lowering reagent utilization), increasing L/G, or using a chemical additive. The FGDPRISM model is well suited for evaluating these options to help the utility choose the most economical approach.

2.2.9 Internal Tray

One additional option that has been considered by many FGD system owners to improve SO_2 removal is the installation of a counterflow tray. The effect of a tray on SO_2 removal efficiency is discussed in detail in Part I, Section 4.2.1--Absorber Design Alternatives. A tray will increase slurry holdup time within the absorber and will tend to improve gas-liquid distribution. Both of these effects will tend to increase SO_2 removal. However, the tray will also tend to agglomerate fine droplets produced by the spray nozzles, converting this slurry to "rain" which may provide less surface area for mass transfer than the fine droplets. Therefore, the location of the tray within the absorber is very important. FGDPRISM includes a provision for modeling a counterflow tray. To date, the model has only been applied to a few FGD systems with trays, so this option should be used with caution. The model users should work closely with the tray vendor and/or model support personnel who have had experience using the tray option.

2.2.10 Combinations of FGD System Modifications

The FGDPRISM computer model contains provisions for virtually every combination of options that FGD system owners, operators, and vendors have considered for enhancing SO_2 removal. The model should serve as a valuable tool for optimizing system operations at either an existing SO_2 removal level or an elevated level. A critical step in this process is calibration of the model, which requires good operating data over a range of conditions. The quality of the model predictions will be only as good as the quality of model input data, both for calibration and for extrapolation to alternate operating conditions.

2.3 References

1. Electric Power Research Institute. Limestone Selection Methodology for Wet FGD Systems. RP 1877-1. Palo Alto, California, 1993.

3.0 PROPOSAL EVALUATIONS

The second major area where the FGDPRISM computer tool can be used by utilities and their consultants is as an aid in evaluating proposals from vendors for new FGD systems. The model was used by nine U.S. utilities in designing and evaluating FGD systems to meet Phase I requirements of the Clean Air Act Amendments of 1990. Since these systems are under construction, no actual full-scale system data are available to compare with model predictions at this time.

At the proposal evaluation stage, the FGD system does not yet physically exist; therefore, the model cannot be calibrated with existing performance data. Thus, application of the model requires an experienced user who is familiar with the model's capabilities and limitations. There are several major areas where FGDPRISM can help in evaluating the technical portion of FGD system proposals from vendors:

- Material balances can be used to confirm vendor calculations and/or extract information about assumptions that have been made;
- Material balances can be used to compare predicted and guaranteed:
  - Additive consumption rates,
  - Reagent and makeup water consumption rates, and
  - Byproduct and wastewater compositions and generation rates; and
- Process simulations can be used to qualitatively compare relative SO_2 removal capabilities.

Each of these three areas is discussed in the following sections with respect to the data requirements, application methodology, and model limitations.

3.1 Material Balances for Information Extraction

A very powerful and useful part of FGDPRISM is the material balance capability. Next to the complete system simulation option, this is the most-used part of the model. An overall FGD system material balance is performed on the basis of a single absorber module. A complete system material balance can also be made by modeling the total system as a single absorber module. As mentioned in Section 2.1, the system material balance models the feed, liquid, and byproduct streams of the FGD system, but does not model the scrubber details.

3.1.1 Data Requirements

The data required for performing an FGD system material balance are essentially the same as previously shown in Table 2-1 for making a system simulation. Although data about the absorber module internals (nozzles, headers, trays, etc.) and reaction tank are not required in order to conduct a material balance, most of this information will be contained in the vendors' proposals. Items specific to each vendor's design would include information such as reagent ratio (reagent utilization), reagent particle size distribution, byproduct and absorber slurry solids content, wastewater blowdown quantity (if any), and filter cake wash rate. Much of these data are typically contained in the process flow diagram for the design conditions. The vendors' proposals may also contain this same information for several unit loads or alternative coal sulfur levels.

3.1.2 Methodology

A material balance calculation can be used to extract information about a process design that may not be readily apparent from the process flow diagram. Typically, the process flow diagrams in vendor proposals show only selected information about the slurry composition. However, a material balance calculation can be used to determine what assumptions were made. For example, the amount of HCl assumed to be removed from the flue gas is important in determining the amount of liquid blowdown required to maintain a maximum dissolved chloride level. All vendor material balance calculations should be checked to ensure that all designs were prepared on a consistent basis. For example, if two vendors specify different blowdown rates, wastewater treatment facility size and cost could be affected. If the two proposals are to be compared on a consistent basis, then the underlying assumptions should be the same.

Other common questions regarding vendor proposals can be addressed by material balance calculations:

- What is the assumed inerts content of the limestone?
- What is the assumed available magnesium in the limestone?
- What is the assumed HCl removal from the flue gas?
- What is the assumed ash removal in the absorber?
- What is the assumed dolomite (non-reactive calcium and magnesium) content of the limestone?

Each of these questions can have an effect on the FGD system's design, and thus on the system's cost and ability to meet process guarantees. Addressing these issues and evaluating the vendor's design basis is an important part of the technical evaluation procedure.

3.1.3 Limitations

One limitation of using the material balance option in FGDPRISM is that the SO_2 removal is a user input (i.e., it is not calculated by the model). As a result, the material balance results are valid only for the modeled conditions and will not be accurate if the actual SO_2 removal is different. However, the purpose of the material balance in this case is to extract information about the vendor's assumptions in the design stage that may not be readily apparent from the information supplied in the proposal. For this purpose, it is not important if the actual SO_2 removal is the same as the design value. Comparing results for various SO_2 removals will be addressed in Section 3.3.

Another limitation of the material balance approach is that steady state is assumed. After initial startup, it may take weeks or even months for an FGD system to approach steady state with respect to liquor composition. Therefore, the material balance results should be compared to actual FGD system conditions after reaching steady state conditions. This should be considered when the system is started up and is being tested with respect to performance guarantees. For the purpose of extracting design assumptions, this limitation is not important.

3.2 Material Balances for Verifying Material Quantities and Compositions

Material balances can be performed to predict the amount of reagent that will be consumed, the amount and composition of byproduct solids that will be produced, the amount and composition of wastewater blowdown that will be produced (to maintain a given chloride concentration), the amount of chemical additive that will be consumed (if additives are used), and the amount of fresh makeup water that will be required. The predicted values can then be compared to the values contained in the vendors' proposals. This will ensure that the guarantee points are consistent with the design points.

3.2.1 Data Requirements

The data required for making these types of material balances are the same as discussed in the previous section. In fact, information extracted from that effort may be needed for performing the calculations described here. For example, in a forced-oxidation process that produces commercial-quality gypsum, the composition of the byproduct solids will be part of the FGD system's guarantee requirements. If there is too much inert material (unreacted reagent and other insoluble compounds), then the gypsum specification cannot be met. Therefore, it is important to know the vendors' assumptions with respect to the amount of inert material in the limestone and the amount of ash that is removed from the flue gas.

3.2.2 Methodology

The amount of reagent consumed is typically guaranteed by vendors in one of two ways: a total mass rate (kg/day), or an overall reagent utilization. In either case, FGDPRISM's material balance option can be used to verify the consistency between the vendor's guarantee point and the design operating point. If additional reagent is required to meet the specified SO_2 removal efficiency, other areas of the process, such as the reagent preparation equipment and byproduct solids composition, can be affected.

The amount and composition of byproduct solids is also computed by material balance. In some processes, there are guarantees associated with the solids, such as in the production of commercial-quality gypsum. As stated above, the material balance capabilities of the FGDPRISM model can be used to ensure that the vendor's design assumptions are consistent with the guarantees.

FGDPRISM's material balance capabilities can be used to estimate the composition of the wastewater leaving the system at a given rate of blowdown or to estimate the rate of blowdown required to maintain a desired process liquor composition. This can be very useful in verifying the chloride and chemical additive levels of the process streams in the FGD system.

An additional capability of the FGDPRISM material balance module is that it predicts the amount of chemical additive that must be added to achieve a desired steady-state concentration in the process liquor. These calculations are based on semi-empirical fits of pilot and full-scale chemical additive consumption data. If a vendor's design is based on the use of chemical additives, then the proposal should include an additive consumption rate guarantee. The material balance portion of FGDPRISM can be used to predict organic acid additive consumption rates that can be compared to the vendor's guarantees, thus providing a method of evaluating the conservativeness of the guarantee.

Finally, material balances can be performed to predict the amount of makeup water that will be required by the FGD system. Generally, the FGD system should be designed such that the maximum amount of fresh water possible can be used for mist eliminator washing. The FGDPRISM material balance module estimates evaporation rates on the basis of specified inlet flue gas conditions. The amount of water evaporated plus the amount of water leaving the FGD system by other means determines how much fresh water can be added. When proposals contain makeup water consumption guarantees, material balances can be performed to verify that these values are reasonable.

3.2.3 Limitations

The same limitations discussed in Section 3.1.3 apply to these types of material balances. In addition, it should be pointed out that the chemical additive consumption calculations are based on semi-empirical relationships determined from experimental-, pilot-, and full-scale data. These are not exact calculations, but will provide the user the best possible estimate of additive consumption prior to construction and operation of the system.

The assumptions that SO_2 removal efficiency is known and that the system is at steady state must be made in order to perform material balances. These assumptions do not affect the use of material balances in calculating the quantities of raw materials that may be used or the amount of byproduct solids that will be produced. If these quantities are averaged over a reasonable period of time (as should be required when testing any guarantee), then the program's steady-state assumptions will be valid.

3.3 Process Simulations for Relative SO_2 Removal Efficiency Predictions

The third area where FGDPRISM can be used as a tool for evaluating FGD system vendor proposals is in examining the relative SO_2 removal capability of the various designs. Since the FGD systems being modeled do not yet exist, FGDPRISM cannot be calibrated using actually operating data. FGD system performance is very much site-specific, and mass transfer coefficients cannot be accurately predicted from first principles, as discussed in Section 2.0. Therefore, the model cannot be used to accurately predict how much SO_2 will be removed by each of the proposed system designs for comparison to the guarantees. However, the model can be used to qualitatively compare the designs with respect to the degree of conservatism that has been built into the design by each vendor.

3.3.1 Data Requirements

The information required for FGDPRISM to simulate an FGD system was presented in Section 2.0. It includes information about all streams entering and leaving the FGD system (makeup water, untreated flue gas, reagent, chemical additives, byproduct solids, and wastewater blowdown) as well as detailed information about the absorber internals, reaction tank volume, and slurry recirculation rates. All of this information may not be supplied with vendors' proposals. Specifically, a proposal may not contain the desired level of information about the absorber internals (e.g., nozzle locations, droplet size, etc.). If not initially provided, this information should be requested from the vendors. Alternatively, a common set of typical values can be used for all proposals, so that they are compared on a consistent basis.

3.3.2 Methodology

Since the mass transfer coefficients for each vendor's design are not known, typical values must be used. As stated above, one approach would be to use a common set of values (such as the FGDPRISM program's default values) to perform the simulations for each vendor's proposal, and then compare the predicted SO_2 removal efficiencies on a relative basis. The absolute values of the predicted removal efficiencies should **NOT** be used solely to judge the actual ability of a particular vendor's design to achieve the guaranteed SO_2 removal efficiency. While the default values for mass transfer film thicknesses and reagent dissolution rate constants contained in FGDPRISM are based on experience at many full-scale sites, the values determined for those sites varied considerably. These variations are attributable to the differences at each site with respect to gas-liquid distribution, reagent type, and other site-specific factors.

Using the program's default values for the mass transfer film thicknesses and limestone dissolution rate constants should allow the utility (or its consultants) to make relative judgments about the various proposals. The detailed design information from each vendor should be assembled into an FGDPRISM input data file. Then the model can be run to calculate the predicted SO_2 removal efficiency. The ranking of the predicted removal efficiencies will be an indication of the relative level of conservatism that has gone into each design. This relative ranking should be qualified, however, by any unique design features that have been incorporated by the vendors. For example, if one vendor has included a special inlet or outlet gas ductwork design that is claimed to improve gas/liquid distribution within the absorber, then using the same mass transfer film thicknesses as other designs may not give full credit to this design. Considering these types of design differences and deciding how much credit to give innovative designs requires a great deal of engineering judgment and experience. The evaluators may wish to ask such vendors to provide additional data to support the claims that they make concerning their innovations.

3.3.3 Limitations

The most significant limitation to the use of FGDPRISM to compare the relative SO_2 removal capability of different designs is that the physical system does not yet exist; and, therefore, the model cannot be calibrated. Operating data from similar systems can perhaps be used, but usually an exact duplicate does not exist because of site-specific factors.

The use of FGDPRISM to verify SO_2 removal efficiency requires a great deal of experience with FGD systems in general as well as with the model. The utility engineer must be aware of all the site-specific factors that can influence performance and must be able to assess the effect of the design innovations the vendors may propose.

4.0 SYSTEM DESIGN/SPECIFICATION

The utility engineer typically does not design an FGD system, but must be very familiar with the options available to the designer (vendor) so that a good specification can be written. In this section, the potential uses of the FGDPRISM model in helping the utility engineer prepare a technically sound bid specification for an FGD system will be discussed. There are two general aspects of FGDPRISM that are extremely useful in developing a specification for an FGD system. These are overall system material balances and complete system simulations. Each of these calculations will be discussed in the following sections, followed by a discussion of the limitations of the model in this application.

4.1 Overall System Material Balances

A great deal can be revealed about a process by making overall material balances. For example, the engineer can estimate the composition of the liquor and solids leaving the FGD system, which is generally the same as the liquor that is recirculated from the reaction tank to the absorber. As discussed in the preceding sections, this composition is influenced by many factors, including the amount of HCl removed from the flue gas, the solids concentration of the byproduct solids, the amount of liquid blowdown removed from the system, the composition of the makeup water and reagent, the level of oxidation achieved, the amount of lime/limestone added per mole of SO_2 removed, the amount (if any) of chemical additive used, and many other factors.

One critically important component in many FGD systems is the chloride level in the process liquor. A liquor chloride concentration that is too high can result in corrosion problems if the appropriate materials of construction are not specified. High chloride concentrations can also adversely affect system performance. As a result, higher L/G ratios, lower reagent utilization values, or the use of chemical additives may be required to maintain the desired SO_2 removal. The level of chlorides that can be expected can be estimated in advance by performing material balances. In this calculation, the user specifies complete information about all of the inlet streams (flue gas, lime/limestone reagent, makeup water, and chemical additives) as well as the outlet flue gas stream. Then, by specifying the desired chloride concentration and the solids concentration of the byproduct solids, the amount of liquid blowdown from the system required to achieve this chloride level can be determined. FGDPRISM results for this type of study are illustrated in Figure 4-1. For this example, the model was used to calculate the blowdown stream flow rate for chloride concentrations ranging from 20,000 ppm to 50,000 ppm and byproduct solids concentrations of 80 to 95 weight percent. Alternatively, FGDPRISM has an optional calculation mode in which the user can specify the blowdown flow rate and the model will calculate the corresponding chloride concentration for a given byproduct solids content.

Knowing the range of chloride concentrations that might be expected will allow the utility engineer to prepare an appropriate specification that addresses these important design issues. Appropriate materials of construction must be specified to be consistent with the expected liquor pH and composition. If a wastewater treatment system is required and included with the FGD specification, the amount and composition of wastewater blowdown coming from the FGD system must be known. In addition, if holding tanks or ponds are required, then they can be sized on the basis of the expected flow of wastewater from the FGD system.

Many recent FGD systems have been specified as forced-oxidation processes, with some producing commercial-quality gypsum for use in wallboard manufacture or other industries. The commercial-quality gypsum produced for use in these industries must meet material specifications such as those listed in Part I, Section 4.1.6--Regional Demand for Commercial-Quality Gypsum.

The material balance capabilities of FGDPRISM can be used to determine the design and operating conditions that will produce the required gypsum quality. An example of this type of analysis is illustrated in Figure 4-2. The figure shows results from a series of material balances made using FGDPRISM. The percent purity of the byproduct solids is

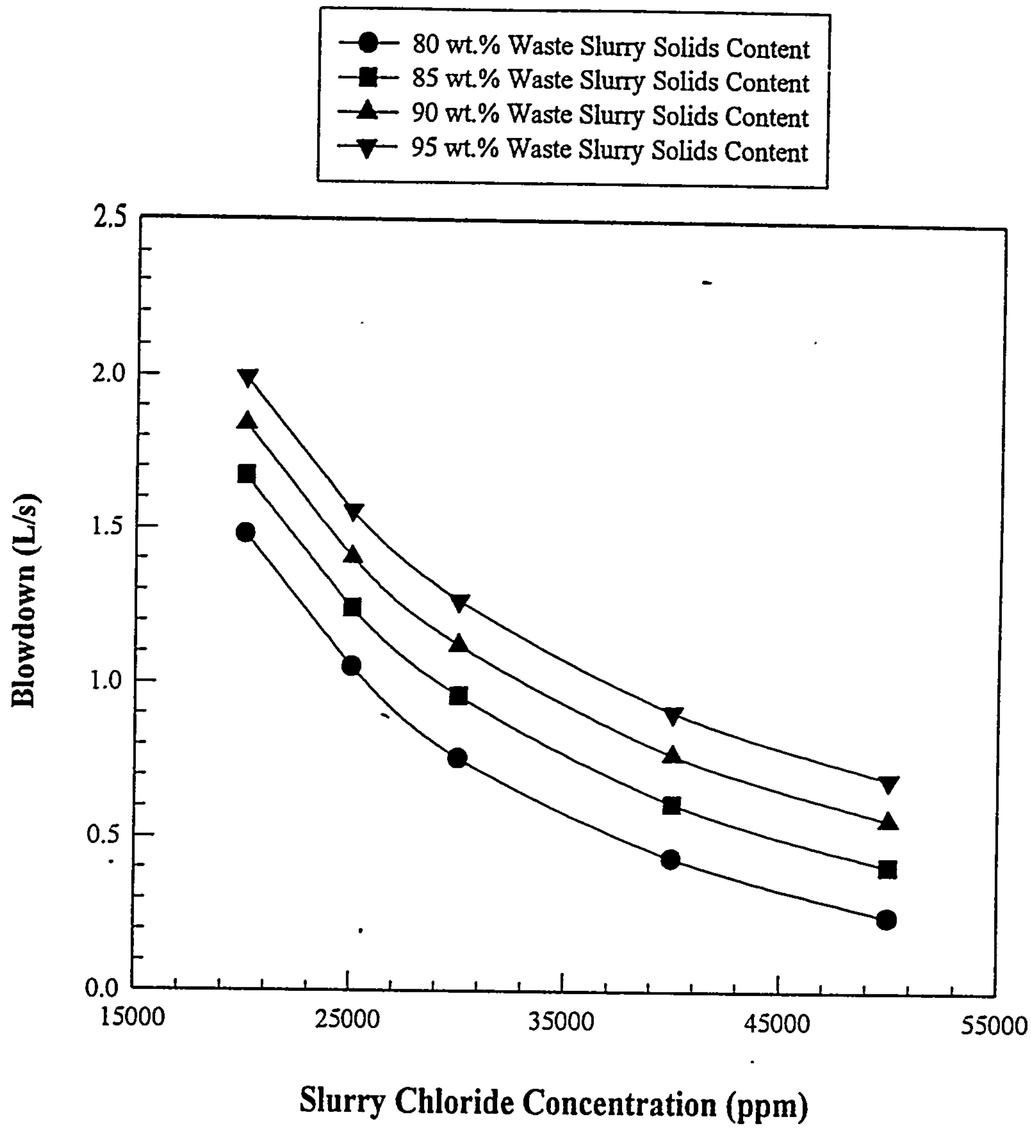

Figure 4-1. Calculated Blowdown Flow Rate vs. Specified Chloride Concentration

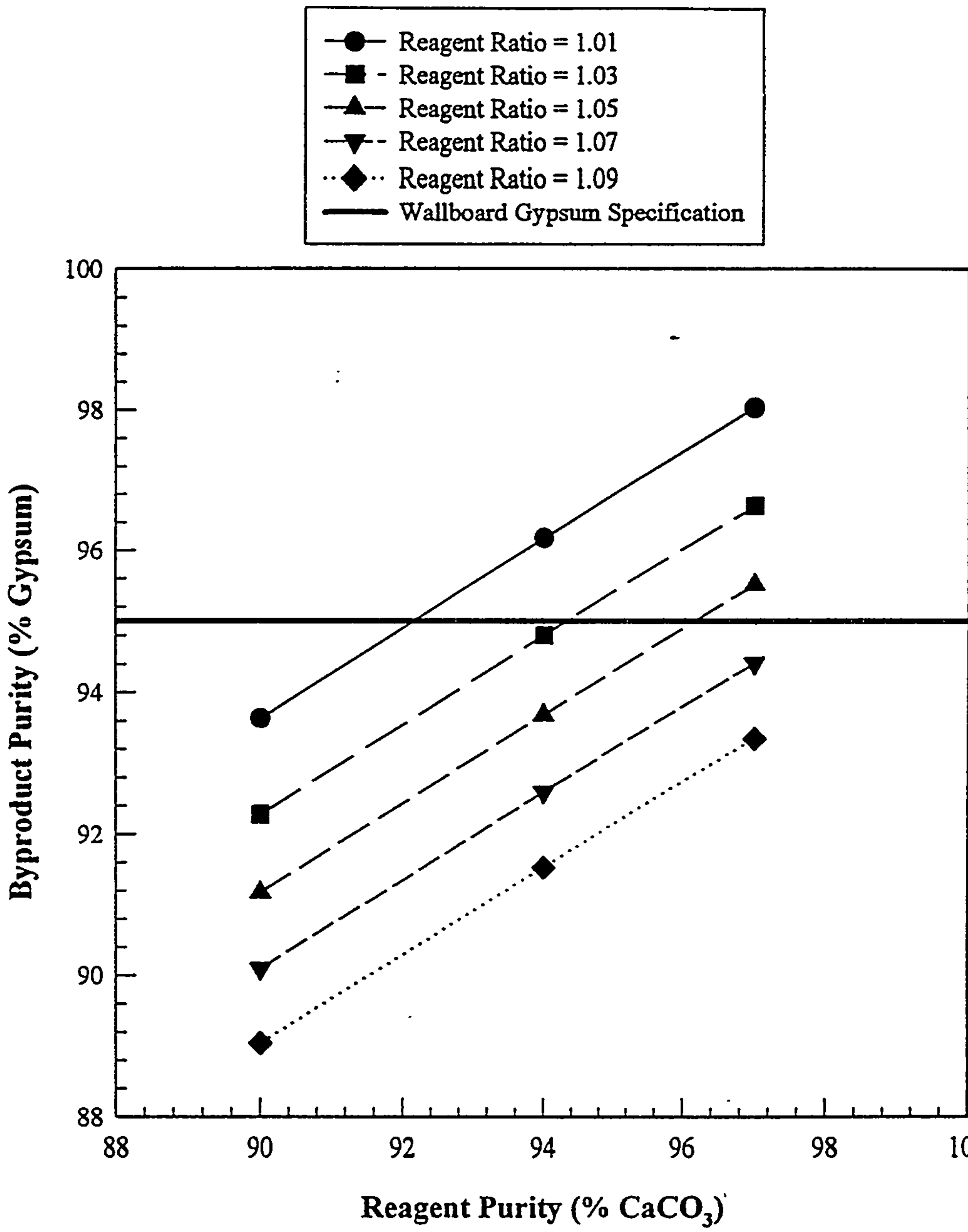

Figure 4-2. Example FGDPRISM Material Balance Results

plotted versus the limestone reagent purity (% $CaCO_3$). The different lines in Figure 4-2 represent operation at different reagent ratios (the inverse of reagent utilization). The solid horizontal line indicates the minimum gypsum content of the byproduct required to meet the quality specifications for gypsum used in wallboard manufacture. As shown in the figure, only certain operating conditions will produce a byproduct that meets these specifications. If the reagent ratio is too high or the reagent purity is too low, then the gypsum specification cannot be met.

The results of calculations similar to those shown in Figure 4-2 may be used in preparing specifications for the limestone reagent. That is, a limestone purity of at least 95% $CaCO_3$ may be required to meet the gypsum quality specification. Alternatively, the FGD specification may be written so that a maximum reagent ratio of 1.05 is specified in the design. This type of information is very important to consider before the system is designed, built, and operating. Proper specification of the FGD system and/or limestone reagent should eliminate the need for expensive post-installation modifications that may be necessary to meet the desired byproduct quality (e.g., adding more absorber spray pumps and headers).

4.2 System Simulations

The system simulation option of FGDPRISM allows the user to predict SO_2 removal for a given process design. However, the model requires that the user input mass transfer film thicknesses, which normally are derived by calibrating the model using actual operating data. In this application (design or specification of a new system), the model cannot be calibrated. Typical values for the mass transfer film thicknesses can be used, or if data from similar designs are available, then the model can be calibrated for those systems and approximate mass transfer film thicknesses can be derived from that calibration. This model application requires an experienced user who is familiar with the capabilities and limitations of the model. Typical uses for FGDPRISM in this mode during the design or specification stage of an FGD system include setting a minimum L/G ratio, setting a minimum absorber size, and examining the effects of system chemistry (chlorides, chemical additives, etc.) on system design and performance. A discussion of these model uses is presented below.

4.2.1 Specifying a Minimum L/G Ratio

Some utilities in the past have felt a need to specify a minimum L/G ratio in the FGD system specification. The reasons for doing this vary from utility to utility, but could include poor performance experiences with other FGD systems, plans for burning higher sulfur coal in the future, or a desire for more flexibility and design margin than vendors would normally provide. FGDPRISM can provide a means for determining a reasonable minimum L/G ratio for a given FGD system process design.

If the utility has other FGD systems that are performing satisfactorily, then the model could be calibrated to these systems. The mass transfer parameters that are extracted can be used as inputs in simulations of the planned system to predict SO_2 removal efficiency as a function of L/G ratio. Then, on the basis of the desired SO_2 removal efficiency, a minimum acceptable L/G ratio can be selected for the specification.

Another approach taken by some utilities is to specify a minimum L/G ratio on the basis of achieving a higher SO_2 removal efficiency, say 95%, with chemical additives, but designing for 90% removal efficiency without additives. FGDPRISM is well suited for performing this type of analysis to aid the utility engineer in preparing the FGD system specification. A series of simulations can be performed to define removal efficiency as a function of L/G ratio at various levels of chemical additives, as shown in Figure 4-3. Then, an appropriate L/G ratio and DBA concentration can be selected to satisfy both constraints. In Figure 4-3, for example, 90% removal efficiency without chemical additives requires an L/G ratio of approximately 13.7 L/Nm^3, and 95% removal efficiency for the same L/G ratio requires 250 ppm DBA.

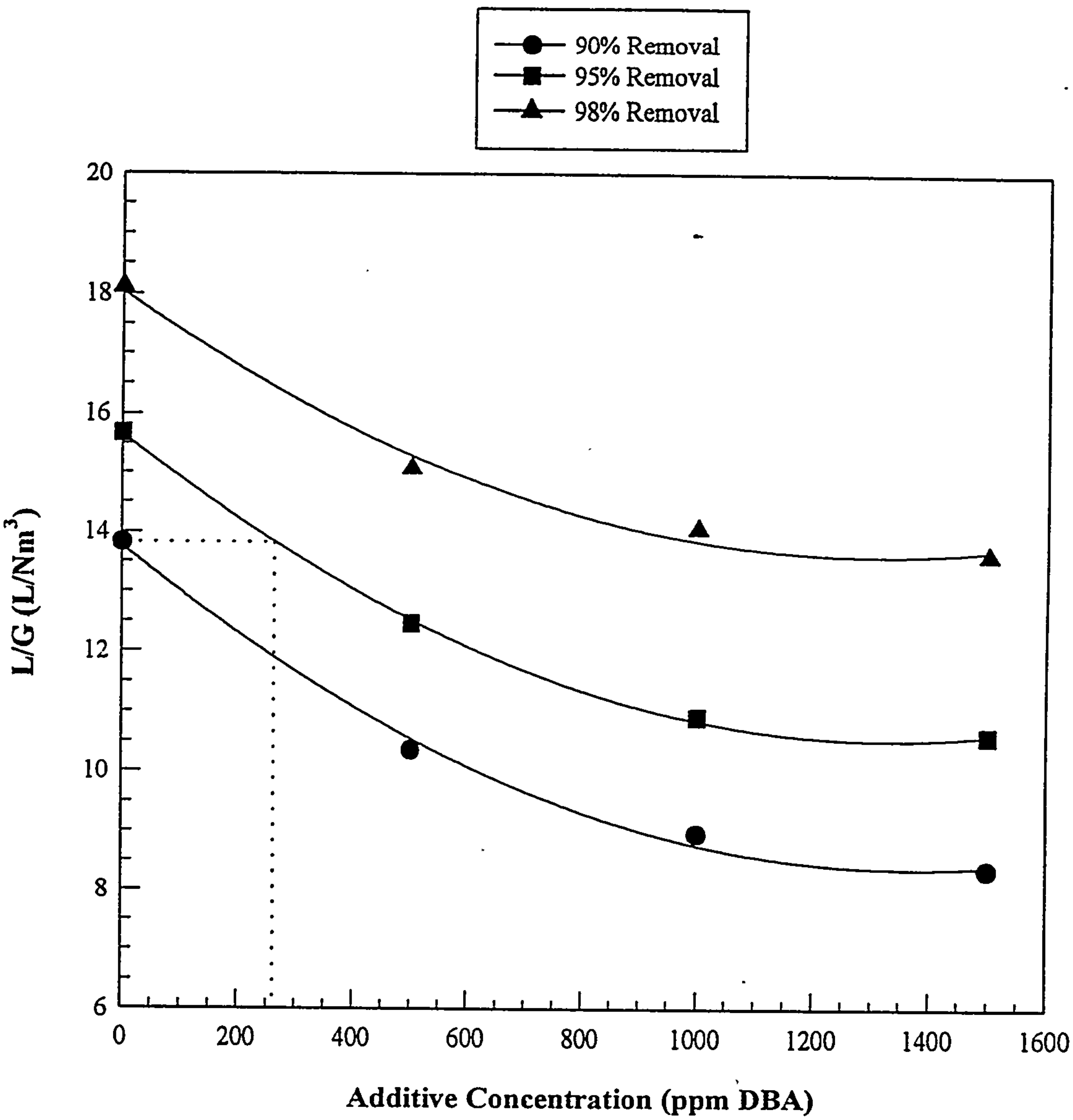

Figure 4-3. Example FGDPRISM Predictions for L/G vs. DBA Concentration

The specified minimum L/G ratio can also be associated with a desired maximum reagent ratio (minimum utilization). As discussed in Section 4.1, a maximum reagent ratio can be specified to keep the byproduct solids at a minimum gypsum content for forced-oxidation systems designed to produce commercial-quality gypsum. Figure 4-4 shows example FGDPRISM results; the SO_2 removal efficiency is plotted as a function of L/G ratio for different reagent ratios. Conducting this type of analysis prior to preparing a specification will allow the utility engineer to determine how sensitive the design L/G ratio is to different reagent ratios. As shown in the figure, higher reagent ratios result in lower L/G values for a specified SO_2 removal efficiency. For example, at 90% SO_2 removal efficiency, and a reagent ratio of 1.03, an L/G ratio of about 15.2 L/Nm^3 (105 gal/1000 ft^3) is required. If the reagent ratio is raised to 1.10, however, the L/G ratio required to achieve the same removal efficiency drops to about 13.0 L/Nm^3 (88 gal/1000 ft^3). A technical and economic evaluation of such alternatives can result in significant reductions in capital and operating costs for a new FGD system.

4.2.2 Setting a Minimum Absorber Size

Some utilities have written specifications that specify a minimum tower height and/or distance between spray headers. In the past, this was thought to have a significant effect on system performance. However, more recent studies (1) have shown that the impact of having the two uppermost headers in service versus the two lowest headers is small, even for a tower with as many as six total headers. The magnitude of this difference can be predicted by FGDPRISM, and the model has been shown to accurately predict full-scale performance as a function of headers in service.

The practice of setting a maximum gas velocity (typically specified as a minimum absorber diameter) has been prevalent for many years in FGD system specifications. Recent studies have shown that operation at higher absorber gas velocities may provide performance and cost advantages (1). While FGDPRISM is able to match absorber performance data at different gas velocities, it has been necessary to modify the mass transfer

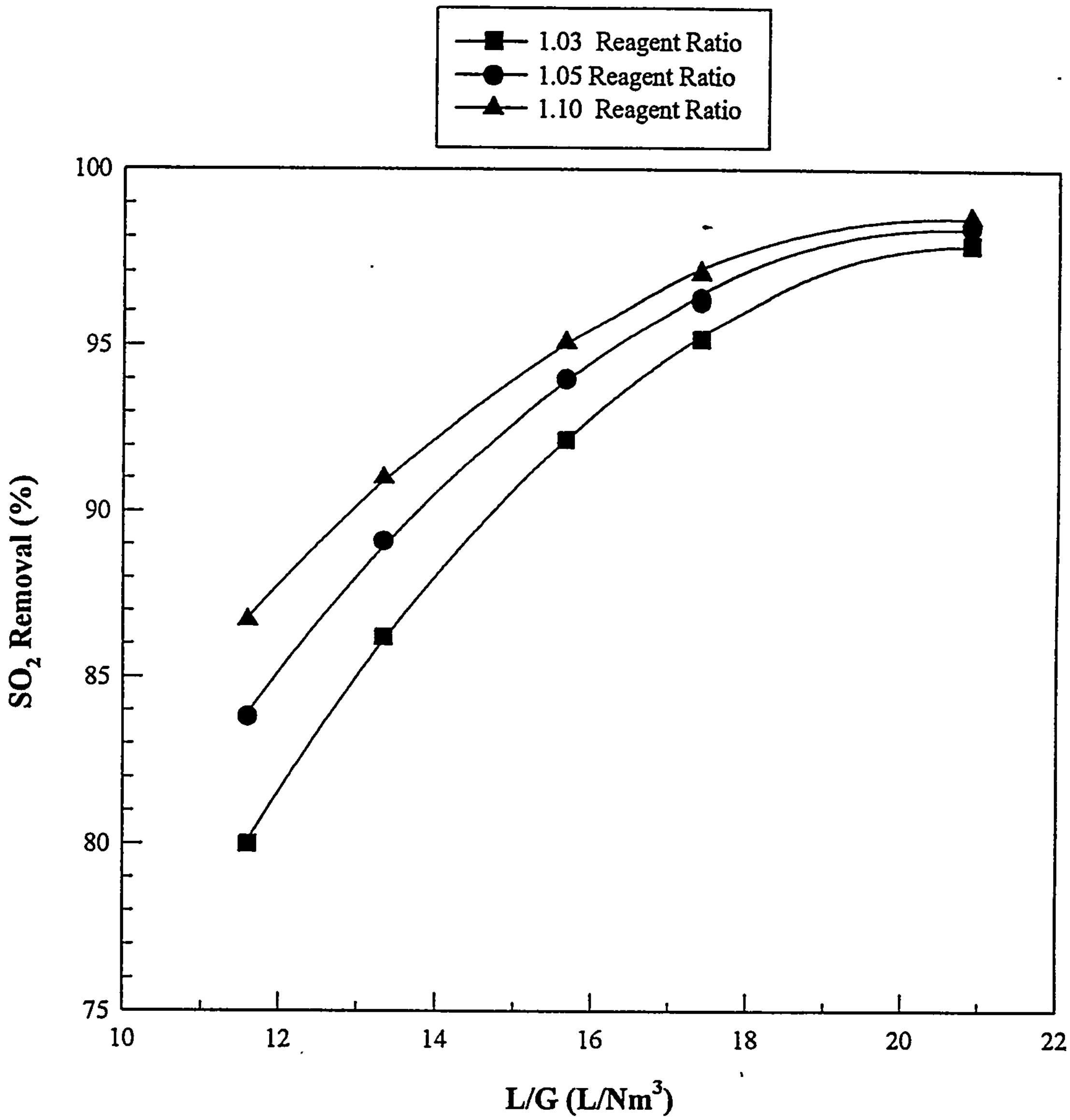

Figure 4-4. Example FGDPRISM Results for SO_2 Removal vs. L/G with Varying Reagent Ratio

film thicknesses as a function of gas velocity, as discussed earlier in Part IV, Section 2.1--FGDPRISM Model Calibration. Thus, the model could be used to examine the impact of smaller-diameter towers (higher absorber gas velocity) on SO_2 removal efficiency and absorber design. However, that application would require a very experienced user as well as someone who is very experienced with FGD systems in general, because of operating problems that may be encountered at elevated gas velocities, such as excessive mist eliminator carryover.

4.2.3 Examining Chemistry and Reagent Effects

FGDPRISM excels in its ability to predict the effects of process chemistry on FGD system performance, and years of research have gone into the development of methods for predicting and evaluating chemistry effects on FGD systems. Some of the chemical and operating variables that the utility engineer might want to investigate prior to preparing an FGD specification include process liquor chloride concentration, chemical additive concentration, lime/limestone reagent quality, and limestone grind fineness.

The mechanisms of how chloride enters an FGD system and how it is controlled are presented in Part I, Section 3.5.1--Dissolved Solids (Chlorides) Concentration and Part IV, Section 4.1--Overall System Material Balances. The effects of process liquor chloride concentration on SO_2 removal efficiency can be predicted by FGDPRISM using the system simulation option. Thus, the chlorides not only affect material selection, but they can also affect the design L/G ratio or required reagent utilization. For any given design where chloride will be controlled with a wastewater blowdown, a series of simulations should be performed to examine the magnitude of the effect of variations in the liquor chloride level. The results of these simulations can be used to modify the specification with respect to the minimum L/G ratio or reagent utilization.

The effect of different chemical additives and different additive concentrations can also be predicted by FGDPRISM. Thus, if chemical additives are being considered for a new FGD system, the model should be used to examine what potential benefit can be derived from various designs. As stated earlier in this section, some utilities have specified that the FGD system be designed to achieve one level of SO_2 removal efficiency without chemical additives and another, higher level with additives. FGDPRISM can help the utility decide what levels the system can reasonably achieve.

The effects of reagent quality (CaO and MgO or $CaCO_3$ and $MgCO_3$ contents) and (for limestone-based processes) limestone grind fineness can also be predicted by FGDPRISM. Typically, the utility provides a reagent composition in the specification for the FGD system, and the vendor will specify a reagent ratio (or utilization) and a grind fineness (if applicable) for their design. The reactivity of the reagent is generally addressed by the vendor, who usually has a reactivity test that the reagent must pass. The utility engineer can use FGDPRISM to help determine minimum reagent composition values through material balances, as stated earlier in Section 4.1. However, for a limestone-based process, if several limestone sources are available and differ considerably in composition or reactivity, the utility engineer may want to perform system simulations to investigate the impact of each limestone on system performance and then select the appropriate composition or range of values for inclusion in the specification.

4.3 Limitations

The major limitation of FGDPRISM for use as a design tool is the variations in mass transfer film thicknesses that have been determined for different full-scale calibrations. This means that there is a fairly wide range of values, and choosing one that will be valid for a specific application is difficult. As the model is applied to more full-scale systems, the database of available information grows and model developers can offer better advice regarding selection of appropriate parameters. However, using typical values to set the minimum L/G ratio and absorber size, or to examine the effects of process chemistry and reagent qualities, is a reasonable and valuable application of the model. The user should be experienced and aware of the variations in mass transfer film thicknesses and the impact that they can have on predicted performance and system design.

A final word of caution is offered to the utility engineer applying FGDPRISM for process design or specification purposes. The user should be familiar with the model as well as with FGD systems in general. For example, the model does not make any predictions concerning mist eliminator performance. The mist eliminator can be affected by process chemistry and by the absorber mechanical design. The utility engineer needs to know what the limitations of the model are, and how to temper the results with practical operating and engineering experience.

4.4 References

1. Noblett, J.G., T.M. Shires, and R.E. Moser. "Recent Applications of FGDPRISM for Operations Optimization and SO_2 Removal Enhancement." Presented at the 1995 SO_2 Control Symposium, Miami, Florida, March 28-31, 1995.

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PART V
FGD SYSTEM CASE STUDY

1.0 INTRODUCTION

Part V is a case study in using this **Electric Utility Engineer's FGD Manual** in the preparation of a purchase specification and in the evaluation of proposals received from vendors.

1.1 Objectives

The objectives of Part V are the following:

- To demonstrate how the information contained in Parts I and II of this manual can be used to improve the technical content of an FGD system purchase specification;
- To demonstrate how the techniques presented in Part III of this manual can be used to evaluate proposals received in response to the purchase specification; and
- To illustrate how the FGDPRISM computer program discussed in Part IV can be used to establish design parameters for the specification and evaluate vendor designs.

1.2 Organization

As illustrated in Figure 1-1, Part V is divided into four major topics: a brief introduction, the case study assumptions, the development of specification parameters, and the evaluation of proposals.

Section 2.0 presents the design assumptions used as the technical and economic bases for this case study. These assumptions were selected to represent a typical FGD system

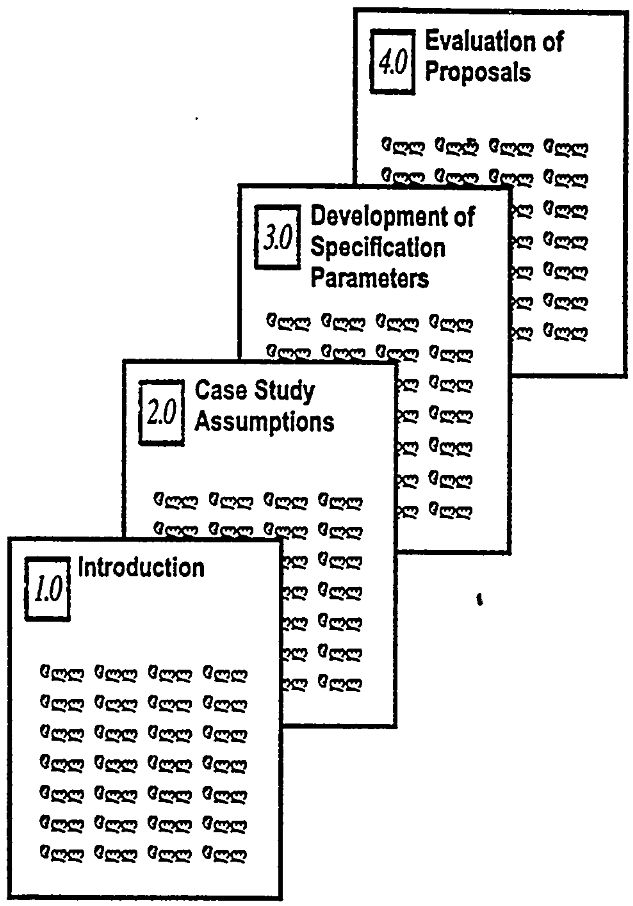

Figure 1-1. Part V Organization

installation requiring relatively high SO_2 removal efficiency and located at a site with limited room for byproduct disposal.

Section 3.0 illustrates the development of the technical parameters and economic evaluation factors for an FGD system purchase specification. Justifications for each parameter and factor are presented along with brief discussions of the potential effects of alternative selections.

Section 4.0 presents an illustration of the technical and economic evaluation of two hypothetical proposals received in response to the purchase specification. The evaluations conclude with technical and economic rankings of the two proposals and an identification of the most advantageous choice based on the case study plant assumptions.

ELECTRIC UTILITY ENGINEER'S FGD MANUAL

PART II—MAJOR MECHANICAL EQUIPMENT

PART III—FGD PROPOSAL EVALUATIONS

PART IV—USE OF FGDPRISM IN FGD SYSTEM MODIFICATION, PROPOSAL EVALUATION, AND DESIGN

PART V—FGD SYSTEM CASE STUDY

U.S. DEPARTMENT OF ENERGY
PITTSBURGH ENERGY TECHNOLOGY CENTER

2.0 CASE STUDY ASSUMPTIONS

The development of a case study requires establishing a set of assumptions on which the study can be based. These assumptions can be divided into the following classifications:

- Generating unit assumptions;
- Environmental regulation assumptions;
- Reagent availability assumptions;
- Byproduct market assumptions;
- Makeup water quality and availability assumptions;
- Scope-of-supply assumptions; and
- Economic assumptions.

It should be noted that although these assumptions form a reasonable basis for the development of an illustrative case study, they are relatively arbitrary and are not meant to represent the actual design conditions at any specific location. These assumptions influence the selection of the FGD process, method of byproduct disposal, and other design decisions; a different set of assumptions could result in a very different set of design decisions.

2.1 Generating Unit Assumptions

As stated several times in the previous parts of this manual, many of the decisions regarding the design of an FGD system are strongly affected by the characteristics of the generating unit to which the system will be applied. Throughout the manual, numerical examples have been based on a 500-MWe plant burning a bituminous coal containing 2% sulfur. This case study will expand upon this same set of conditions. A typical fuel analysis is presented in Table 2-1. An actual specification would contain ranges for each fuel

Table 2-1

Assumed Design Coal Analysis

Constituent	Composition Limit
Higher heating value, kJ/kg (Btu/lb)	23,240 (10,000)
Moisture, %	12.0
Carbon, %	57.5
Hydrogen, %	3.7
Nitrogen, %	0.9
Chlorine, %	0.1
Sulfur, %	2.0
Ash, %	16.0
Oxygen, %	7.8

characteristic based on current and anticipated future fuels. The effects of fuel characteristic assumptions on FGD system design are discussed in Part I, Section 4.1.1--Fuel Property Range.

The case study assumes that the FGD system will be installed on an existing 500-MWe unit located in the central United States. A second 500-MWe unit also is assumed to be located at this site, but no FGD unit will be installed on the second unit at this time. The arrangement of the FGD system should consider the installation of an FGD system on the second unit at a later date. The site is assumed to have good-transportation access by both road and rail, but barge deliveries are not possible. A layout of the two-unit site is illustrated in Figure 2-1. The effects of site conditions on FGD system design are discussed in Part I, Section 4.1.5--Site Conditions.

The unit is assumed to be base-loaded, with an annual capacity factor of 65 percent. For simplicity, the net plant heat rate at all unit loads is assumed to be 2.93 watts of heat input per watt of electrical power output (10,000 Btu/kWh). This results in a heat input to the boiler of 1,465 MW (5.0×10^9 Btu/hr) at full load.

2.2 Environmental Regulation Assumptions

Three sets of environmental regulations are assumed to be applicable to the case study unit: air pollutant emission regulations, wastewater discharge regulations, and solid waste disposal regulations.

2.2.1 Air Pollutant Emission Regulations

A discussion of air pollutant emission regulatory factors governing FGD system design is provided in Part I, Sections 4.1.3--Regulatory Requirements. For the case study, the generating unit is assumed to be subject to provisions of Phase II of the U.S. Clean Air Act Amendments of 1990, and the site is assumed to be located in an area that currently meets all

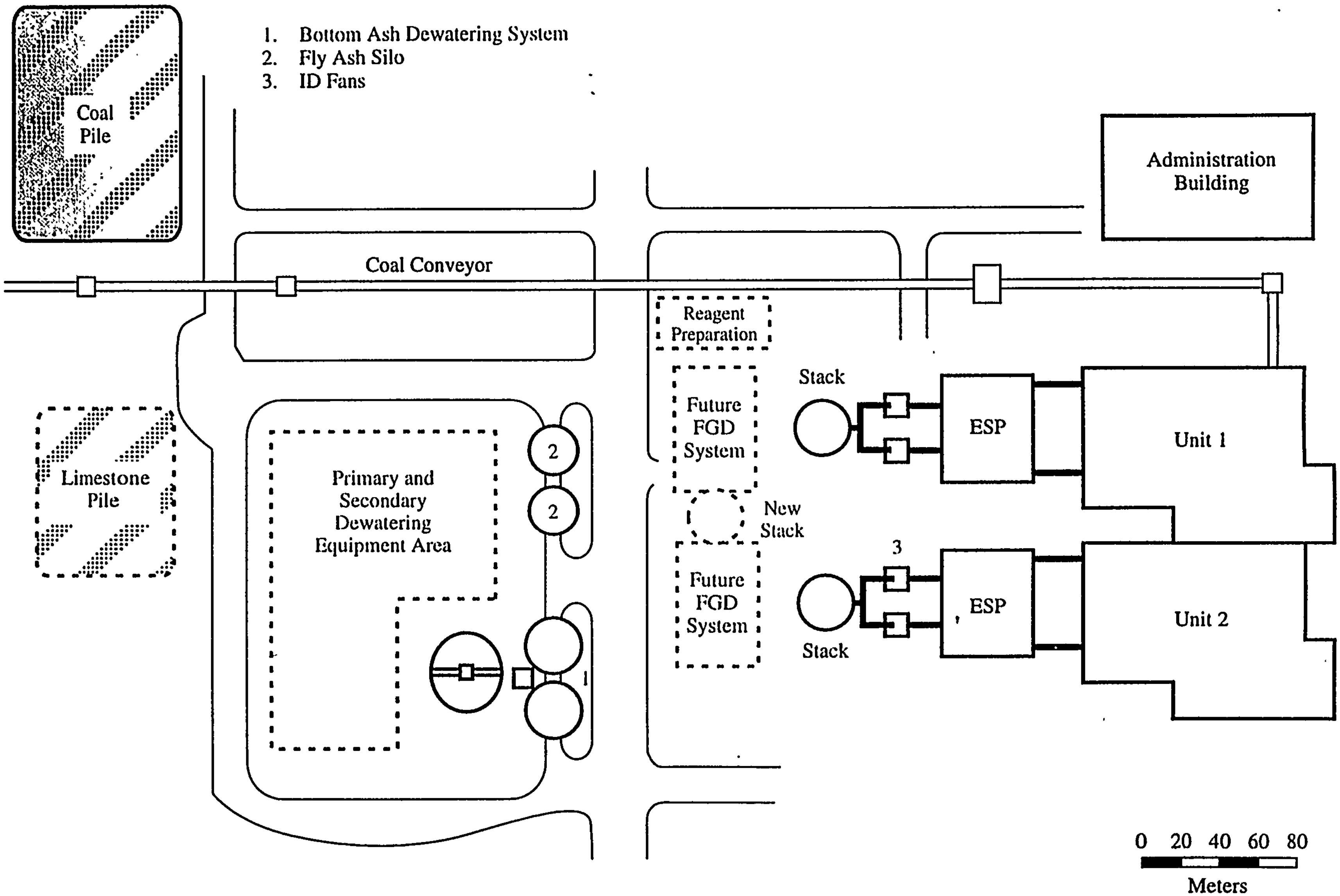

Figure 2-1. Case Study Generating Station Layout

applicable ambient air quality standards for SO_2. At an actual installation, the establishment of the design SO_2 removal efficiency is normally based on an extensive study of numerous alternatives, including fuel switching and purchase or trading of SO_2 emission allowances from other generating units. For this case study, it is assumed that the electric utility has determined that an FGD system is required and should be designed to remove 95% of the SO_2 generated by the design fuel.

It is further assumed that the existing unit is currently in compliance with all applicable particulate emission regulations. The FGD system will be required to operate with no net increase in the emissions of particulate matter. Opacity will be monitored upstream of the FGD system and reheat of the flue gas leaving the absorber modules will not be required either for limiting opacity or to improve dispersion of the plume.

Although the FGD system will remove essentially all hydrogen chloride (HCl) from the flue gas, it is assumed that the FGD system design is not influenced by removal requirements for this parameter.

2.2.2 Wastewater Discharge Regulations

Wastewater discharge regulations are very site-specific, as discussed in Part I, Section 4.1.7--Wastewater Discharge Limitations. For the case study, it is assumed that the unit is located adjacent to a large river capable of accepting a discharge of high-chloride wastewater without resulting in violations of ambient water quality standards or restricting any approved water use. The blowdown from the FGD system must meet limitations for total suspended solids (TSS), biochemical oxygen demand (BOD), chemical oxygen demand (COD), metal ions (e.g., arsenic, beryllium, cadmium, chromium, copper, lead, nickel, mercury, selenium, and zinc), and pH.

2.2.3 Solid Waste Disposal Regulations

It is assumed that the applicable regulations would permit the byproduct solids produced by the FGD system to be disposed of as nonhazardous wastes in an on-site landfill, pond, or gypsum stack, if sufficient land were available. For all three alternatives, the disposal area would require a double liner with a leachate collection system, as discussed in Part I, Section 4.8.4--Ultimate Disposal.

2.3 Reagent/Chemical Availability Assumptions

The regional availability of reagent has a major effect on the decision of whether to base the FGD process on a lime or limestone reagent, as discussed in Part I, Section 4.1.5--Site Conditions. For this case study, it is assumed that high-calcium limestone is available from quarries within 50 miles of the plant site and that delivery is possible by either truck or rail. The delivered cost of limestone is assumed to be $11 per metric ton ($10 per ton). Lime is assumed to be available from a supplier located 150 miles from the site with delivery possible by either truck or rail. The delivered cost of lime is assumed to be $66 per metric ton ($60 per ton). Because of the high cost of lime and the assumed potential to market a commercial-quality gypsum byproduct (discussed below), it is assumed that the utility has decided to install a limestone-based FGD system.

The assumed typical composition of the high-calcium limestone reagent is presented in Table 2-2. This composition will be used for producing FGD system material balances. In an actual specification, the value of each limestone constituent would also be expressed as a range in order to cover the expected day-to-day variations in limestone delivered from the quarry, and the FGD system would be guaranteed to meet performance requirements with any limestone with a composition that fell within these ranges. The assumed limestone contains 3% magnesium carbonate, of which at least half typically would be soluble and, therefore, available as a source of additional liquid-phase alkalinity (see Part I, Section 3.0--Process Chemistry). To ensure a conservative FGD system design, the effects of

Table 2-2

Assumed Limestone Reagent Composition

Constituent	Value, %
Calcium carbonate	97.0
Magnesium carbonate	1.4
Calcium sulfate	0.5
Silicon dioxide	0.5
Aluminum oxide	0.5
Ferrous oxide	0.1

the soluble magnesium carbonate fraction in improving FGD system performance typically are not considered. However, if actual magnesium availability data are available on the prospective limestone source(s), then the effect of soluble magnesium might be considered in the FGD system process design.

For this case study, it is assumed that dibasic acid (DBA) is available as a 50% solution delivered by tanker truck. The delivered cost is assumed to be $0.53/kg ($0.24/lb) dry. While DBA storage and feed equipment will be included in the specification, the base system will **not** use any chemical additive to meet the FGD system performance guarantees.

2.4 Byproduct Market Assumptions

Part I, Sections 4.1.6--Regional Demand for Commercial-Quality Gypsum and 4.8.6--Other Gypsum Production Operating Considerations discuss production of byproduct gypsum and the influences of producing commercial-quality gypsum on the FGD system. For purposes of the development of this case study, it is assumed that the electric utility has conducted a study of the potential for commercial use of byproduct gypsum in the vicinity of the generating station and has identified a wallboard manufacturer within 20 miles of the station. Negotiations with this firm are assumed to have resulted in an agreement to accept all of the gypsum produced by the FGD system, with shipments to the wallboard production facility 5 days per week, 50 weeks per year. The wallboard production facility is assumed to be closed for two weeks every year for an extended maintenance outage. The wallboard production facility will handle shipping to its plant and will pay the utility $2.20 per tonne of commercial-quality gypsum ($2.00 per ton).

The byproduct gypsum produced by the FGD system must meet the quality specification presented in Table 2-3. The agreement is assumed to stipulate that the wallboard production facility will not accept any byproduct that does not meet the composition

Table 2-3

Assumed Commercial-Quality Gypsum Specification

Constituent	Composition Limit
Mean particle size, µm, minimum	20
Free water, weight % Goal Maximum	 <10 15
Calcium sulfate, dry weight %, minimum	95
Calcium sulfite, dry weight %, maximum	2
Inert material,* dry weight %, maximum	5
Chloride, mg/kg dry, maximum	100
Sodium, mg/kg dry, maximum	75
Magnesium, mg/kg dry, maximum	50
Total water soluble salts, mg/kg dry, maximum	600
pH range	6.5-8.0

* Inert material includes fly ash and the unreactive portion of the limestone reagent (shale, silicon dioxide, etc.).

requirements and to contain a reward/penalty clause of \$0.27 per tonne* (\$0.25 per ton) for every percentage point of free water under or over the specified 10% (e.g., at 5% free water, the utility receives an additional \$1.35 per tonne; at 12% free water, the utility receives \$0.54 per tonne less). The facility will accept no gypsum with more than 15% free water. Byproduct that does not meet the quality or free water specifications, or that exceeds the capacity of the temporary storage area because it cannot be shipped to the wallboard production facility, must be placed in an on-site landfill.

2.5 Makeup Water Quality and Availability Assumptions

Part I, Section 4.1.4--Makeup Water Quality and Availability discusses the influences of makeup water on the design of the FGD system. For the case study, it is assumed that the utility engineers desire to minimize additional demands on the station's existing service water system and to reduce where possible the volume of existing discharges of plant wastewater. Therefore, the principal source of makeup water will be cooling tower blowdown. Service water use will be limited to critical areas such as shaft seals, vacuum pump seals, and byproduct wash water. The assumed compositions of the cooling tower blowdown and service water are presented in Table 2-4. These compositions will be used for producing FGD system material balances. As with the reagent composition in Table 2-2, in an actual specification, the value of each makeup water constituent would also be expressed as a range in order to cover the expected day-to-day variations in water quality, and the FGD system would be guaranteed to meet performance requirements with any composition that fell within these ranges. The specified water quality ranges of values would be based on either historical plant data or other water source data.

2.6 Scope-of-Supply Assumptions

Purchase specifications for FGD systems can be structured to cover many different scope-of-supply options. Historically, the FGD system specification scope has

* 1 tonne = 1000 kg.

Table 2-4

Assumed Makeup Water Analyses

Constituent	Composition	
	Cooling Tower Blowdown	Service Water
Calcium, mg/L	270	48
Magnesium, mg/L	50	20
Sodium, mg/L	100	20
Potassium, mg/L	10	2
Sulfate, mg/L	830	190
Carbonate, mg/L	30	20
Chloride, mg/L	110	20
pH, units	8.4	7.4

ranged very widely depending on the philosophy and capabilities of the electric utility and the scope of services of its architect/engineering (A/E) firm. Some utilities and A/Es prefer to limit the FGD system vendor's scope of supply. In such cases, the utility or A/E may develop separate specifications for large equipment items (such as isolation dampers, absorber spray pumps, booster fans, and high-voltage electric motors), foundations, support steel, and buildings. Even erection of the FGD system vendor's equipment may be delegated to other contractors. Other utilities may develop "turn-key" specifications that place furnishing and erecting of the FGD system and most support systems within the FGD system vendor's scope of supply. One U.S. electric utility has installed an FGD system under a set of specifications that required the vendor to design, build, own, and operate the FGD system. The FGD system specifications at a specific site may fall anywhere within this very broad range.

The case study is based on a furnish-and-erect specification with the following interface points and scopes of supply.

- **Flue Gas Handling Equipment.** All ductwork, dampers, and expansion joints from the outlets of the existing ID fans to the absorber module inlet and from the absorber module outlet to the stack liner on the new stack. All ductwork, dampers, and expansion joints for the bypass duct from the ID fan outlets to the absorber outlet plenum. Any modifications to the existing ID fans or stack liner will be supplied and installed by others under separate specifications.

- **SO_2 Removal Equipment.** The absorber module, reaction tank, mist eliminators (MEs), corrosion resistant linings, absorber spray pumps, oxidation air blowers, and all associated piping and valves.

- **Reagent and Chemical Additive Equipment.** All equipment required to produce the reagent slurry; reagent slurry and chemical additive storage tanks, reagent slurry and chemical additive feed pumps; and all associated piping and valves. The bulk material handling equipment including reagent unloading, stackout, and reclaim equipment, conveyors, and day bins would be furnished and erected under separate specifications.

- **Byproduct Handling Equipment.** Primary and secondary dewatering equipment; underflow and overflow storage tanks; conveyors; temporary gypsum storage enclosure, and all associated pumps, piping, and valves.

- **Makeup Water Supply.** The electric utility will provide a single connection point for service water and a single connection point for FGD system makeup water. The FGD system vendor will be responsible for all pumps, piping and valves for distribution of service water and FGD system makeup water within the vendor's scope of supply.

- **Wastewater Treatment Equipment.** A single discharge point to a wastewater treatment system supplied under other specifications.

- **Electrical and Control Equipment.** All power and control wiring, conduit and raceways, electric drives, switch gear, transformers, instruments, controls, and control panels for equipment furnished under these specifications. The electric utility will furnish a single electrical power connection, and the FGD system vendor will be responsible for all power distribution equipment beyond that point. The electrical grounding grid will be furnished and installed under separate specifications.

- **Foundations and Enclosures.** The vendor's equipment will be erected on foundations furnished and installed under other specifications. All support steel, access platforms and stairs, equipment enclosures, and buildings housing FGD vendor's equipment also will be furnished and erected under separate specifications. This includes all fire protection; lighting; and heat, ventilation, and air conditioning (HVAC) equipment. The FGD system vendor will be responsible for locating and designing all floor trenches and sumps. The FGD system vendor will be responsible for furnishing data on foundation and support requirements, access requirements, space conditioning requirements, etc. to the appropriate contractor(s).

- **Miscellaneous Support Systems.** The FGD system vendor will design, furnish, and erect the ME wash water tank, the reaction tank emergency dump tank, and the instrument and service air compressors. The design and construction of the byproduct solids landfill will be conducted under separate specifications. The continuous emission monitoring (CEM) system will also be furnished and erected under separate specifications.

2.7 Economic Assumptions

Economic assumptions are needed to conduct the economic evaluation of the proposals received. Although all of the assumptions in this section are utility-specific, the economic assumption are also dependent on economic conditions both at the time of the evaluation and projected during the operating life of the FGD system. In most cases, the utility has a set of economic assumptions that it uses for all economic evaluations. In the case study these following values will be used:

- Economic evaluation period--30 years;
- Interest rate--10%;
- Escalation rate--5%;
- Levelized fixed charge rate:
  - 30 years--16.5%,
  - 10 years--22.5%; and
- Sum of the present worth factors for 30 years--9.47.

It is recommended that the utility will provide these data to the vendors to aid them in their design optimization.

3.0 DEVELOPMENT OF SPECIFICATION PARAMETERS

On the basis of the case study assumptions contained in the preceding section, this section provides an example of developing the FGD system purchase specification's technical parameters. The specification's technical parameters can be grouped into six general classifications:

- FGD system design basis parameters;
- FGD system performance requirements;
- FGD process parameters;
- FGD system equipment parameters;
- Proposal economic evaluation factors; and
- FGD system guarantees and warranties.

3.1 FGD System Design Basis Parameters

Every purchase specification contains information that provides the vendors with the data on which to base their system designs and performance guarantees. This information covers the following:

- Scope of equipment and services to be provided;
- The characteristics of the flue gas to be treated;
- Any design limitations imposed by the site; and
- Characteristics of owner-furnished utilities.

3.1.1 Scope of Equipment and Services

As was described in Section 2.6--Scope of Supply, the case study is based on a furnish-and-erect specification. A detailed listing of the interface points and scope of supply is presented in that section. The interface points must be carefully defined for each interface between equipment furnished by the FGD vendor and equipment furnished by the utility under separated specifications. Any critical interface conditions (such as temperature, pressure, etc.) should be included in the definition. Without such definitions, conflicts during design or construction are certain to occur.

A common scope of equipment and services conflict occurs where equipment furnished by the FGD vendor must be connected to existing equipment or equipment furnished under other specifications, such as the inlet ductwork's connections to the existing ID fans. While drawings (if available) can be very helpful in defining interface points, precise specification wording is still needed. For example, the specification drawings may clearly indicate the location of the interface between the existing fans and vendor-furnished ductwork; however, are expansion joints required at these locations, and if so, who provides them? If the specification clearly states that the interface between vendor- and owner-furnished equipment will be a specific flanged ductwork connection (or connections) and that any required expansion joints will be provided by the vendor (or utility), then this type of problem can be avoided.

Similar problems occur at interfaces with owner-furnished utilities (see Section 3.1.4 below). The specification should contain wording such as, "Service water at 345 kPa (50 psi) will be provided at a single valved connection located near the existing chimney, as shown on the drawings. The vendor is responsible for all pumps, piping, and valves downstream of the outlet flange of the owner-furnished isolation valve."

3.1.2 Flue Gas Characteristics

The specification should contain the design values for flue gas flow rate, temperature, pressure, and composition, as shown in Table 3-1. Although the flue gas composition and volume can be readily calculated on the basis of the design coal composition and fuel burn rate, there is considerable leeway in the calculation of the total flue gas composition and flow rate. The values used in this calculation for parameters such as excess combustion air, air heater leakage, and in-leakage from the ductwork and particulate control device are all determined by the engineering judgment of the utility engineer. While the initial tendency may be to use very conservative values for each of these parameters, this can easily result in calculation of an unrealistically large volume of the flue gas to be treated by the FGD system, one that may never be experienced in actual operation. In some cases, such assumptions could result in a calculated flue gas flow rate that exceeds the maximum capacity of the ID fans. Such unrealistic flue gas volumes will result in overly conservative design of the ductwork, absorber, and other equipment whose design is influenced by flue gas volume, and can also increase the capital and operating costs of this equipment. In most new FGD systems, the FGD system flue gas composition and flow rate are calculated using the same set of assumptions as those used to design the particulate control device and ID fans. In retrofit application, the design flow rate should not exceed the maximum capability of the ID fans, and may be lower based on actual operating experience.

Specifications based on an owner-calculated flue gas volume and composition are preferred over specifications based on a specified fuel and combustion characteristics, and vendor-calculated volume and composition. The recommended approach standardizes the design basis for all vendors and eliminates unnecessary variations in vendor mass balances that can complicate the proposal evaluation process.

Table 3-1 presents the flue gas characteristics at both design conditions and 65% unit load. Although the system design and guarantees will be based on the design conditions, the flue gas characteristics at one or more additional load points are useful for

Table 3-1

Specified Flue Gas Conditions

Parameter	Design Value			
	65% Load		Design	
Flow rate, Nm^3/s (acfm)	406	(1,147,000)	625	(1,790,000)
Temperature, °C (°F)	129	(265)	136	(277)
Pressure, kPa-gage (inwg)	1.25	(5.0)	1.5	(6.0)
Composition, kg/s (lb/hr)				
N_2	357	(2,833,000)	549	(4,358,000)
O_2	30	(237,600)	46	(365,600)
CO_2	86	(685,100)	133	(1,054,100)
H_2O	24	(191,100)	37	(294,100)
SO_2	1.6	(13,000)	2.5	(20,000)
HCl	0.042	(335)	0.065	(515)
Particulate	0.012	(98)	0.019	(150)

evaluating the performance of the FGD system over a range of operating conditions. The 65% load point was selected because the operating costs of the proposed systems will be economically evaluated at that condition in Section 4 of this part of this manual. In general, flue gas characteristics should be provided for any operating condition for which the specification requires the vendor to provide mass balances or performance guarantees.

The flue gas SO_2 and HCl values are especially important in the design of the FGD system. Obviously, the SO_2 content is the basis for many process variables and equipment sizing decisions, particularly the reagent preparation and byproduct solids dewatering subsystems. The HCl content affects materials-of-construction decisions throughout the FGD system.

Special note should be made of potential transient flue gas conditions. For example, in the event of an air heater failure, the flue gas temperature may rapidly increase up to 370°C (700°F) for up to 15 minutes. The specification should identify such transient conditions and establish the desired system response. While the FGD system is typically not expected to meet its performance guarantees during such transient conditions, there should be no damage to equipment.

3.1.3 Site Limitations

Figure 2-1 in the previous section presented the case study plant's physical layout. Drawings of this type should be included in the specification to direct the vendors where specific FGD system components should be located. The example figure indicates areas available for the FGD system and the byproduct dewatering equipment. An actual specification would also include drawings of the following site limitations:

- Other generating plant equipment, buildings, and structures;
- Underground utilities and utility corridors;
- Roads and access corridors;

- Construction laydown and storage areas; and
- Material delivery routes and unloading areas.

For construction of a retrofit FGD system, these drawings would also include drawings of any equipment (such as ID fans) to which the new equipment must be connected. Detailed mechanical and structural drawings can usually be delayed until the FGD system vendor has been selected.

Unless there are specific reasons for limiting the vendor's arrangement alternatives, it is recommended that the utility resist the temptation to provide a detailed equipment arrangement as part of the specification. As discussed in Part I, Section 4.11--Equipment Arrangement Considerations, vendors can be very creative in their designs, particularly in difficult retrofit situations. These creative approaches often can save the utility significant capital and operating costs using the lessons learned at other installations.

3.1.4 Owner-Furnished Utilities

For the example case study, the electric utility is assumed to furnish makeup and service water, electric power, limestone reagent, and chemical additive. The specified characteristics of each of these utilities are discussed in the following paragraphs. If the electric utility had determined that flue gas reheat was required due to the need to enhance plume dispersion, the reheat energy source (steam, hot water, fuel oil, etc.) could be an additional owner-furnished utility.

As stated in the assumptions listed in Section 2, instrument and service air equipment are the responsibility of the vendor in this case study. This is a common practice for a retrofit application because the existing instrument and service air compressors are unlikely to have sufficient excess capacities to furnish the FGD system's additional requirements. If the FGD system is being installed during the initial construction of the power plant, the needs of this system are frequently incorporated into the design of the plant's equipment.

Makeup and Service Water

For this case study, makeup water at 207 kPa (30 psi) and service water at 345 kPa (50 psi) will be provided to the FGD system vendor at valved connections located near the existing chimney. A single connection will be provided for each source, with the vendor responsible for providing water to the absorber module, reagent preparation, and byproduct dewatering areas from this point. The number and locations of these connections may vary with site-specific factors and equipment layouts.

The chemical compositions of makeup and service water for this case study were presented in Table 2-4 and must be provided to the FGD system vendors. The vendors use these data to determine the optimum quality water for each FGD system demand (i.e., mist eliminator wash, seal water, slurry preparation water) and to perform an overall water balance for the system. For the case study, no maximum available quantities for these two sources have been identified. Because cooling tower blowdown is being used as the source of makeup, it would not typically be necessary to limit the amount used by the FGD system. At an actual plant, the quantity of service water may be limited by the capacity of the existing service water treatment system. If so, this quantity should be contained in the specification.

Electric Power

The utility will furnish 4160-volt ac power to the input leads of a single vendor-furnished transformer. The specification should also contain the utility's requirements governing their standard operating voltages of electric motor drives of various size ranges, lighting, and HVAC equipment in order to ensure the FGD system electrical system is consistent with the system serving the remainder of the power plant. For example, the specification might require all electric motor drives under 225 kW (300 hp) to use 480-volt ac power and motors over this size to use 4160-volt ac power.

Limestone Reagent

The FGD vendor's responsibility for the reagent preparation starts at the outlet of the limestone day bins. At this point, the limestone size range will be 19 mm by 0 mm (3/4 in. by 0 in.) The chemical composition of the limestone reagent was presented in Table 2-2.

Chemical Additive

Dibasic acid (DBA) feed equipment will be provided by the FGD system vendor, but DBA will not be used to meet the system SO_2 removal performance guarantees. DBA will be provided to the plant as a 50% solution.

3.2 FGD System Performance Requirements

The FGD system specification contains specific requirements concerning the performance of the system. The requirements contained in the case study specification are as follows:

- **SO_2 Removal Efficiency**--The FGD system's SO_2 removal efficiency is obviously the primary system performance requirement. The case study specification requires that the FGD system remove a minimum of 95% of the inlet SO_2 at all conditions up to and including the design basis flue gas conditions in Table 3-1 without the use of chemical additive.

- **Particulate Emission Rate**--Because the FGD system vendor has no control over the inlet particulate content of the flue gas, it is typically very difficult to obtain a guarantee of a particulate removal efficiency or even an outlet emission rate. As a compromise, the case study specification will require that the outlet particulate emission rate not exceed the inlet rate (no net increase in particulate emissions).

Historically, this requirement has been used for many FGD installations in the United States.

- **ME Droplet Carryover**--The performance of the ME can be specified in several different manners including liquid carryover rate [$L/s\text{-}m^2$ (gpm/ft^2)], outlet droplet loading [g/Nm^3 ($grains/ft^3$)], and percentage removal of a given droplet size [99.9% removal of droplets greater than 40 μm]. The case study specification will specify that the liquid carryover rate not exceed 0.0033 $L/s\text{-}m^2$ (0.005 gpm/ft^2) at design flue gas flow conditions.

- **Byproduct Composition**--The specification's byproduct composition requirements are based on producing a commercial-quality gypsum. These requirements were listed in Table 2-3.

If the FGD system in this case study had included flue gas reheat in its design, the outlet flue gas temperature would have been included in this list. Similarly, if the vendor's scope of supply had included treatment of the FGD system blowdown stream prior to discharge, then the quality of the treated effluent would also have been included.

3.3 FGD Process Parameters

The FGD system specification could contain requirements for the following process parameters:

- Minimum liquid-to-gas ratio (L/G);
- Minimum reagent utilization (or maximum reagent ratio);
- Minimum sulfite oxidation level;
- Reagent grind fineness;
- Maximum slurry chloride concentration;
- Absorber spray slurry solids content; and
- Absorber reaction tank slurry solids residence time.

In the past, some specifications have contained requirements for all of these parameters. More recent specifications, however, have varied widely in the level of detail given to the FGD system process parameters. The level of detail included depends on the utility's willingness (and ability) to accept a portion of the responsibility in the system's design and the utility's level of trust in the use of performance guarantees to ensure that the FGD vendors use adequate design margins. Each process parameter that is specified reduces the vendors' ability to optimize their process designs and may increase capital and operating costs.

For the case study it will be assumed that the utility will specify the maximum slurry chloride level and reaction tank slurry solids residence time. The utility has also indirectly set requirements on the minimum reagent utilization efficiency and sulfite oxidation level, since these parameters are controlled by the need to produce commercial-quality gypsum as a byproduct. The gypsum quality specification, presented earlier in Table 2-3, results in requirements to achieve over 95% limestone utilization and 98% sulfite oxidation. The specification will allow the remaining process parameters to be optimized by the FGD vendors as part of their design.

A maximum slurry chloride level of 20,000 mg/L was selected for three reasons. First, it is assumed that the governing regulatory agency will permit the discharge of an FGD system blowdown stream containing 20,000 mg/L or less of chloride to a local river (See Part I, Section 4.9--Chloride Purge and Wastewater Treatment).* Second, this chloride level allows the vendors to consider the use of relatively lower-cost alloys in the construction of the absorber module (see Part I, Section 5.6.1--Alloy Products and Corrosion Resistance). Third, this chloride level has relatively little effect on the other process parameters in attaining the desired SO_2 removal efficiency (see Part I, Section 3.6.2--Dissolved Solids Concentration).

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* This is an assumption made for this case study example and should not be considered to be applicable at any specific site (see Part I, Section 4.1.7--Wastewater Discharge Limitations).

A reaction tank slurry solids retention time of 15 hours was selected as a good compromise between capital cost and improvements in reagent utilization (See Part I, Section 4.3.1--Reaction Tank Volume). Longer times would improve utilization (or allow coarser limestone grind fineness) but would increase the capital cost of the tank.

If the utility had decided to specify additional process parameters (e.g., L/G, reagent grind fineness, etc), these interrelated parameters could be optimized using the FGDPRISM computer program, as described in Part IV, Section 4.2--System Simulations. It should be noted, however, that parameters such as L/G must be optimized for each type of absorber that will be permitted by the specification. This can result in specifying different minimum/maximum values for each absorber type.

3.4 FGD System Equipment Parameters

Part I--Design Considerations provides information on the design of the absorber module, reaction tanks, mist eliminators, and major support subsystem equipment. Part II--Major Mechanical Equipment contains discussions of 15 categories of major FGD system mechanical equipment. Additional sections could be written on other mechanical components, electrical equipment, control instruments, and structural design considerations. For all of the equipment discussed in Parts I and II, the FGD system specification could establish requirements for the following:

- Applicable design codes and standards;
- Required performance and design criteria;
- Acceptable materials of construction; and
- Acceptable manufacturers.

Judicious selection of equipment requirements is necessary to ensure that the FGD system achieves a high level of cost-effectiveness, maintainability, and reliability and to ensure that the proposals received from competing FGD system vendors are technically comparable (see Part III--Technical Evaluations). Conversely, however, limiting the FGD vendors' choices in the four criteria listed above can reduce the potential for the vendors to use creative or new solutions to the design problems posed by an FGD system.

A list of organizations whose published codes and standards are typically referenced in the United States is presented in Table 3-2. This list should not be considered complete; it is meant only to indicate that a large number of organizations have requirements that must be considered in the design and construction of the FGD system.

Tables 3-3 through 3-13 provide summaries of the performance/design criteria and materials of construction of some of the major subsystems and components of the FGD system used in development of the case study. These parameters and materials follow the recommendations contained in Parts I and II of this manual. Numerous design codes and standards apply to the design and construction of a large, complex system such as an FGD system.

A list of qualified manufacturers for the many components that make up an FGD system is beyond the scope of this manual. Such lists are maintained by experienced consultants, architect/engineers, electric utilities, and FGD vendors. While demonstrated experience with the equipment in similar FGD system service is the most certain method of ensuring that efficient, maintainable, and reliable equipment is procured, innovative methods of addressing FGD system operating requirements are continually being developed and introduced to the marketplace.

3.5 Proposal Economic Evaluation Factors

During the development of a proposed FGD system design, the FGD vendor must often weigh tradeoffs between capital and operating costs, between reagent and electric power costs, and between initial costs and maintenance costs. This is very similar to the

Table 3-2

Typical Codes and Standards Organizations

ACI	American Concrete Institute
AISC	American Institute for Steel Construction
AMCA	Air Moving and Conditioning Association
ANSI	American National Standards Institute
API	American Petroleum Institute
ASCE	American Society of Civil Engineers
ASHRAE	American Society of Heating, Refrigerating, and Air Conditioning Engineers
ASME	American Society of Mechanical Engineers
ASTM	American Society for Testing and Materials
AWS	American Welding Society
AWWA	American Water Works Association
EJMA	Expansion Joint Manufacturers Association
FM	Factory Mutual
HI	Hydraulic Institute
IEEE	Institute for Electrical and Electronics Engineers
IES	Illumination Engineers Society
IGCI	Industrial Gas Cleaning Institute
ISA	Instrument Society of America
NACE	National Association of Corrosion Engineers
NEC	National Electrical Code
NEMA	National Electrical Manufacturer's Association
NESC	National Electrical Safety Code
NFPA	National Fire Protection Association
OSHA	Occupational Safety and Health Administration
PFI	Piping Fabricators Institute
SBC	Standard Building Code
SJI	Steel Joint Institute

Table 3-3

Ductwork and Damper Design Parameters

Parameter	Value	Notes
Flue Gas Velocity		See Part II, Section 3.0. The outlet duct maximum velocity is set to minimize liquid re-entrainment in the wet duct. A higher velocity is used in the bypass duct since it will be used only in emergency situations.
Inlet ductwork	18.3 m/s (60 ft/s), maximum	
Outlet ductwork	15.2 m/s (50 ft/s), maximum	
Bypass ductwork	24.4 m/s (80 ft/s), maximum	
Duct Configuration		See Part II, Section 3.0. Circular cross-section outlet ductwork would greatly reduce the number of internal duct stiffeners and reduce the potential for liquid re-entrainment. Floors of the outlet duct must be sloped to drain lines and the drain lines must be routed to floor sumps.
Inlet ductwork	▸ Rectangular cross section	
Outlet ductwork	▸ Rectangular cross section ▸ Circular cross section	
Bypass duct	▸ Rectangular cross section	
Damper Type		See Part II, Section 4.0. When closed, the inlet and outlet isolation dampers must be capable of maintaining man-safe operating conditions in the module while the module is bypassed.
Inlet isolation	Man-safe guillotine	
Outlet isolation	Man-safe guillotine	
Emergency bypass	Double multi-louver	
Materials of Construction		See Part I, Section 5.0 and Part II, Sections 3.3 and 4.3. All specified materials of construction are the minimum allowable in the service. Where required by a specific design, the vendor must use more erosion- and corrosion-resistant materials.
Inlet ductwork — Upstream of damper	▸ Carbon steel	
Downstream of damper	▸ C-class alloy plate	
Outlet ductwork	▸ C-class alloy wallpaper ▸ Foamed borosilicate glass block-lined carbon steel ▸ FRP	

Table 3-3

(Continued)

Parameter	Value	Notes
Materials of Construction (continued)		
Bypass ductwork		
Upstream of damper	▸ Carbon steel	
Downstream of damper	▸ C-Class alloy wallpaper ▸ Foamed borosilicate glass block-lined carbon steel	
Inlet and outlet isolation dampers		
Interior frame	▸ C-class alloy	The exterior portions of all dampers that are never in contact with the flue gas can be fabricated from carbon steel.
Damper blade	▸ Superaustenitic stainless steel	
Seal strips	▸ C-class alloy	
Bypass damper		
Interior frame	▸ C-class alloy (upstream and downstream)	
Upstream damper blade	▸ Carbon steel	
Downstream damper blade	▸ C-class alloy	
Seal strips	▸ C-class alloy	

Table 3-4

Absorber Module and Reaction Tank Design Parameters

Parameter	Value	Notes
Number and Capacity	1-100%	See Part I, Section 6.0. FGD systems of this size have been demonstrated to achieve good reliability without the use of a spare.
Type	▸ Countercurrent or cocurrent ▸ Spray tower ▸ Spray/tray tower ▸ Packed tower ▸ Dual-loop ▸ Jet bubbling reactor	See Part I, Sections 4.2.1. An actual installation may wish to limit the acceptable types of absorbers more than indicated in this table. This decision should be based on the utility's investigation of the operating histories of existing systems.
No. of Spare Spray Levels (where applicable)	1	See Part I, Sections 4.2.1 and 6.3.2. Spare spray levels are not applicable to jet bubbling reactors. For some absorber types, such as cocurrent absorbers, the intention of this requirement may be better met by requiring a spare slurry spray pump.
Nominal Flue Gas Velocity Countercurrent absorbers Cocurrent absorbers	 3 m/s (10 ft/s) 6 m/s (20 ft/s)	See Part I, Sections 4.2.1. Since the maximum flue gas velocity in countercurrent absorbers is an area of active research in the FGD industry, a higher specified value may be more common in the future.
Reaction Tank Solids Retention Time, minimum	15 hours	See Part I, Sections 4.3. Longer retention times may be required by some processes. Some vendors may take exception and provide data justifying shorter times.
Materials of Construction	▸ Superaustenitic stainless steel or C-class alloys ▸ Reinforced resin-lined carbon steel ▸ Chlorobutyl rubber-lined carbon steel ▸ Ceramic tile-lined carbon steel or concrete	See Part I, Sections 4.2.2 and 4.3.5. While all of these materials are suitable for operation at 20,000 mg/L chloride, the utility may wish to limit the list of acceptable materials based on operating experience or other factors. The vendor must use more erosion- or corrosion-resistant materials where required by specific design conditions.

Table 3-5

Mist Eliminator Design Parameters

Parameter	Value	Notes
Orientation	Horizontal or vertical	See Part I, Sections 4.2.1 and 4.4.1. Unless the utility has a strong preference for one or the other of these orientations, this should be left to the FGD system vendor as part of the optimization of the ME design.
Number of Stages	2	See Part I, Section 4.4.4. Two stages are recommended for either orientation. The specific design such as blade type and spacing may either be specified or left to the FGD system vendor to optimize.
Nominal Flue Gas Velocity Vertical MEs Horizontal MEs	 3.0 m/s (10 ft/s) 7.6 m/s (25 ft/s)	See Part I, Section 4.2.1. These values are typical. The maximum flue gas velocity through the MEs is a subject of on-going research and higher velocities may be justified for some designs.
Wash Intensity Vertical ME Front of first stage Back of first stage Front of second stage Horizontal ME Front of first stage Back of first stage Front of second stage	 1.0 L/s-m^2 (1.5 gpm/ft^2) 0.34 L/s-m^2 (0.5 gpm/ft^2) 0.34 L/s-m^2 (0.5 gpm/ft^2) 1.0 L/s-m^2 (1.5 gpm/ft^2) 0.7 L/s-m^2 (1.0 gpm/ft^2) 0.7 L/s-m^2 (1.0 gpm/ft^2)	See Part I, Section 4.4.6.
Maximum Calcium Sulfate Relative Saturation in ME Wash Water	50%	See Part I, Section 4.4.6.
Materials of Construction	▸ Fiber-reinforced plastic (FRP) ▸ Glass-coupled polypropylene ▸ Polysulfone	See Part I, Section 4.4.5. Each FGD vendor tends to standardize on one or two materials based on its experience at other installations.

Table 3-6

Reagent Preparation System Design Parameters

Parameter	Value	Notes
Number and Capacity Ball mill equipment trains Reagent slurry storage tank Chemical additive storage tank	 2-100% capacity at design conditions 1-24 hours at design conditions 1-40 tonnes (10,000 gal)	See Part I, Section 4.7.2 and Part II, Section 10.0. Preliminary calculations indicate that each mill would have a capacity of approximately 45 tonnes/h (50 ton/h) based on the FGD system design conditions and the reagent preparation system operating hours specified below.
Ball Mill Type	▸ Horizontal ▸ Vertical	See Part II, Section 10.0.
Operating Hours	8 hours per day, 7 days per week	See Part I, Section 4.7.2. This can vary depending on utility preferences and the desire to minimize the number and capacity of ball mills. Fewer operating hours increase the required capacity of the reagent slurry storage tank(s).
Design DBA Concentration in Absorber Reaction Tank	1000 mg/L	See Part I, Section 4.7.3. The additive is usually fed into the reagent slurry storage tank. The design concentration in the reaction tank is needed for the vendor to size the chemical additive feed equipment.
Materials of Construction Tanks Reagent slurry storage tank Chemical additive storage tank Piping Reagent slurry piping Chemical additive piping	 ▸ Rubber-lined carbon steel ▸ Reinforced resin-lined carbon steel ▸ Type 304 stainless steel ▸ Rubber-lined carbon steel ▸ Type 304 stainless steel	See Part I, Section 4.7.4. All limestone reagent preparation equipment should be selected considering that reclaim water with 20,000 mg/L chlorides may be used as the primary slurry makeup water. The vendor must use more erosion- or corrosion-resistant materials where required by specific design conditions.

Table 3-7

Byproduct Dewatering System Design Parameters

Parameter	Value	Notes
Type of Dewatering Equipment		See Part I, Section 4.8 and Part II, Sections 11.0, 12.0, 13.0, and 14.0. Because this system is producing commercial-quality gypsum and is being retrofit at a existing site where space is at a premium, only hydrocyclones will be allowed for primary dewatering. Some systems may not require primary dewatering prior to the secondary dewatering equipment.
Primary dewatering	▸ Hydrocyclone	
Secondary dewatering	▸ Horizontal vacuum filter ▸ Centrifuge	
Number and Capacity		See Part I, Sections 4.8 and 6.0.
Primary dewatering	20% spare hydrocyclones (1 spare for every 5 operating), minimum	
Secondary dewatering	2 operating (minimum) units plus 1 spare unit of the same size	This would permit three 50%-capacity units, four 33%-capacity units, etc.
Underflow storage tank	1 to 12 hours at design conditions	
Materials of Construction		See Part I, Section 4.8.5 and Part II, Sections 1.0, 12.0, 13.0, and 14.0. All materials of construction must be suitable for highly abrasive conditions and slurry chloride levels up to 20,000 mg/L. The vendor must use more erosion- or corrosion-resistant materials where required by specific design conditions.
Primary dewatering equipment	▸ Rubber-lined hydrocyclones	
Secondary dewatering equipment	▸ Reinforced resin-lined carbon steel ▸ Rubber-lined carbon steel ▸ FRP ▸ Polypropylene	
Underflow storage tank	▸ Reinforced resin-lined carbon steel ▸ Chlorobutyl rubber-lined carbon steel ▸ Ceramic tile-lined carbon steel or concrete	

Table 3-8

Absorber Spray Pump Design Parameters

Parameter	Value	Notes
Type	Horizontal centrifugal	See Part II, Section 5.1.1.
Design margins	10% on flow, 15% on head	See Part II, Section 5.3.3.
Maximum capacity per pump	2200 L/s (35,000 gpm)	See Part II, Section 5.2.3.
Speed reducer	▸ Below 300 kW--belt or gear ▸ Above 300 kW--gear	See Part II, Section 5.2.3.
Shaft seal type	Mechanical	See Part II, Section 5.2.3.
Materials of construction Impeller	▸ Rubber-lined casing	See Part II, Section 5.3
Casing	▸ Hard metal impeller ▸ Rubber-lined cast iron	See Part II, Section 5.3

Table 3-9

Tank Agitator Design Parameters

Parameter	Value	Notes
Type	Top- or side-entry	See Part II, Section 6.1.
Maximum impeller tip speed	5.0 m/s (16.5 ft/s)	See Part II, Section 6.2.2.
Side-entry shaft seal type	Mechanical	See Part II, Section 6.2.2.
Materials of construction		
Top-entry agitators	▸ Chlorobutyl rubber-lined impellers and shafts	See Part II, Section 6.3.
Side-entry agitators	▸ Chlorobutyl rubber-lined or erosion- and corrosion-resistant alloy	See Part II, Section 6.3.

Table 3-10

Piping Design Parameters

Parameter	Value	Notes
Maximum fluid velocity		See Part II, Section 7.2.3.
Clear liquor	▸ Maximum--3 m/s (10 ft/s)	
Slurry	▸ Maximum--2.4 m/s (8 ft/s) ▸ Minimum--1.5 m/s (5 ft/s)	
Materials of Construction		See Part II, Section 7.3.
Makeup water piping	▸ Carbon steel ▸ FRP ▸ EHDPE	
Process slurry	▸ Rubber-lined carbon steel ▸ FRP with AR lining ▸ EHDPE	
Process liquor	▸ Rubber-lined carbon steel ▸ FRP ▸ EHDPE	
Chemical additive	▸ 300-series stainless steel	

Table 3-11

Valve Design Parameters

Parameter	Value	Notes
Type		See Part II, Section 8.1, Table 8-1.
Slurry isolation	▸ Packingless knifegate	
Process liquor isolation	▸ Knifegate ▸ Pinch/diaphragm ▸ Butterfly ▸ Ball/plug	
Slurry/process liquor flow control	▸ Pinch/diaphragm/concentric orifice ▸ Butterfly (clear liquor only) ▸ Ball/plug	
Chemical additive isolation/flow control	▸ Ball/plug ▸ Gate ▸ Globe	
Materials of Construction		See Part II, Section 8.3.
<u>Slurry isolation</u>		
Body	▸ Rubber-lined carbon steel	
Blade	▸ Austenitic stainless steel	▸ Because the knifegate blade is normally completely isolated from the slurry, it can be fabricated from less corrosion-resistant materials than the piping system in which it is installed.
<u>Process liquor isolation</u>		
Body	▸ Rubber-lined carbon steel	
Internals	▸ Rubber-lined carbon steel ▸ Corrosion resistant alloy ▸ Plastic-lined carbon steel	

Table 3-11

(Continued)

Parameter	Value	Notes
Materials of Construction (continued)		See Part II, Section 8.3.
<u>Slurry/Process liquor flow control</u>		
Body	▸ Rubber-lined carbon steel	
Internals	▸ Rubber ▸ Ceramic-lined carbon steel	
<u>Chemical additive isolation/flow control</u>		
Body	▸ 300-series stainless steel	
Internals	▸ 300-series stainless steel	

Table 3-12

Spray Nozzle Design Parameters

Parameter	Value	Notes
Type		See Part II, Section 9.2.1, Table 9-1.
Absorber slurry spray	▶ Full-cone ▶ Hollow-cone (tangential or axial)	
Absorber packing flooding	▶ Full-cone	
ME wash	▶ Full-cone	
Vacuum filter wash	▶ Full-cone (flat spray pattern)	
Emergency quench	▶ Full-cone ▶ Hollow-cone (tangential or axial)	
ME wash nozzle spray angle	90°, maximum	See Part II, Section 9.2.2.
Nozzle attachment		See Part II, Section 9.2.2.
Absorber slurry spray	▶ Flanged ▶ Mechanical coupling	
Absorber packing flooding	▶ Flanged ▶ Mechanical coupling	
ME wash	▶ Flanged ▶ Screwed	
Vacuum filter wash	▶ Flanged ▶ Screwed	
Emergency quench	▶ Flanged ▶ Screwed	

Table 3-13

Process Tank Design Parameters

Parameter	Value	Notes
Type		See Part II, Section 16.1 and 16.2.
Thickener/hydrocyclone overflow tank	Above-grade, open-top, non-agitated	
Thickener/hydrocyclone underflow tank	Above-grade, open-top, agitated	
Makeup/ME wash water tank	Above-grade, open-top, non-agitated	
Reaction tank emergency dump tank	Above-grade, open-top, agitated	
Capacity		See Part II, Section 16.2.
Thickener/hydrocyclone overflow tank	12 hours at design conditions	
Thickener/hydrocyclone underflow tank	24 hours at design conditions	
Makeup/ME wash water tank	8 hours at design conditions	
Reaction tank emergency dump tank	Same volume as reaction tank	

Table 3-13

(Continued)

Parameter	Value	Notes
Materials of Construction		See Part II, Section 16.3.
Thickener/hydrocyclone overflow tank	▸ Reinforced resin-lined carbon steel	▸ Corrosive conditions--20,000 mg/L chloride.
Thickener/hydrocyclone underflow tank	▸ Reinforced resin-lined carbon steel ▸ Chlorobutyl rubber-lined carbon steel ▸ Ceramic tile-lined carbon steel or concrete	▸ Corrosive conditions--20,000 mg/L chloride. ▸ Erosive conditions--45 to 55% solids.
Makeup/ME wash water tank	▸ Painted carbon steel	▸ Mildly corrosive condition, 110 mg/l chloride.
Reaction tank emergency dump tank	▸ Reinforced resin-lined carbon steel ▸ Chlorobutyl rubber-lined carbon steel ▸ Ceramic tile-lined carbon steel or concrete	▸ Corrosive conditions--20,000 mg/L chloride. ▸ Erosive conditions--25% solids.

process that the utility engineer will follow in comparing the proposals received. It is advantageous to the utility to provide the vendors with some of the more important economic factors so that these design tradeoffs will be made considering the factors that are most critical to the utility. The following is a list of economic evaluation factors that will be used in the case study and that could be included in the equipment specification:

- Levelized fixed charge rate, 16.5%;
- Annual capacity factor, 65%;
- Annual cost levelizing factor (30 years), 1.618;
- Levelized reagent cost, $14.50 per tonne;
- Levelized SO_2 emission credits, $160 per tonne;
- Levelized gypsum revenue, $2.55 per tonne;
- Levelized gypsum moisture bonus, $0.31 per tonne for each 1% under 10% moisture in the final dewatered material.
- Levelized electric power cost, $0.080 per kWh;
- Levelized cost of flue gas pressure drop, $780,000 per year per kPa of pressure drop between the ID fan outlet and the stack breeching (i.e., the vendor's scope of supply);
- Levelized service water cost, $0.98 per m^3;
- Levelized cooling tower blowdown (FGD system makeup water) cost, $0.25 per m^3;
- Levelized wastewater treatment cost, $0.40 per m^3; and
- Levelized operating/maintenance labor cost, $40 per hour.

Because the case study will be evaluated using the capital recovery period method (see Part III, Section 3.3--Economic Evaluation of Total Cost), the annual costs are expressed in terms of levelized costs rather than first-year costs.

3.6 Guarantees and Warranties

The specified performance guarantees and equipment warranties are based on the data provided in the specification. The specification should clearly state that the FGD system must be able to meet the guarantees and warranties at any operating conditions that fall within the specified data ranges for coal (Table 2-1), reagent quality (Table 2-2), makeup water qualities (Table 2-4), and flue gas characteristics (Table 3-1). The FGD system must be operated within the requirements of the specified process parameters (Section 3.3).

3.6.1 Performance Guarantees

Table 3-14 presents the performance guarantees that will be included in the case study specification. Depending on site-specific factors, the number of guarantees specified could be expanded or reduced. Several of the additional guarantees that might be required at another site or under a different set of assumptions are listed in Table 3-15. It is very important that the specification require all of the specified guarantees to be met simultaneously. Otherwise, the vendor has the option of optimizing the system to meet only a few of the guarantees at a time, then changing the system configuration to meet another set. This is critical for related guarantees such as SO_2 removal efficiency, byproduct solids quality, and maximum electric power demand.

The specification will also contain requirements that the performance guarantees will be tested during two test programs. The first test program will be conducted after the vendor certifies that the equipment is ready for testing. If the FGD system does not meet all of the performance guarantees, the system will be modified at the vendor's expense and the first test program will be repeated. The second test will be conducted 12 months after the FGD system demonstrates compliance with the guarantees. The system reliability test will be conducted between the first and second performance tests. The specification will specifically state that the vendor is responsible for any system or equipment modifications required to meet the performance or reliability guarantees.

Table 3-14

Case Study Specification Guarantees

Parameter	Value
Minimum SO_2 removal efficiency, %	95
Outlet particulate matter emissions, $\mu g/m^3$	No net increase from inlet concentration
Maximum ME liquid carryover rate, L/s-m^2	0.0002
Byproduct solids quality	See Table 2-3
Maximum flue gas pressure drop, kPa	Vendor-supplied value
Makeup water requirement, Instantaneous, m^3/h 24-hour average, m^3/h	 Vendor-supplied value Vendor-supplied value
Service water requirement, Instantaneous, m^3/h 24-hour average, m^3/h	 Vendor-supplied value Vendor-supplied value
Liquid blowdown rate, m^3/h	Vendor-supplied value
Maximum electric power demand, Instantaneous, kW 24-hour average, kW	 Vendor-supplied value Vendor-supplied value
Minimum system availability or maximum equivalent forced outage rate, %	Vendor- or utility-supplied value

Table 3-15

Other Potential Specification Guarantees

Parameter	Value
Minimum reagent utilization, %	Vendor- or utility-supplied value
Minimum reagent grind fineness, % less than 40 μm	Vendor- or utility-supplied value
Maximum chemical additive consumption, kg/h	Vendor- or utility-supplied value
Minimum L/G, L/1000 m^3	Utility-supplied value
Minimum calcium sulfite oxidation, %	Utility-supplied value
Minimum reheated flue gas temperature, °C	Utility-supplied value
Maximum reheater energy consumption, kJ/h (depends on reheat energy source)	Vendor-supplied value
Wastewater composition, maximum or minimum by component	Vendor- or utility-supplied values
Maximum byproduct moisture content, %	Vendor-supplied value

Typically, the specification contains wording regarding payment of monetary damages by the vendor if the system cannot be modified to meet the specified guarantees. While such procedures are useful in compensating the utility for excessive power consumption or makeup water use, monetary damages may not be useful if the FGD system is unable to meet its required SO_2 removal efficiency or to produce commercial-quality gypsum. In most cases, there is an upper limit to the vendor's liability; therefore, careful review of the vendor's proposal is critical to identifying any design deficiencies early in the proposal review process when the vendor's design can be modified at the least cost.

Most commonly, the actual flue gas conditions during the test programs will not be exactly those contained in the specification. The specified conditions contained design margins that are not likely to be experienced in actual operation. Therefore, the specification should require the vendor to provide correction curves for extrapolating the performance of the FGD system based on the actual test conditions. These curves should be guaranteed and will be the basis for calculating any monetary damages.

3.6.2 Equipment Warranties

The FGD system vendor will be required to provide the following equipment warranties:

- The FGD system will be capable of stable, automatic operation and load-following from 25% load through the specified maximum design conditions.
- The materials used in fabrication of the FGD system components will be suitable for the erosive and corrosive conditions present.* The utility-specified materials are minimum requirements. If the vendor determines that more erosion- or corrosion-resistant materials are required by the

* Although this phrase is found in many FGD system specifications, it is effective only if specific measurements of material suitability are provided. For example, the rubber linings of slurry pumps are specified to have a minimum life of one year in normal service.

vendor's design, alternative materials meeting these requirements shall be used.

- Either the absorber module shell and internals shall be capable of withstanding a temperature excursion to 370°C for 15 minutes without permanent damage, or provisions shall be included in the design to quench the flue gas during the loss of electrical power to the FGD system under these conditions.

- The capacities of the reagent preparation equipment and byproduct handling equipment shall be not less than the rates stated in the vendor's equipment data sheets.

- When closed, the inlet and outlet isolation dampers shall be capable of providing man-safe isolation of the absorber module with the generating unit operating at design conditions using the bypass duct.

4.0 EVALUATION OF PROPOSALS

The technical and economic evaluation of the proposals received from the FGD system vendors requires the combined efforts of many individuals over a time period lasting from several weeks to several months. The duration of this effort depends upon the number of evaluators assigned to the project, the number and quality of the proposals received, the number of alternatives considered, and other factors. The evaluation team is expected to prepare a proposal evaluation report, which often can exceed 100 pages of text, tables, and figures and covers a wide variety of technical and economic issues.

This example evaluation will describe two case study proposals, provide technical and economic evaluations of each, and provide a purchase recommendation.

4.1 Proposals Received

It is not practical to provide a complete, detailed proposal evaluation report in this case study. Instead, the major aspects of the evaluation process will be illustrated by reviewing two hypothetical proposals. To simplify the example, the two proposals evaluated are similar in many technical aspects, as shown in Table 4-1. Actual proposals received from FGD system vendors often can vary much more widely. Critical vendor performance guarantees are presented in Table 4-2.

4.1.1 Vendor A's Proposal

The proposal submitted by Vendor A is illustrated in Figures 4-1, 4-2, and 4-3. The proposed FGD system uses a single absorber module, 17.2 m in diameter,* with an integral reaction tank and five spray levels (one of which is a spare). Each spray level has two independent spray headers, and each header is served by a single absorber spray pump for

* In order to simplify the discussions of the example proposals, only metric units will be used in the case study proposal evaluation.

Table 4-1

Technical Summary of Proposals Received

Item	Specified	Vendor A	Vendor B
Ductwork and Dampers			
Inlet ductwork flue gas velocity, m/s	18.3	18.3	18.3
Outlet ductwork flue gas velocity, m/s	15.2	15.2	15.2
Bypass ductwork flue gas velocity, m/s	24.4	24.4	24.4
Inlet damper type	Man-safe guillotine	Man-safe guillotine	Man-safe guillotine
Outlet damper type	Man-safe guillotine	Man-safe guillotine	Man-safe guillotine
Bypass damper type	Double multi-louver	Double multi-louver	Double multi-louver
Materials of construction			
Inlet duct (downstream of damper)	See Table 3-3 for specified materials of construction.	C-276 alloy plate.	C-276 alloy plate.
Outlet duct & bypass duct (downstream of damper)		1.6-mm C-276 wallpaper on carbon steel.	Foamed borosilicate glass block on carbon steel.
Inlet damper		C-276 alloy plate.	C-276 alloy plate.
Bypass damper (upstream/downstream)		Carbon steel/C-276 alloy plate.	Carbon steel/C-276 alloy plate.
Outlet damper		C-276 alloy plate.	C-276 alloy plate.
Absorber Module			
Number/capacity of modules	1-100%	1-100%	1-100%
Module diameter, m	NS*	17.2	17.4
Gas velocity, m/s	3.0	3.05	3.02
Number of spray levels, operating/spare	1 spare	4+1	5+1
Number of spray headers per level	NS	2	1
Spacing between spray headers, m	NS	1.5	1.5
Liquid to gas ratio, L/Nm^3	NS	18.0	17.7
Materials of construction	See Table 3-4 for specified materials of construction.	3.5-mm C-276 alloy cladding on carbon steel.	AR** reinforced resin-lined carbon steel.
Absorber Reaction Tank			
Tank diameter/depth, m	NS	17.2/9.2	20.4/7.0
Slurry solids retention time, h	15	15	15
Slurry solids, %	NS	15	15
Number and type of agitators	NS	4 side-entry.	5 side-entry.
Materials of construction	See Table 3-4 for specified materials of construction.	3.5-mm C-276 alloy cladding on carbon steel.	AR reinforced resin-lined carbon steel.

Table 4-1

(Continued)

Item	Specified	Vendor A	Vendor B
Mist Eliminators			
Orientation	Vertical or horizontal	Vertical	Vertical
Number of stages	2	2	2
Gas velocity, m/s	3.0	3.05	3.02
Wash intensity			
Front of first stage	1.0	1.0	1.1
Back of first stage	0.34	0.35	0.34
Front of second stage	0.34	0.35	0.34
Materials of construction	See Table 3-5 for specified materials of construction.	Fiber-reinforced plastic (FRP).	Polysulfone.
Reagent Preparation System			
Mill type	Horizontal or vertical	Vertical	Horizontal
Number and capacity of mills	2-100%	2-100%	1-100%
Reagent slurry solids, %	NS	35	40
Reagent slurry storage tank volume, m^3	NS	2 x 350 (24 h total)	1 x 685 (27 h)
DBA storage tank volume, tonnes	12	12	13
Materials of construction			
Reagent slurry storage tank	See Table 3-6 for specified materials of construction.	AR reinforced resin-lined carbon steel.	AR reinforced resin-lined carbon steel.
DBA storage tank		FRP.	Type 304 stainless steel.
Byproduct Solids Dewatering System			
Primary dewatering hydrocyclones	20% sparing.	Central cluster of 6 (1 spare).	One cluster of 4 (1 spare) per vacuum filter
Underflow storage tank volume, m^3	NS	425 (12 h)	None
Secondary dewatering equipment type	Horizontal vacuum filter or centrifuge.	Horizontal vacuum filter.	Horizontal vacuum filter
Number of secondary dewatering equipment	2 operating + 1 spare.	2 operating + 1 spare.	2 operating + 1 spare
Materials of construction			
Hydrocyclones	See Table 3-7 for specified materials of construction.	Rubber-covered carbon steel.	Rubber-covered carbon steel.
Underflow storage tank		AR reinforced resin-lined carbon steel.	Not applicable.

Table 4-1

(Continued)

Item	Specified	Vendor A	Vendor B
Absorber Spray Pump			
Design margins (head/flow), %	10/15	10/15	10/15
Capacity, L/s	2200	1536	2415
Speed reducer	Belt or gear.	Belt.	Gear.
Seal type	Mechanical.	Mechanical.	Mechanical.
Materials of construction			
Casing	See Table 3-8 for specified materials of construction.	Rubber-lined ductile iron.	Rubber-lined ductile iron.
Impeller		Rubber-covered ductile iron.	Hard metal.
Piping			
Maximum fluid velocity, m/s			
Clear liquor	3.0 max	3.0	3.0
Slurry	2.4 max/1.5 min.	3.0 max/1.5 min.	3.0 max/1.5 min.
Materials of construction			
Makeup water	See Table 3-10 for specified materials of construction.	Carbon steel & FRP	Carbon steel & FRP
External absorber spray piping		Rubber-lined carbon steel.	FRP with AR lining.
Internal headers		Rubber-lined & -coated carbon steel.	FRP with AR lining and coating.
Reagent slurry		Rubber-lined carbon steel.	FRP with AR lining.
DBA		FRP.	304 stainless steel.
Process liquor		FRP.	FRP & EHDPE.
Spray Nozzles			
Absorber			
Type & spray angle, degrees	Full- or hollow-cone/NS.	Hollow-cone/120.	Hollow-cone/120.
Attachment method	Flanged or mech. coupling.	Flanged.	Flanged.
Mist eliminator wash			
Type & spray angle, degrees	Full cone/90.	Full-cone/90.	Full-cone/90.
Attachment method	Flanged or screwed.	Screwed.	Screwed.
Material of construction			
Absorber	See Table 3-12 for specified materials of construction.	Silicon carbide.	Silicon carbide.
Mist eliminator		904L stainless steel.	FRP.

* NS = not specified   ** AR = abrasion-resistant

Table 4-2

Vendor Guarantees

Parameter	Specified	Vendor A	Vendor B
SO_2 removal efficiency, %	95	95	96
Outlet particulate matter emissions, mg/Nm^3	No net increase	No net increase	No net increase
Maximum ME liquid carryover rate, $L/s\text{-}m^2$	0.0002	0.0002	0.0002
Byproduct composition*			
Gypsum, % (dry weight)	95 min.	95	95
Inerts, % (dry weight)	5 max.	5	5
Chlorides, ppm (dry weight)	100 max.	100	50
Moisture content, %	15 max.	10	8
Reagent utilization, %	NS**	97	95
Flue gas pressure drop, kPa			
Design conditions	NS	1.49	1.61
65% load	NS	0.61	0.66
Total makeup water consumption, m^3/h			
Design conditions	NS	124.6	123.5
65% load	NS	81.0	80.3
Service water consumption, m^3/h			
Design conditions	NS	14.4	18.0
65% load	NS	14.4	18.0
Liquid blowdown rate, m^3/h			
Design conditions	NS	12.2	12.6
65% load	NS	7.9	7.9
Electric power demand, kW			
Design conditions	NS	10,900	11,000
65% Load	NS	7,000	7,500
Minimum system availability, %	NS	97	96

* Selected byproduct guarantee requirements (See Table 2-3).
** NS = not specified.

Note: 1 kPa = 4 inwg; 1 m^3/h = 4.4 gpm

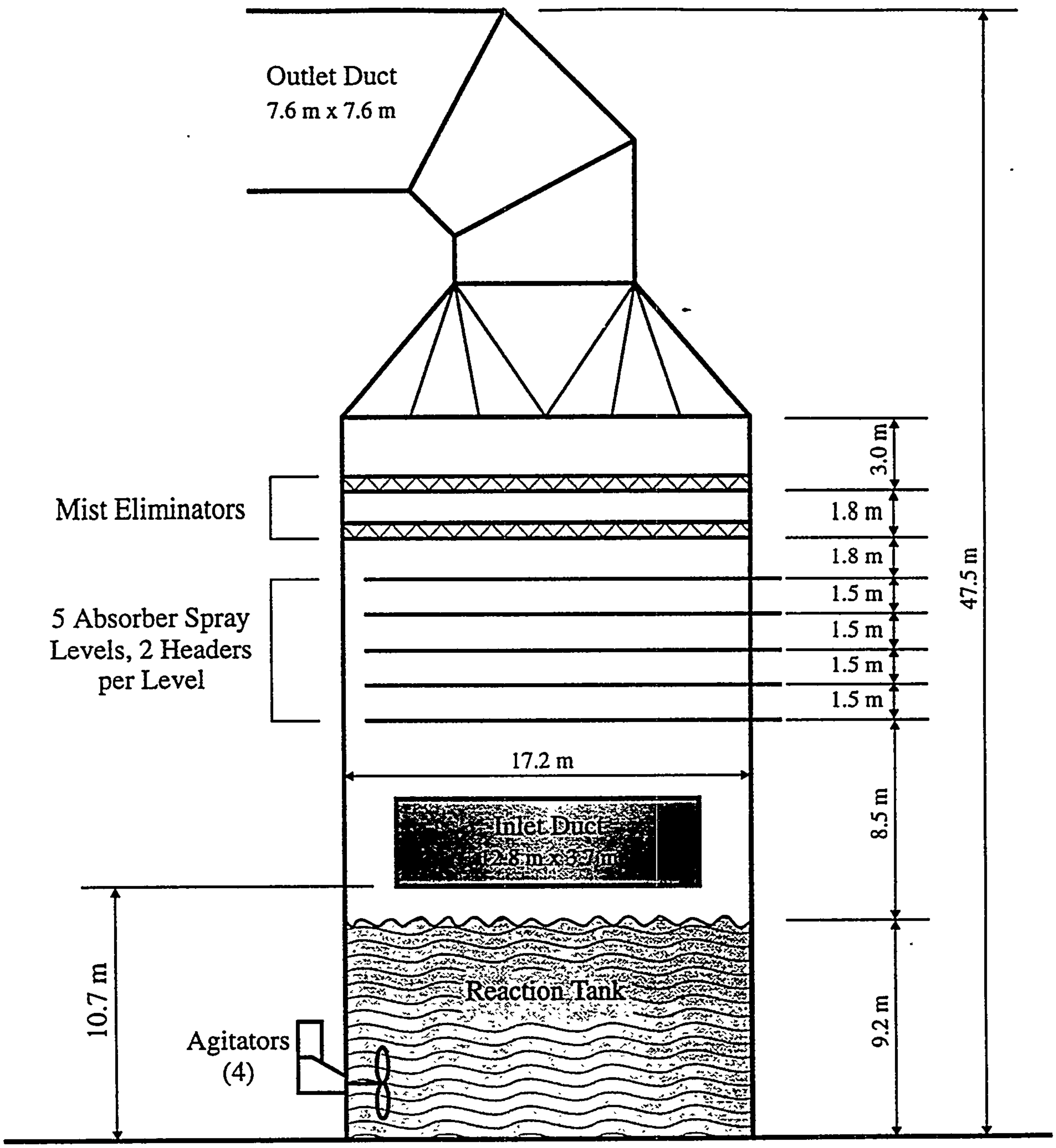

Figure 4-1. Vendor A Absorber Module Elevation

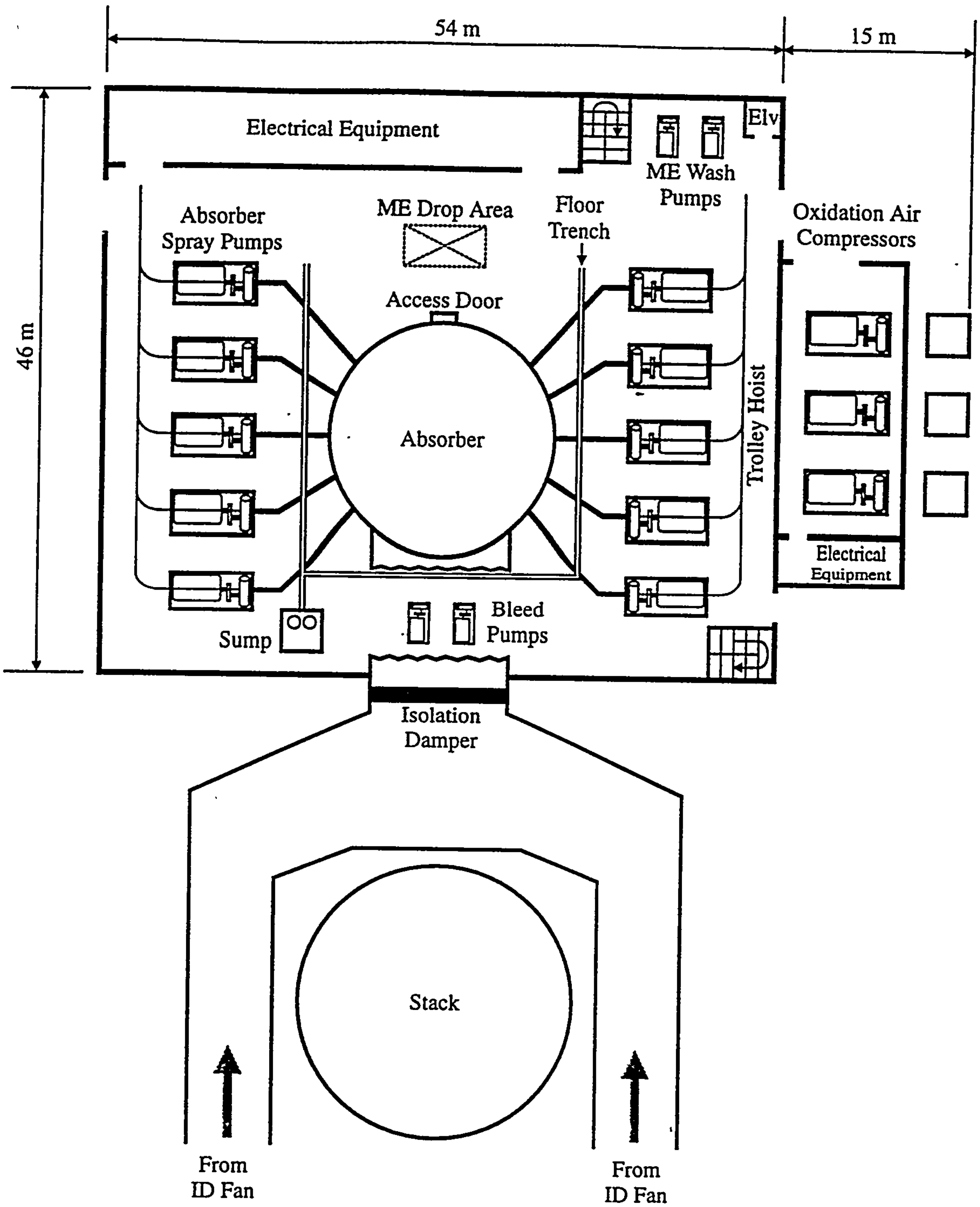

Figure 4-2. Vendor A Absorber Module Plan View

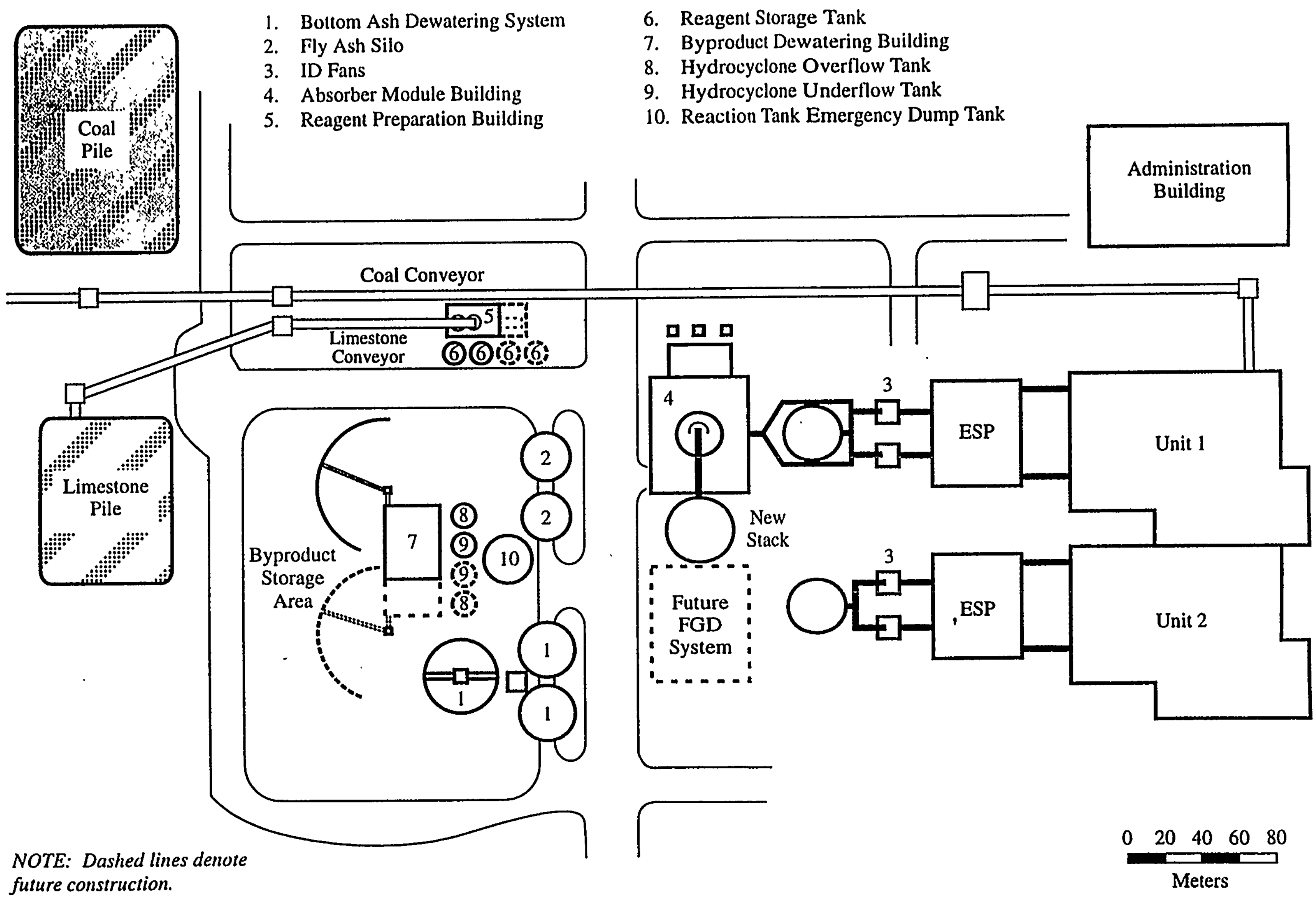

Figure 4-3. Vendor A Overall Layout

a total of 10 pumps. The reaction tank is 9.2 m deep and provides the specified 15 hours of solids retention time. The inlet duct is rectangular in cross section, 12.8 m wide by 3.7 m high. The absorber outlet is a truncated cone connecting to rectangular cross section ductwork, 7.6 m wide by 7.6 m high. The total height of the absorber from grade to the roof of the outlet ductwork is 47.5 meters.

Vendor A has elected to fabricate the absorber module from C-276, a corrosion-resistant nickel alloy. The proposed inlet duct material is solid alloy plate, while the absorber and reaction tank are fabricated of alloy-clad carbon steel. The outlet duct is carbon steel with an alloy wallpaper.*

Vendor A has proposed to use two 45-metric-ton-per-hour vertical ball mills to produce the required limestone reagent slurry. Each vertical mill is preceded by a 45-metric-ton-per-hour hammer mill to reduce the maximum size of the limestone feed to 6 mm. The 35% solids slurry is stored in two 350-m^3 tanks. The proposed design allows either ball mill to discharge to either slurry storage tank.

Primary dewatering would be provided by a central hydrocyclone cluster consisting of six hydrocyclones (one of which is a spare) discharging into a 425-m^3 underflow storage tank. The 50% solids underflow can be pumped to any of three 50%-capacity horizontal vacuum filters for secondary dewatering.

Vendor A has guaranteed the specified 95% SO_2 removal efficiency based on a liquid-to-gas ratio (L/G) of 18.0 L/Nm^3 and a reagent utilization of 97 percent. The performance guarantees are discussed in detail in a later section.

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* See Part I, Section 5.0--Materials-of-Construction Options for detailed descriptions of the proposed materials of construction.

4.1.2 Vendor B's Proposal

As shown in Figures 4-4, 4-5, and 4-6, Vendor B has proposed a similar FGD system but with some significant variations. Vendor B's proposed system uses a single absorber module with an integral reaction tank as did Vendor A's, but with six spray levels (one spare), and only one spray header per level. Typically, the additional spray level would increase the overall height of the absorber by approximately 1.5 meters. However, to reduce the absorber's overall height, Vendor B has proposed a reaction tank that is 3 m larger in diameter than the absorber. This reduces the reaction tank depth from 9.2 m to 7.0 m without reducing the solids retention time. The absorber outlet uses a truncated cone which connects to a rectangular outlet duct 11.1 m wide by 6.0 m high. The outlet duct transition is more abrupt than Vendor A's proposal resulting in less ductwork. As a result, the overall height from grade to the roof of the absorber outlet duct is 41.1 m, 6.4 m less than Vendor A's design.

Vendor B has proposed using C-276 alloy only in the inlet duct. The absorber module and reaction tank are fabricated of abrasion-resistant, reinforced resin-lined carbon steel. The outlet ductwork is carbon steel, lined with foamed borosilicate glass block.

Vendor B has taken exception to the specification and proposes to use a single 45-metric-ton-per-hour horizontal ball mill. This exception will be discussed later. The mill will produce a 40% solids reagent slurry which will be sent to a 685-m^3 reagent slurry storage tank. No hammer mills are required by the horizontal ball mill.

Vendor B has eliminated the need for a hydrocyclone underflow storage tank by proposing a dedicated cluster of four hydrocyclones for each of three 50%-capacity horizontal vacuum filters. In the proposed system, a hydrocyclone cluster and vacuum filter would operate as a single unit. One hydrocyclone in each cluster would be a spare. The advantages and disadvantages of this approach will be discussed later.

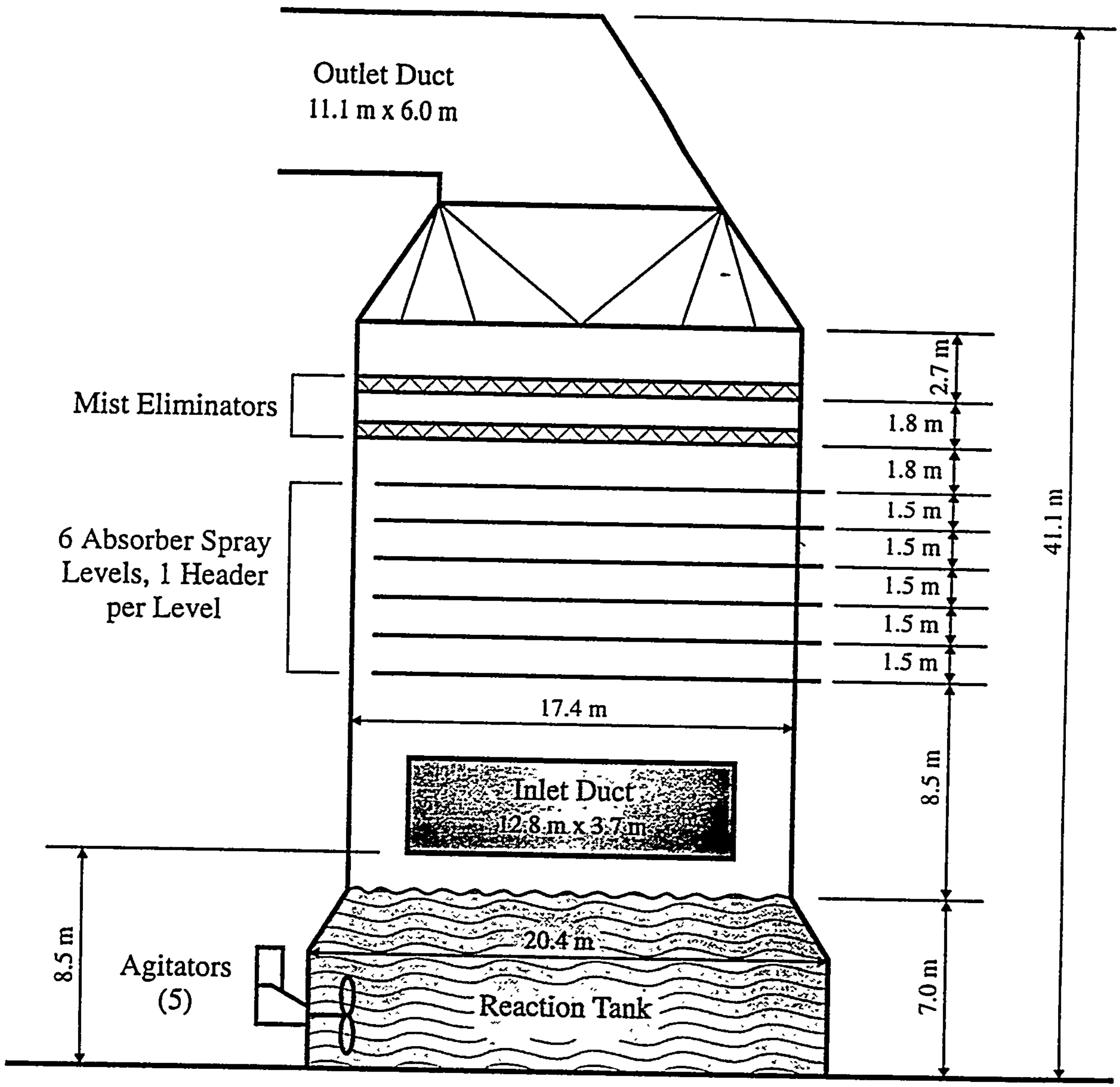

Figure 4-4. Vendor B Absorber Module Elevation

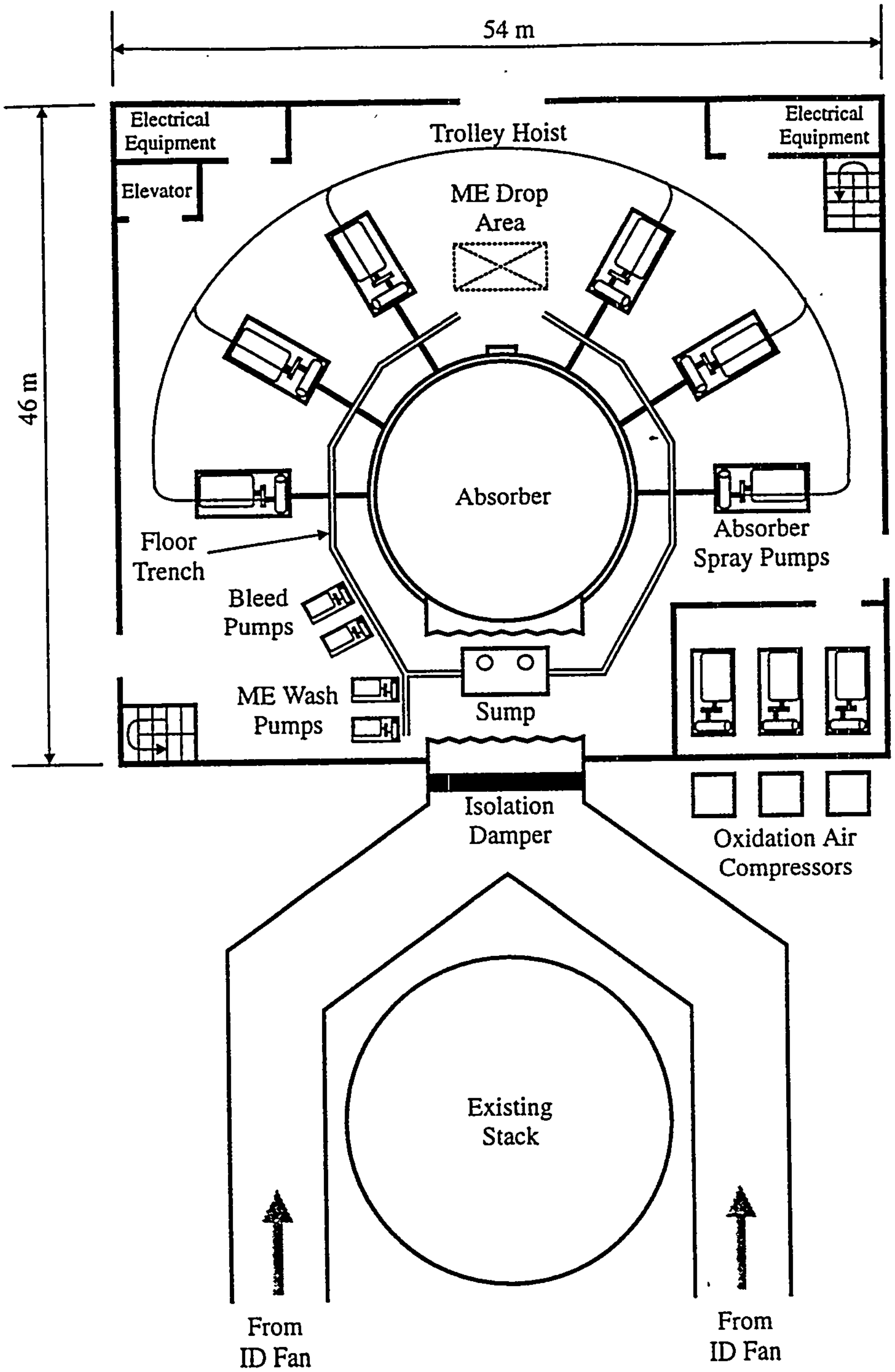

Figure 4-5. Vendor B Absorber Module Plan View

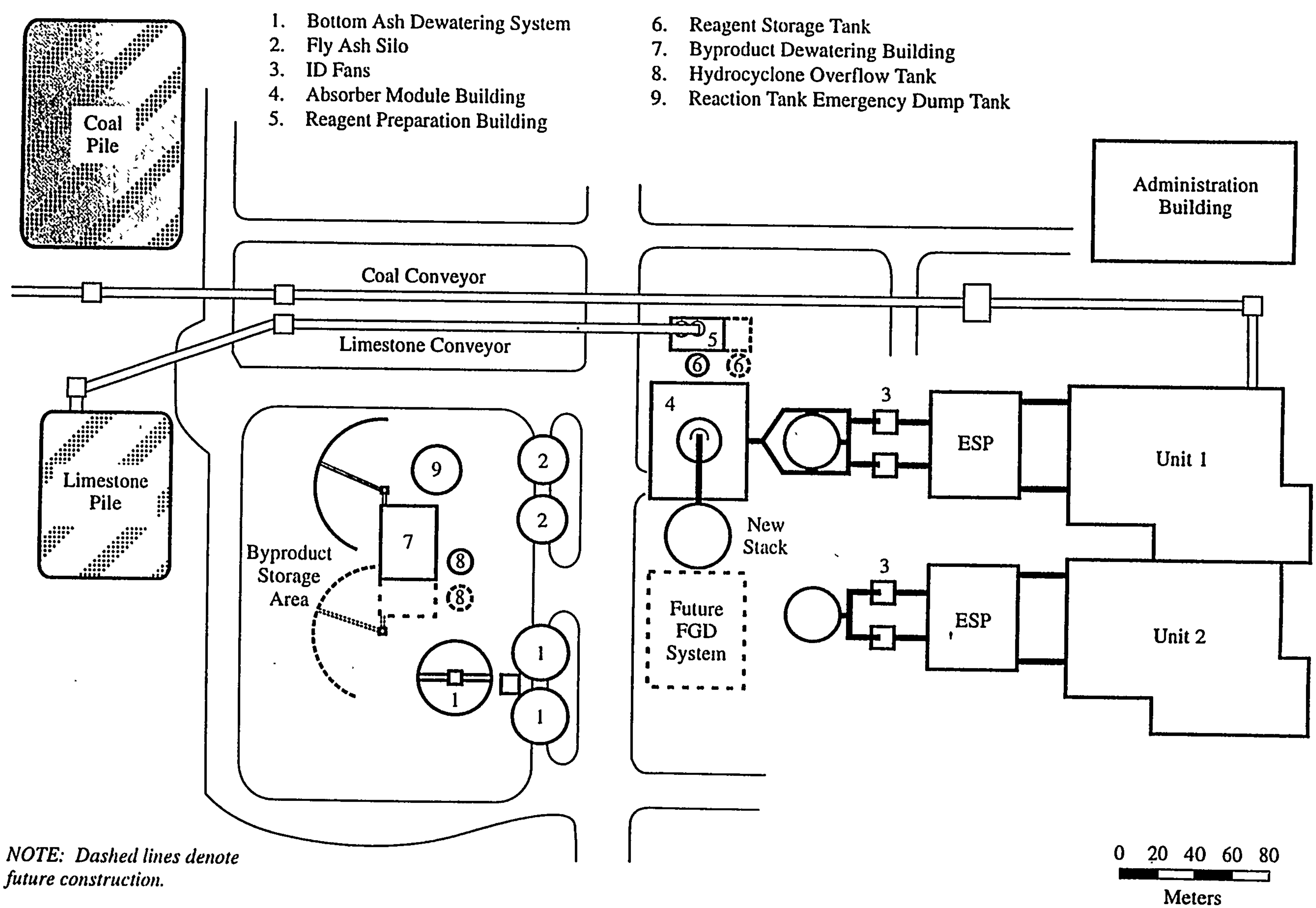

Figure 4-6. Vendor B Overall Layout

By slightly reducing the reagent utilization to 95%, Vendor B has been able to guarantee 96% SO_2 removal efficiency at approximately the same L/G ratio as Vendor A. There would be a small increase in the unreacted $CaCO_3$ content of the byproduct solids, but the specified byproduct quality would still be met.

4.2 Technical Evaluation of Proposals

Part III, Section 2.0--Technical Evaluations lists the following as important aspects of the technical evaluation:

- Does the proposal contain the specified performance guarantees?
- Does the proposal contain the specified equipment and material warranties?
- Does the proposed equipment meet the specified technical requirements?
- Does the proposed system cover the specified scope of supply?
- Are proposed exceptions to the equipment technical requirements and scope of supply acceptable?
- Is the proposed FGD system arrangement acceptable in terms of the plant area used and effects on other plant equipment and systems?
- Does the proposed FGD system arrangement allow for sufficient accessibility to efficiently maintain and operate the equipment?
- Is the proposed control and instrumentation equipment sufficient to achieve stable operation of the FGD process?
- Can the proposed design reasonably be expected to achieve the required performance guarantees?

This section of the manual will briefly review the two proposals in light of each of these criteria.

4.2.1 Evaluation of Performance Guarantees

A review of the vendor guarantees in Table 4-2 indicates that both vendors have met the specified performance guarantees. Vendor B, however, has guaranteed a slightly greater SO_2 removal efficiency and significantly drier byproduct solids.

While the benefit to a U.S. utility of a 1% increase in SO_2 removal efficiency might be quantified as increased SO_2 emission allowances, it will not be used in this proposal evaluation. Although not guaranteed, it is very likely that Vendor A's proposed system would perform equally well. An evaluation of the two proposals using the FGDPRISM™ program determined that both systems are predicted to achieve the specified SO_2 removal efficiency of 95% using the design operating conditions and proposed system designs. The use of FGDPRISM is discussed in Section 4.2.9--Evaluation of Ability to Achieve Performance Guarantees. It is assumed, therefore, that the systems are capable of achieving the same SO_2 removal efficiency.

Both vendors guarantee to meet the specified byproduct solids composition limits. Vendor B, however, has proposed a different horizontal vacuum filter supplier than Vendor A and guarantees a byproduct filter cake with only 8% moisture. This is a significant factor in the evaluation because the agreement with the wallboard production facility contains a reward clause of $0.31 per tonne (levelized for 30 years) for every 1% the byproduct moisture is below 10 percent. Therefore, achieving 8% byproduct moisture increases the revenue from byproduct solid sales by $0.61 per ton; an increase of 24% in the price. As with the vendors' SO_2 removal efficiencies, it is possible that Vendor A could also attain 8% cake moisture but has been more conservative in setting performance guarantees.

Flue gas pressure drop is a function of many factors, including the flue gas velocity and the number of spray levels. Vendor B's proposal has approximately the same module diameter as Vendor A's and one additional spray level. Therefore, it is not unexpected that Vendor B would have a slightly greater maximum flue gas pressure drop guarantee than Vendor A. Vendor B also has a slightly greater electric power demand despite a lower L/G. This is the result of Vendor B's use of higher pressure spray nozzles and less efficient absorber slurry pumps.

The total makeup water and service water demands of the two proposals are approximately equal, with Vendor B's proposal requiring 25% more service water than Vendor A. Although Vendor B's proposal uses less service water for washing the byproduct gypsum filter cake than Vendor A's, it uses more for mist eliminator washing. Perhaps because there is less moisture lost in the filter cake, Vendor B has a slightly greater liquid blowdown rate at maximum conditions. At 65% load, the blowdown rates for the two proposals are approximately equal. Since most of the water leaves the FGD system as evaporation in the outlet flue gas, it is typical that there is relatively little difference in the total amount of makeup water required by the two proposals.

Both vendors have guaranteed very high system availability (See Part I, Section 6.0--System Reliability). Vendor A's higher guaranteed availability value may reflect more operating experience with the proposed design or an attempt to achieve a competitive advantage. For the purposes of the evaluation, both proposals are considered to be equal.

4.2.2 Evaluation of Equipment Warranties

This case study does not contain a detailed description of an evaluation of equipment warranties. It is assumed that both vendors have passed along the mechanical equipment vendors' equipment warranties and that both have met the requirements of the specification.

4.2.3 Evaluation of Technical Requirements

An evaluation of the proposals' adherence to the technical requirements of the specification is often the most intensive and time-consuming activity in the proposal evaluation. In many cases, the vendors will identify where they have taken exception to the specification. In these cases, the evaluator can quickly determine whether it is acceptable or requires a technical adjustment. In many cases, however, the exception may be more subtle and difficult to identify.

In reviewing the technical data in Table 4-1, several technical exceptions can be found. Additional exceptions, not listed in the table, are also included as illustrations of typical vendor proposals.

Absorber Gas Velocity

Both vendors have exceeded the specified maximum absorber gas velocity of 3.0 m/s. These exceptions are considered acceptable for two reasons: 1) the values are only very slightly above the specified value and would not significantly affect the operation of the FGD system and 2) both vendors have provided the specified mist eliminator (ME) liquid carryover guarantee, which is a major factor in setting this value.

Materials of Construction

In general, both vendors have used the specified materials of construction throughout their proposal. In the absorber module, reaction tank, and outlet ductwork, however, the vendors chose very different design philosophies.

Vendor A has elected to make extensive use of C-class alloy construction. The absorber and reaction tank are fabricated of carbon steel with a 3.5-mm C-276 alloy cladding. The outlet duct is wallpapered with 1.6 mm of C-276 alloy. Both of the alloy linings are guaranteed by the vendor to last 15 years with only minor repairs to the weld seams and are expected to last the 30-year life of the system without replacement. Compared to Vendor B's proposed materials, this construction has a relatively higher initial capital cost but lower annual maintenance costs. The absorber spray piping is rubber-lined (outside the absorber module) or rubber-lined and -covered (inside the absorber module).

Vendor B has selected abrasion-resistant reinforced resin linings for the absorber and reaction tank. The outlet ductwork is lined with foamed borosilicate glass blocks. These materials generally have lower initial capital cost but higher annual maintenance costs. During the lifetime of the FGD system, the reinforced resin linings will need to be periodically patched and eventually replaced. Typically, a portion of the glass blocks must be replaced every year. For this case study, it is assumed that Vendor B has guaranteed the following:

- Annual replacement of the reinforced resin linings will not exceed 3% of the lined surface area;
- The reinforced resin lining replacement interval will be 10 years or greater; and
- Annual replacement of the glass block ductwork lining will not exceed 2% of the lined surface area.

Vendor B has proposed that the costs of lining replacements (material only) in excess of the guaranteed amounts will be paid by the vendor for the initial 10-year warranty period.

Vendor A has proposed the use of fiber-reinforced plastic (FRP) in lieu of the specified Type 304 stainless steel for fabrication of the DBA tanks and piping. A 50% solution of DBA must be maintained above 30°C at all times; therefore, the tank and piping must be heat-traced and insulated. While FRP is chemically suitable for the service, the heat-tracing design must ensure that localized temperatures above 100°C do not occur. Considering all factors, this material substitution is deemed acceptable.

Reagent Preparation System

Vendor A has proposed a reagent preparation system that meets all of the specification requirements. Vendor B, however, has cited operating data from their existing systems indicating that failure of the ball mill is extremely rare. As a result, Vendor B has offered a single 100% capacity horizontal ball mill. Space has been reserved in the reagent preparation building for a second mill that could be put in at a later date, if required. This space could also be used for a ball mill to serve Unit 2 if an FGD system is installed on that unit in the future. This is a major departure from the specification and will be the source of a technical adjustment charge.

Byproduct Solids Dewatering System

Vendor B has also proposed a byproduct solids dewatering system that does not meet all of the requirements of the specification. By providing a hydrocyclone cluster for each vacuum filter, Vendor B has been able to eliminate the underflow storage tank (filter feed tank) and the filter feed pumps. This results in a more compact design and lower capital and operating costs. However, the underflow storage tank provides a process equalization function and, as a result, minor, transient variations in the hydrocyclone operation or byproduct solids dewatering characteristics are dampened.

Absorber Spray Pump

Vendor B has proposed absorber spray pumps that exceed the specified maximum pump capacity of 2200 L/s by 10 percent. The vendor proposes to use a recently developed pump model that is manufactured by a company experienced in pumping FGD system slurries. The proposed pump, however, has limited operating experience in FGD service. Vendor B has submitted the relatively limited amount of data available to show that this pump has performed reliably in this and similar services.

Slurry Piping Fluid Velocity

Both vendors have proposed maximum fluid velocities in slurry piping of 3.0 m/s instead of the specified 2.4 m/s. Both vendors' proposals list successful application of slurry piping with this velocity.

Specified Electrical Motor Supplier

Vendor A has proposed the use of electric motor drives manufactured by a company not listed in the specification as an acceptable vendor. The utility proposal evaluation team determined that this supplier is not acceptable and required Vendor A to provide a cost adjustment for providing electric motors furnished by one of the specified suppliers.

Witnessed Absorber Spray Pump Test

The specification requires the absorber spray pump manufacturer to conduct a full-scale hydraulic performance test of a sample pump in the manufacturer's shop prior to shipment. This test must be witnessed by a representative of the utility. Vendor B has quoted conducting this test as an option and has provided a cost addition to the base proposal price. This test might have been waived if Vendor B had proposed a pump model that had extensive use in similar service; however, because a relatively new pump model was proposed, the witnessed test is considered to be necessary.

Alternative Valve Suppliers

Vendor A proposed the use of slurry control valves manufactured by a company not listed in the specification as an acceptable vendor. Vendor B made a similar proposal for the knifegate valves on the absorber suctions. The utility proposal evaluation team determined that neither of these alternative valve suppliers is acceptable. Vendor A furnished a cost adjustment for furnishing control valves from a specified supplier. Vendor B agreed to provide knifegate valves from a specified supplier at no additional cost.

4.2.4 Evaluation of Scope of Supply

A review of the vendor's proposals indicates that Vendor A has neglected to include the expansion joints at the interface between the utility- and vendor-furnished ductwork. Vendor B has included in his scope of supply the electrical grounding grid that will be provided and installed by another contractor under a separate specification. In all other instances, the vendors are assumed to meet the case study's specified scope of supply.

4.2.5 Evaluation of Technical Exceptions and Scope of Supply

The variations from the specified technical requirements and scope of supply may be handled in one of three ways:

- The exception can be accepted without cost adjustment;
- The vendor can be instructed to supply a cost adjustment for meeting the specification requirement as part of the proposal evaluation; or
- The utility can estimate the cost to comply with the specification (if necessary), and the actual cost can be discussed with the successful vendor as part of final negotiations.

In the case study, the higher-than-specified flue gas velocity in the absorber, the use of FRP for DBA tanks and piping, and the higher-than-specified slurry piping flow velocities are assumed to be acceptable to the utility evaluators. These are relatively minor variations and are generally covered either by performance guarantees or by equipment warranties.

Vendor B's proposal to furnish a single ball mill is deemed to be unacceptable to the utility evaluators, and the vendor was instructed to provide a cost adjustment for including a second mill. The vendor was not asked to add a second reagent slurry storage tank. Both vendors were also asked to provide cost adjustments for meeting the specified scope of supply. Vendor A provided the cost of adding the ductwork expansion joints and Vendor B provided a cost for deleting the electrical grounding system.

Vendor B's proposed elimination of the hydrocyclone underflow tank has both advantages and disadvantages. Elimination of the tank reduces congestion around the FGD system, eliminates the power requirements of the tank agitator and underflow pumps, and reduces maintenance costs associated with the tank lining, pumps, and slurry piping. These factors are considered to compensate for the loss of the desirable process equalization provided by the tanks.

Vendor B's proposal to use absorber spray pumps with capacities higher than specified will be discussed with the vendor in the event that this proposal is determined to have the lower total evaluated costs. This decision was based on the reputations of the FGD system vendor and pump manufacturer and on the relatively small increase above the specified maximum. Under different circumstances, the decision might have been to require the vendor to meet the specification requirements.

4.2.6 Evaluation of Equipment Arrangement

In general, Vendor A's proposed arrangement is somewhat less effective than Vendor B's. Vendor A has proposed the oxidation air compressors in a location that prevents the reagent preparation building from being located adjacent to the absorber module building. The proposed reagent preparation building location requires longer reagent slurry lines that must cross a plant road. This increases both initial capital cost and annual operating and maintenance (O&M) costs. Vendor A has placed reaction tank emergency dump tank in a location that would facilitate the joint use of this tank by a future FGD system installed on Unit 2. Vendor B's elimination of the underflow storage tank results in a less crowded arrangement of the byproduct dewatering equipment.

4.2.7 Evaluation of Maintenance Accessibility

Both vendors' proposed equipment arrangements provide for relatively good access to the critical FGD system components for maintenance. The separation of the absorber spray pumps from each other and the building wall could be increased to provide better access. Vendor B's arrangement of the absorber spray pumps minimizes congestion around the pumps.

4.2.8 Evaluation of Controls and Instrumentation

While both vendor's proposed controls and instrumentation equipment meet the specification requirements, Vendor A's control logic diagrams are assumed to be more complete. Vendor B has selected the same control instrument supplier used by the main generating plant, simplifying replacement parts inventories and operator training.

4.2.9 Evaluation of Ability to Achieve Performance Guarantees

As stated earlier, Vendor A has guaranteed to meet the specified SO_2 removal efficiency of 95% at design conditions while Vendor B has guaranteed 96 percent. The FGDPRISM program was used to evaluate both proposals using previous data from a similar open spray tower. The input data were modified as needed to match the vendors' proposed designs. The results of the simulation showed that Vendor A's design was predicted to achieve 94.7% removal efficiency and Vendor B's design was predicted to achieve 96.1 percent. The program also verified that both vendors' material balances are reasonable.

As discussed in Part III, Section 3.0--Proposal Evaluation, the use of FGDPRISM to verify SO_2 removal efficiency is limited. In this case study, the program's results can be interpreted to indicate that both designs are reasonably likely to meet the specified removal efficiency. The fact that Vendor A's predicted value is less than the specified 95% should <u>not</u> be considered an indication that the system would be unable to meet the specification. The program is not sufficiently accurate for this purpose. However, the fact that Vendor B's design is predicted to be slightly more efficient may be an indication that it is more conservatively designed, and that the vendor's guarantee of 96% SO_2 removal efficiency may be based on justified technical considerations.

4.2.10 Weighting of Technical Evaluation Criteria

Two examples of technical evaluation weighting tables for the case study proposals are presented in Tables 4-3 and 4-4. The proposals' scores on each of the technical evaluation factors are assumed to be the average of the scores from several technical reviewers who performed independent reviews of the proposals. As discussed in Part III, Section 2.10--Overall Weighting of Technical Evaluation Criteria, the evaluation of the technical aspects of the proposed FGD system designs is a subjective process using the specific utility's priorities. This is illustrated by the fact that Table 4-3 indicates that Vendor B's proposal has the higher technical score, while Table 4-4 indicates that Vendor A's proposal is technically superior. In both cases, the rating scores given to each technical aspect of the proposals are the same; the difference is the weighting factor assigned to each evaluation factor.

The weighting factors in Table 4-3 are the same as those used in Part III. This example gives 50% of the total weighting factors to the equipment arrangement category. The integration of the FGD system receives the highest weighting factor of all technical evaluation criteria. Each of the remaining major evaluation categories receives 10% of the total. This distribution indicates that the utility's greatest concern is the operation and maintenance of the FGD system and its influences on the existing station equipment. Using these weighting factors, Vendor B's proposal ranks above Vendor A's.

The weighting factors used in Table 4-4 shift a portion of the emphasis to the attainment of the technical requirements, giving this evaluation category 25% of the total weight. Table 4-4 also increases the weighting factor for maintainability/reliability from 10%

Table 4-3

Overall Technical Evaluation Weighting Table, Example 1

Evaluation Criteria	Weighting Factor	Vendor A		Vendor B	
		Score (1 - 10)	Weighted Score	Score (1 - 10)	Weighted Score
Attainment of Technical Requirements					
Chemical	5	5	2.5	6	3.0
Mechanical	2	5	1.0	4	0.8
Electrical	1	7	0.7	4	0.4
Structural	2	4	0.8	7	1.4
Subtotal	10		5.0		5.6
Attainment of Scope of Supply	10	4	4.0	5	5.0
Differential Support Equipment Requirements	10	5	5.0	6	6.0
Equipment Arrangement					
Integration with other equipment	20	4	8.0	6	12.0
Limitations on future construction	5	5	2.5	7	3.5
Maintenance access	15	6	9.0	5	7.5
Operation and supervision	10	5	5.0	4	4.0
Subtotal	50		24.5		27.0
Maintainability/Reliability	10	7	7.0	4	4.0
Controls and Instrumentation	10	5	5.0	7	7.0
Total	100		50.5		54.6

Table 4-4

Overall Technical Evaluation Weighting Table, Example 2

Evaluation Criteria	Weighting Factor	Vendor A		Vendor B	
		Score (1 - 10)	Weighted Score	Score (1 - 10)	Weighted Score
Attainment of Technical Requirements					
Chemical	10	5	5.0	6	6.0
Mechanical	5	5	2.5	4	2.0
Electrical	5	7	3.5	4	2.0
Structural	5	4	2.0	7	3.5
Subtotal	25		13.0		13.5
Attainment of Scope of Supply	5	4	2.0	3	1.5
Differential Support Equipment Requirements	5	5	2.5	7	3.5
Equipment Arrangement					
Integration with other equipment	10	4	4.0	6	6.0
Limitations on future construction	5	5	2.5	7	3.5
Maintenance access	15	6	9.0	5	7.5
Operation and supervision	10	5	5.0	4	4.0
Subtotal	40		20.5		21.0
Maintainability/Reliability	15	7	10.5	4	6.0
Controls and Instrumentation	10	5	5.0	7	7.0
Total	100		53.5		52.5

to 15% of the total. This distribution results in a much closer technical ranking of the two proposals, with Vendor A's proposal receiving a slightly greater score than Vendor B's proposal.

A comparison of Tables 4-3 and 4-4 indicates that even with relatively wide variation of the weighting factors, the two proposals are relatively equal on a technical basis. Frequently during proposal evaluations, several different weighting factor combinations are used to develop a more complete picture of the competing proposals' technical advantages and disadvantages. Evaluating the results of changes to the weighting factors and proposal scores is a common method of judging the sensitivity of the total score to the evaluation assumptions.

4.3 Economic Evaluation of Proposals

The economic evaluation of the case study proposals consists of determination of the total initial capital cost and total annual O&M costs and the evaluation of total lifecycle costs and capital recovery period. The assumptions used in this case study economic evaluation are presented in Section 2.7.

As stated in Part III, Section 3.3--Economic Evaluation of Total Costs, there are several classical methods for conducting an economic evaluation of alternatives, including capitalized cost method, annualized cost method, total present value method, and capital recovery period method. Each of these methods is valid and will result in the same overall ranking; however, each has its inherent strengths and weaknesses. The choice among them is based on utility management preferences and standard economic evaluation procedures. This case study will use the capital recovery method described in Part III, Section 3.3 because it is frequently used by electric utilities to justify capital expenditures and it provides a good comparison of the relative effects of capital and annual costs on the evaluation.

In conducting an economic evaluation by the capital recovery basis, the evaluator determines the **total initial capital cost*** and calculates the cumulative **present value** of the **fixed charges** on this amount over the total operating life of the system. The evaluator then projects the annual O&M costs for each year of operation. For each year, the cumulative total present value is then calculated using the following formula:

$$\Sigma_x \text{ PV of Total Cost} = \Sigma_L \text{ PV of Fixed Charges} + \Sigma_x \text{ of Annual Costs} \quad \textbf{(4-1)}$$

where: Σ_x PV = Cumulative present value from commercial operation through year "x"; and
Σ_L PV = Cumulative present value for life of system.

4.3.1 Determination of Total Initial Capital Cost

The total initial capital cost is the total cost of the FGD system and its support equipment. The total cost consist of the following:

- Vendor's base proposal cost;
- Technical adjustment costs;
- Scope-of-supply adjustment costs;
- Differential support equipment adjustment costs; and
- Economic adjustment costs.

Each of these cost components is discussed in detail in Part III, Section 3.0. The total initial capital costs for the two case study proposals are presented in Table 4-5.**

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* A glossary of economic evaluation terms is provided in Part III, Section 3.5--Glossary of Terms.

** All costs used in this case study are for purposes of illustration only and <u>should not be considered as estimates of the costs of actual equipment</u>.

Table 4-5

Capital Cost Comparison

Item	Vendor A	Vendor B
Base Proposal Cost	$35,283,000	$33,216,000
Technical Adjustments		
Specified electrical motor manufacturer	$127,000	$0
Witnessed absorber spray pump test	$0	$25,000
Specified knifegate valve manufacturer	$0	No charge
Specified control valve manufacturer	$15,000	$0
Subtotal	$142,000	$25,000
Scope of Supply Adjustments		
Ductwork expansion joints	$65,000	$0
Additional 45-tonne/h ball mill	$0	$1,300,000
Delete electrical grounding system	$0	($90,000)
Subtotal	$65,000	$1,210,000
Total Adjusted Proposal Cost	$35,490,000	$34,451,000
Differential Support Equipment Adjustments		
Absorber building	$1,000,000	Base
Reagent preparation building	Base	$200,000
Byproduct dewatering building	$75,000	Base
Subtotal	$1,075,000	$200,000
Economic Adjustments		
Escalation	$3,223,342	$3,032,980
AFDC	$6,726,543	$7,582,880
Subtotal	$9,949,885	$10,615,860
Total Evaluated Initial Capital Cost	$46,514,885	$45,266,860
Differential Initial Capital Cost	$1,248,025	Base
Levelized Annual Fixed Charges (30 years)*	$7,675,000	$7,469,000

* Levelized fixed charge rate (30 years) = 16.5 percent.

Base Proposal Costs

As shown in Table 4-5, Vendor B's base proposal cost is $2 million (5.5%) less than Vendor A's. This could have been anticipated from Vendor B's use of less expensive materials of construction for the absorber, reaction tank, and outlet ductwork. Also as noted earlier, Vendor B proposed a single ball mill for the reagent preparation system rather than the two mills specified.

Technical Adjustment Costs

The technical adjustment costs applied to each proposal are listed in Table 4-5. Technical adjustments were required for furnishing equipment from a specified electric motor supplier (Vendor A) and control valve supplier (Vendor A) and for conducting witnessed absorber spray pump tests (Vendor B). Vendor B agreed to provide knifegate valves from a specified supplier at no additional cost.

Scope-of-Supply Adjustment Costs

The scope-of-supply adjustment costs listed in Table 4-5 cover both the addition and deletion of equipment. Vendor A's proposal required an adjustment for furnishing the specified ductwork expansion joints. Vendor B's proposal required adjustments for furnishing a second ball mill and deleting the electrical equipment grounding system.

Differential Support Equipment Adjustment Costs

There are three major classifications of differential support equipment adjustment costs in Table 4-5:

- Absorber building--the building enclosing the absorber modules from grade level to just above the upper mist eliminator. This building also encloses the absorber spray pumps and absorber control room. For

Vendor A, this building also contains the primary dewatering hydrocyclones.

- Reagent preparation building--this building encloses the reagent ball mills, classifiers, and reagent feed pumps. The reagent slurry storage tanks will be located outdoors.

- Byproduct dewatering building--this building houses the horizontal vacuum filters and associated equipment. For Vendor B, the primary dewatering hydrocyclone are also located in this building.

These three buildings are large structures with capital costs of several millions of dollars. For this reason, the tabulated values are the estimated differential costs based on the vendors' proposed equipment layouts. For purposes of this case study, it was assumed that Vendor A required more expensive absorber and byproduct dewatering buildings and that Vendor B required a more expensive reagent preparation building. All other support equipment, such as electrical supply, compressed air supply, instrument air supply, and access roads are assumed to be equal for the two proposals and are not listed in the table.

Economic Adjustment Costs

The economic adjustment costs consist of escalation and allowance for funds used during construction (AFDC). Both of these costs depend on each vendor's economic terms and conditions, especially their schedule of payments. The case study's assumed schedule of payments is presented in Table 4-6. These payment schedules are typical of the variations that might be seen in competing proposals.

Vendor A has requested 5% of the contract price to be paid at the award of the contract (working capital). Payment of 85% of the remaining contract price will occur over the next three years of design and construction. For simplicity, these payments will be assumed in the case study to occur at year's end, but in an actual proposal evaluation, the evaluator may wish to estimate payments quarterly or more frequently. The final 10% of the total contract price would be paid after the <u>satisfactory</u> completion of the performance tests.

Table 4-6

Economic Adjustment Costs

	Payment Schedule		Unescalated Payment		Escalated Payment		AFDC[*]	
	Vendor A	Vendor B	Vendor A	Vendor B	Vendor A	Vendor B	Vendor A	Vendor B
Contract award	5%	10%	$1,774,500	$3,445,100	$1,774,500	$3,445,100	$823,545	$1,598,871
1 year after award	15%	20%	$5,323,500	$6,890,200	$5,563,058	$7,234,710	$1,841,372	$2,394,689
2 years after award	30%	30%	$10,647,000	$10,335,300	$11,626,790	$11,394,668	$2,441,626	$2,392,880
3 years after award	40%	30%	$14,196,000	$10,335,300	$16,199,994	$11,964,402	$1,619,999	$1,196,440
Completion of tests	10%	10%	$3,549,000	$3,445,100	$3,549,000	$3,445,100	$0	$0
Total	100%	100%	$35,490,000	$34,451,000	$38,713,342	$37,483,980	$6,726,543	$7,582,880
Escalation					$3,223,342	$3,032,980		

[*] AFDC = allowance for funds used during construction.

	Vendor A	Vendor B
Escalation rate:	4.5%	5.0%
AFDC rate:	10.0%	10.0%

In many contracts, a portion of this final payment is released after the satisfactory completion of the initial performance test and the remainder after the satisfactory completion of the system reliability test. If the FGD system does not meet the specified performance guarantees during the performance tests, the final payment is normally withheld until the FGD system can be modified and retested. For simplicity, a single final payment one year after the completion of construction is assumed in this case study calculation.

Vendor B has requested 10% of the contract price to be paid at the award of the contract, with 80% of the remaining contract price paid in three installments over the next three years. The final 10% is retained until satisfactory completion of the performance test one year after the completion of construction.

Escalation--Escalation is calculated from the date of the proposal to the date of payment (several other start dates are possible and it is important for this date to be stated in the specification). The rate of escalation depends on the escalation index selected. For this case study, it is assumed that Vendor A has selected an index that the utility evaluation team expects to escalate at 4.5% per year. The index selected by Vendor B is expected to escalate at 5% per year. These rates are applied to the entire contract prices. In actual proposal evaluations, the vendors may identify portions of their proposal prices that are firm (not subject to escalation) and different indices for different portions of the project (material and labor, for example). In the case study, the portion of the contract price paid at the completion of the performance test is assumed to be fixed. Variations such as these make the calculation of escalation adjustment costs a complex activity. The use of an electronic spreadsheet greatly aids in this effort.

Table 4-6 indicates the calculated unescalated and escalated payments to each vendor using the vendors' total adjusted proposal cost (base proposal cost, technical adjustment costs, and scope of supply adjustment costs), payment schedule, and rate of escalation. Escalation is the difference between the total adjusted proposal cost and the sum of the escalated payments. The calculated escalation is added to the total adjusted cost in Table 4-5.

AFDC--AFDC is calculated from the date of payment to the date of commercial operation of the system using the escalated costs and vendor's payment schedules. The utility evaluation team has determined to use an AFDC rate of 10 percent. Table 4-6 indicates the AFDC costs of each proposal. The calculated AFDC is added to the total adjusted cost in Table 4-5.

Total Initial Capital Cost

The total evaluated initial capital cost of the two proposals is presented in Table 4-5. Vendor B's proposal has a differential initial capital cost approximately $1.2 million (2.7%) less than Vendor A's. Depending upon the accuracy of the calculation of cost adjustments, this difference may be within the range of error in the analysis.

4.3.2 Determination of Annual O&M Costs

Annual O&M costs are the costs of operating the FGD system. In most cases, these costs are proportional to the unit annual operating load or the amount of SO_2 removed from the flue gas. Annual O&M costs will be evaluated at the generating unit's annual capacity factor of 65 percent. The following annual O&M cost categories were evaluated:

- FGD system electric power consumption;
- Limestone reagent;*
- Byproduct moisture credit;
- Makeup water and service water consumption;

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* Since the use of chemical additive is not required to achieve the required SO_2 removal efficiency, chemical additive costs will not be evaluated.

- Flue gas pressure drop (induced draft fan power consumption);
- Operating and maintenance labor;
- General maintenance materials; and
- Absorber and ductwork lining repairs and replacement.

For several of these cost categories, the consumption rates at 65% load were listed earlier, in Table 4-2. The O&M economic evaluation factors for most of these categories were presented previously, in Section 3.5--Proposal Economic Evaluation Factors.

The annual costs for the two proposals are summarized in Table 4-7. Vendor B's proposal has a differential levelized annual cost of $336,700.

Because the annual O&M costs are evaluated on a differential cost basis, some annual O&M cost categories are not included in the above list. The amount of SO_2 removed determines the volume of byproduct solids produced. Because the two proposals are being evaluated at the specified SO_2 removal efficiency they would generate approximately the same dry weight of gypsum, and the differential revenue from gypsum sales would be zero. The differential revenue from Vendor B's reduced byproduct moisture will be evaluated, however. The technical review of the proposals determined that the volume of wastewater generated was the same in each proposal; therefore, the differential O&M costs of this support system would also be zero.

FGD System Electric Power Consumption

At 65% unit load, Vendor B's proposed system would consume approximately 4.4 million kilowatt-hours more energy per year than Vendor A's. This results in a differential levelized annual cost of $350,400.

Table 4-7

Differential Levelized Annual O&M Cost Comparison

Item	Vendor A	Vendor B
Electric power	Base	$350,400
Limestone reagent	Base	$38,200
Gypsum moisture credit	$0	($86,900)
Cooling tower blowdown makeup water	$5,900	Base
Service water	Base	$8,200
ID fan power	Base	$39,000
Operating & maintenance labor	$83,200	Base
Maintenance material	Base	$50,000
Annual absorber/ductwork lining maintenance	$6,000	$32,900
Total levelized annual O&M cost	$95,100	$431,800
Differential levelized annual O&M cost	Base	$336,700

Limestone Reagent

Vendor B's proposal is based on a reagent utilization of 95% compared to Vendor A's reagent utilization of 97 percent. Based on 95% SO_2 removal efficiency and 65% unit load, Vendor B's proposed system would consume approximately 0.2 tonnes per hour more limestone than Vendor A's. This results in a differential levelized annual cost of $38,200.

Byproduct Moisture Credit

Vendor B's proposed byproduct dewatering equipment produces a filter cake with only 8% moisture, while Vendor A's proposed equipment achieves 10% moisture. Based on 95% SO_2 removal efficiency, either vendor's FGD system would produce approximately 16 tonnes per hour of gypsum (dry weight). The premium of $0.62 per dry tonne for the drier filter cake produces a levelized annual credit of $86,900 for Vendor B.

Makeup Water and Service Water Consumption

Review of the total FGD system water requirements in Table 4-2 indicates that both vendors require approximately the same quantity of total makeup water, 34 L/s at design conditions and 22.5 L/s at 65% load. However, the proposed systems differ in their relative requirements for service water and cooling tower blowdown (the other makeup water source). Vendor A's proposal uses relatively more cooling tower blowdown and has a differential levelized annual cost of $5,900 for this source. Vendor B uses relatively more service water and has a differential levelized annual cost of $8,200 for this source.

Induced Draft Fan Power Consumption

Compared to Vendor A, Vendor B's proposed system has a differential flue gas pressure drop at 65% load of 0.05 kPa. This results in a differential levelized annual cost for induced draft fan power of $39,000.

Operating and Maintenance Labor

O&M labor is not a value guaranteed by the FGD system vendors. The vendors are typically willing to make recommendations on staffing, but the final decisions are made by the utility. For purposes of illustration, it is assumed that after reviewing the proposed equipment and arrangements, the utility has determined that Vendor B's proposed system would require one additional maintenance worker, one shift per day, five days per week. This results in additional levelized annual labor costs of $50,000.

General Maintenance Materials

Like O&M labor, the cost of maintenance materials consumed is not typically guaranteed by the FGD system vendors. For this case study, it is assumed that the utility evaluation team has reviewed the numbers, types, and manufacturers of the proposed equipment and has made an estimate of the differential annual maintenance costs. A differential levelized charge of $50,000 is assessed against Vendor B's proposal.

Absorber and Ductwork Lining Repairs and Replacement

Both the C-class alloys proposed by Vendor A and the reinforced resin linings proposed by Vendor B for lining the absorber, reaction tank, and outlet ductwork require periodic inspection and repair. Typically, this can be conducted during the boiler maintenance outages. Alloy-clad and -wallpapered areas are examined for pitting and damaged welds. Reinforced resin-lined areas are examined for blistering, pinholes, and excessive wear.

For purposes of the bid evaluation, it is assumed that the levelized annual cost of alloy cladding/wallpaper inspection and repair will be \$1.75 per m^2, based on the total clad/lined surface.* The alloy materials are assumed to last the 30-year operating life of the FGD system. The inspection and repair of alloy clad/wallpapered surfaces results in a levelized annual cost of \$6,000 for Vendor A's proposal.

Vendor B's lining replacement guarantee was presented previously, in Section 4.2.3--Evaluation of Technical Requirements. Annual replacement of 3% of the reinforced resin linings and 2% of the foamed borosilicate glass block duct lining are estimated to have levelized costs of \$10.45 per m^2 and \$6.96 per m^2, respectively, based on the total lined surfaces. This results in a levelized annual cost of \$32,900 for Vendor B's proposal.

On the basis of a 30-year operating life for the FGD system and 10-year life of the reinforced resin lining, the absorber/reaction tank will be completely relined during the eleventh and twenty-first years of operation. Assuming 5% escalation over this period, the replacement costs for the first and second lining replacements will be \$1,312,000 and \$2,137,000, respectively. A discussion of the use of these values in the lifecycle cost calculation will be presented in the following section.

4.3.3 Evaluation of Total Lifecycle Costs

The first step in developing the lifecycle costs of the alterative proposals is to determine the total present value of the fixed charges for the life of the system (Σ_L PV of the fixed charges). The levelized fixed charges for Vendor A's and B's proposals were listed in Table 4-5 as \$7,765,000 and \$7,469,000, respectively. For the 30-year life of the system, the Σ_L PV of the fixed charges is determined by multiplying these levelized annual costs by the sum of the present value factors for 30 years. At 10% interest, the sum of the present value

* This cost does not include the cost of erecting the scaffolding required to reach all clad/wallpapered areas inside the absorber and ductwork. Approximately the same amount of scaffolding would be required by either alloy or reinforced resin-lined construction; therefore, erection of scaffolding would not produce any differential cost.

factors for 30 years is 9.427. The resulting Σ_L PV of the fixed charges is approximately \$72.3 million for Vendor A and \$70.4 for Vendor B. In Table 4-8, these costs are credited in year "0," the start of the first year of operation.

Next, as indicated in Equation 4-1, the present value of the annual costs is added to the Σ_L PV of the fixed charges, for each year of operation. For accounting purposes, these costs are credited in December of each operating year. Table 4-7 listed the total levelized annual O&M costs of Vendor A's and B's proposals as \$95,100 and \$431,800, respectively. In Table 4-8, the present value of these annual costs is entered for each year of operation, and a cumulative sum is tabulated.

The cumulative present value of the total cost for each year (Σ_x PV of the total cost) is then calculated by adding the Σ_L PV of the fixed charges with the Σ_x PV of the total annual costs, every year for the life of the FGD system. For Vendor A, Table 4-8 indicates that the Σ_L PV of the fixed charges and annual costs is approximately \$73.2 million. The cumulative present value over the life of the FGD system is shown graphically in Figure 4-7. The value at year "0" is the Σ_L PV of the fixed charges.

Calculating the Σ_L PV for Vendor B's proposal is complicated somewhat by the replacement of the absorber's and reaction tanks' reinforced resin liners in the eleventh and twenty-first year of operation. For the case study, the lining replacements are handled as future capital costs with a 10-year life. The levelized fixed charge rate on equipment with a 10-year life is assumed to be 22.5%, based on the escalated cost. Using the escalated liner replacement costs presented in Section 4.3.2, this results in a levelized annual cost of \$295,000 in years 11 through 20 and \$480,825 in years 21 through 30. These costs are shown in Table 4-8.

Because the lining replacements are being treated as future capital costs, the sum of the present value of the relining fixed charges is charged as a lump sum in the year of the installation. Table 4-8 indicates that the total present value of the first lining replacement

Table 4-8

Capital Recovery Period Analysis

Year	PVF*	Vendor A: PV of Annual Cost	Vendor A: Cumulative PV of Total Annual Cost	Vendor B: PV of Annual Cost	Vendor B: Liner Replacement FC**	Vendor B: PV of Liner Replacement FC	Vendor B: Cumulative PV of Total Annual Cost
0	1.000	$72,351,154	$72,351,154	$70,409,925	$0		$70,409,925
1	0.909	$86,455	$72,437,608	$392,545	$0		$70,802,471
2	0.826	$78,595	$72,516,203	$356,860	$0		$71,159,330
3	0.751	$71,450	$72,587,653	$324,418	$0		$71,483,748
4	0.683	$64,955	$72,652,608	$294,925	$0		$71,778,673
5	0.621	$59,050	$72,711,658	$268,114	$0		$72,046,787
6	0.564	$53,681	$72,765,339	$243,740	$0		$72,290,527
7	0.513	$48,801	$72,814,140	$221,582	$0		$72,512,109
8	0.467	$44,365	$72,858,505	$201,438	$0		$72,713,547
9	0.424	$40,332	$72,898,837	$183,125	$0		$72,896,672
10	0.386	$36,665	$72,935,502	$166,478	$0		$73,063,149
11	0.350	$33,332	$72,968,834	$151,343	$295,200	$699,328	$73,913,821
12	0.319	$30,302	$72,999,136	$137,585	$295,200		$74,051,405
13	0.290	$27,547	$73,026,683	$125,077	$295,200		$74,176,482
14	0.263	$25,043	$73,051,726	$113,706	$295,200		$74,290,189
15	0.239	$22,766	$73,074,492	$103,369	$295,200		$74,393,558
16	0.218	$20,697	$73,095,188	$93,972	$295,200		$74,487,531
17	0.198	$18,815	$73,114,003	$85,429	$295,200		$74,572,960
18	0.180	$17,105	$73,131,108	$77,663	$295,200		$74,650,623
19	0.164	$15,550	$73,146,658	$70,603	$295,200		$74,721,226
20	0.149	$14,136	$73,160,794	$64,184	$295,200		$74,785,410
21	0.135	$12,851	$73,173,645	$58,349	$480,825	$439,162	$75,282,921
22	0.123	$11,683	$73,185,327	$53,045	$480,825		$75,335,966
23	0.112	$10,621	$73,195,948	$48,223	$480,825		$75,384,189
24	0.102	$9,655	$73,205,603	$43,839	$480,825		$75,428,028
25	0.092	$8,777	$73,214,380	$39,853	$480,825		$75,467,881
26	0.084	$7,979	$73,222,360	$36,230	$480,825		$75,504,111
27	0.076	$7,254	$73,229,614	$32,937	$480,825		$75,537,048
28	0.069	$6,595	$73,236,208	$29,942	$480,825		$75,566,990
29	0.063	$5,995	$73,242,203	$27,220	$480,825		$75,594,211
30	0.057	$5,450	$73,247,653	$24,746	$480,825		$75,618,957

Interest rate--10%.
Fixed charge rate: 30 years--16.5%, 10 years--2.5%.

* PVF = present value factor.
** FC = fixed charges.

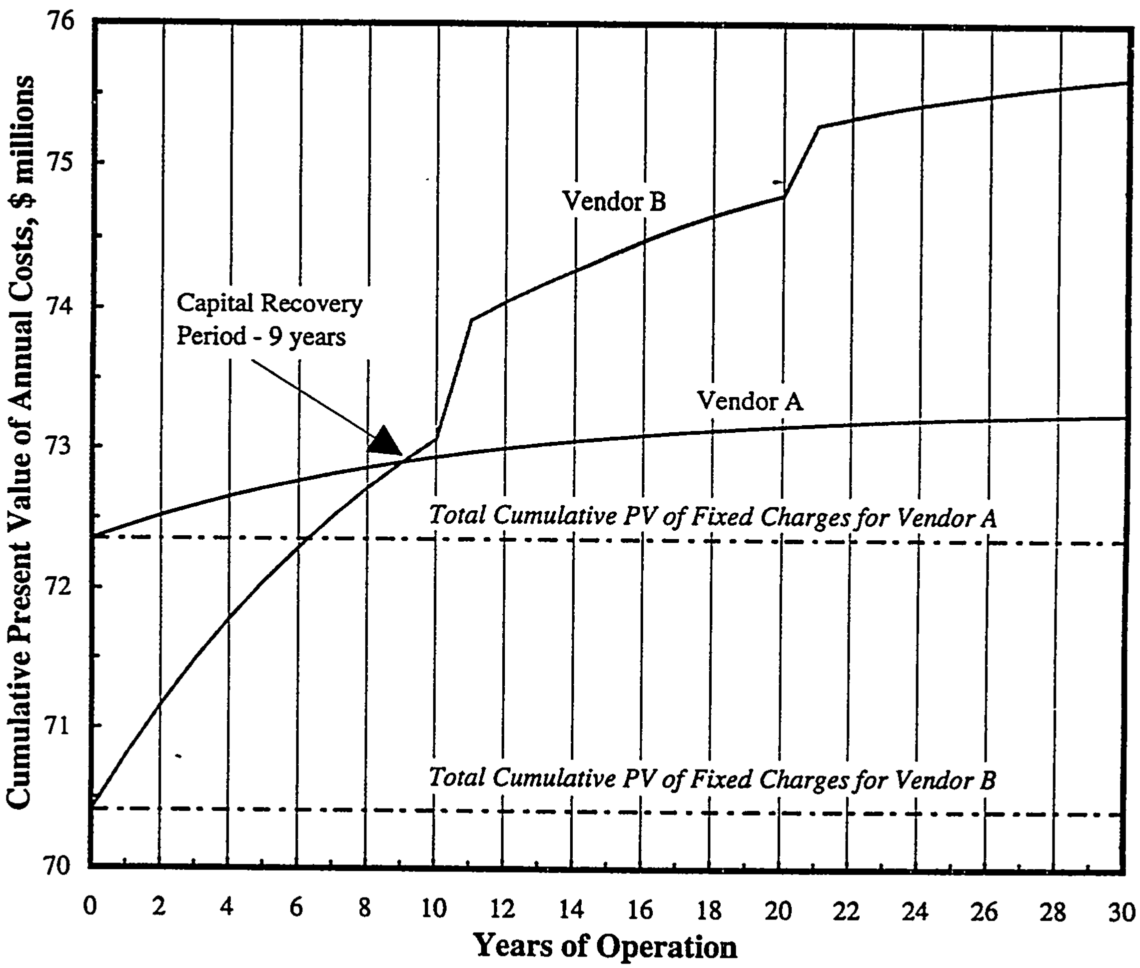

Figure 4-7. Capital Recovery Period Analysis Graph

is $699,328 and the second is $438,162. These two values are then added to the cumulative PV as an additional annual cost for the year of installation.*

As seen in Figure 4-7, this procedure for evaluating the lining replacement results in a sharp jump in the cumulative present value of the annual costs in the eleventh and twenty-first years of operation. The Σ_L PV of the fixed charges and annual costs is approximately $75.6 million.

4.3.4 Capital Recovery Period

As defined in Part III, Section 3.5--Glossary of Terms, the capital recovery period method of comparing alternatives is based on determining in what year of operation the alternatives would have the same Σ_L PV of the fixed charges and annual costs. This date is then compared against the utility's required capital recovery period for justification of capital projects. This is typically in the range of 7 to 10 years. Table 4-8 and Figure 4-7 indicate that the Vendor A's proposal (the higher initial capital proposal) has a capital recovery period of 9 years. Prior to the ninth year, Vendor A's proposal has a higher cumulative present value; after that date, it has a lower cumulative present value.

In the case study example, Vendor A's 9-year capital recovery period appears to meet the utility's requirements for a large capital project and would be the most advantageous proposal on the basis of total evaluated cost.

4.4 Recommended Alternative

Considering both technical and economic evaluations, it appears that the two vendors' proposals are very competitive and that the utility evaluation team could reasonably

* It should be noted that charging the cumulative present value of a lining replacement in a single year does not affect the magnitude of the final answer. Exactly the same Σ_L PV would have been calculated by adding in the present value of the relining fixed charges in each of the 10 years of the lining life.

recommend either. Depending on the technical evaluation weighting factors used, Vendor B's proposal is either superior or approximately equal to Vendor A' proposal. Economically, Vendor A's proposal has a capital recovery period within the utility's guidelines, but Vendor B's Σ_L PV is only 3% greater than Vendor A's, which is within the accuracy of most economic analyses.

Under these circumstances, a decision between the two proposals probably would be made on the basis of subjective factors such as:

- Past experience with the vendor on previous FGD projects;
- Vendor experience with limestone-based forced oxidation system producing commercial-quality gypsum;
- The quality of the vendors' proposals; and
- Availability of vendor resources (qualified technical and administrative personnel).

Often proposals are evaluated on these criteria in exactly the same manner as described previously for conducting the technical evaluation. Weighting factors and scores are assigned for each of the above categories and for the technical quality and evaluated total cost. The contract is awarded to the vendor with the highest overall score using all of these categories. An example evaluation of this type is presented in Table 4-9. Based on this evaluation, the recommendation would be to enter contract negotiations with Vendor A.

Table 4-9

Example of Overall Evaluation Scoring Table

Evaluation Criteria	Weighting Factor	Vendor A		Vendor B	
		Score (1 - 10)	Weighted Score*	Score (1 - 10)	Weighted Score
Past experience with vendor	10	8	8.0	3	3.0
Vendor experience with similar FGD systems	10	5	5.0	7	7.0
Quality and completeness of the proposal submitted	5	6	3.0	5	2.5
Availability of vendor resources	15	8	12.0	5	7.5
Technical quality of proposed system	30	5	15.0	6	18.0
Total evaluated cost	30	6	18.0	5	15.0
Total (out of 100 possible)	100		51.0		43.0

* Weighted Score = Weighting Factor x Score ÷ 10.